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Publication date
2025

Document Version
Final published version

Citation (APA)
Vafa, N., Korswagen, P., & Rots, J. (2025). *Comparative Study of Shear Interface Behavior in Calcium Silicate Bricks with Thick Mortar Joints and Blocks with Thin Mortar Joints*. Paper presented at 15th Canadian Masonry Symposium 2025, Ottawa, Ontario, Canada.
https://www.canadamasonrydesigncentre.com/wp-content/uploads/15th_symposium/127-Vafa.pdf

Comparative Study of Shear Interface Behavior in Calcium Silicate Bricks with Thick Mortar Joints and Blocks with Thin Mortar Joints

Navid vafa[i], Paul Korswagen [ii] and Jon Rots[iii]

ABSTRACT

Terraced buildings with cavity walls are among the most common types of construction in the northern part of the Netherlands. Since 1980, the inner walls of these buildings have been constructed using either calcium silicate bricks (214 × 102 × 75 mm) with thick mortar joints (10 mm) or, more recently, calcium silicate blocks (437 × 198 × 100 mm) with thin mortar joints (3 mm). The shear properties of these units play a crucial role in the seismic response of buildings, particularly in regions like Groningen, which is prone to seismic activity due to artificial extraction. This study investigates the shear interface behavior of these two types of masonry units by testing multiple triplet samples under varying levels of normal stress at the interface. The results provide detailed insights into the shear properties of both brick and block masonry, offering valuable data for enhancing the accuracy of numerical simulations and predicting the structural capacity of these types of masonry buildings.

KEYWORDS

Calcium Silicate Masonry, Shear Triplet, Cohesion, Friction.

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INTRODUCTION

Masonry construction has long been a fundamental component of the built environment, valued for its durability, structural integrity, and architectural appeal. In the northern Netherlands, particularly in Groningen, terraced buildings with cavity walls are a predominant architectural style. Traditionally, the inner walls of these buildings have been constructed using calcium silicate bricks (200 × 100 × 75 mm) with thick cementitious mortar joints (10 mm). More recently, construction practices have transitioned toward larger calcium silicate blocks (420 × 200 × 100 mm) bonded with thin adhesive mortar joints (3 mm). This shift in construction methodology necessitates a comprehensive understanding of the shear interface behavior between these masonry units, especially given the seismic activity in the Groningen region caused by natural gas extraction [1, 2].

The shear properties of the brick-mortar interface play a critical role in determining the seismic performance of masonry structures. The integrity of this interface affects load transfer mechanisms and governs the structural response to lateral forces induced by earthquakes. The Groningen region has experienced induced seismicity, prompting urgent concerns regarding the resilience and safety of existing masonry buildings [3, 4]. Thus, a precise evaluation of shear interface behavior is essential for structural assessments, retrofitting strategies, and numerical modeling aimed at predicting masonry performance under seismic loads.

Previous studies have extensively investigated the mechanical behavior of masonry, with a particular focus on the influence of mortar joint thickness on cohesion and frictional properties [5, 6]. Experimental research has demonstrated that thin-layer mortared masonry exhibits distinct mechanical characteristics compared to thick-joint masonry, particularly in terms of shear strength and failure mechanisms. Moreover, investigations into hollow and solid calcium silicate blocks have highlighted the impact of block geometry and material composition on the overall shear and flexural performance of masonry walls [7]. The deformational behavior at the brick-mortar interface has also been identified as a key factor influencing compressive and shear strength, underscoring the need for precise characterization of interface properties in masonry structures [8].

In the context of seismic performance, numerous studies have evaluated the in-plane cyclic behavior of calcium silicate masonry walls through quasi-static cyclic tests. These tests have provided valuable experimental data on the ability of masonry to withstand lateral loads while offering insights into stiffness degradation and energy dissipation [9]. Numerical simulations have further supplemented these experimental findings, enabling the development of robust computational models to predict masonry behavior under varying loading conditions. However, despite these advancements, there remains a significant gap in the literature concerning the comparative shear interface behavior of traditional calcium silicate bricks with thick mortar joints and modern calcium silicate blocks with thin adhesive mortar.

This study seeks to address this gap by conducting experimental shear triplet tests on both masonry types under varying levels of normal stress at the interface. The findings will contribute to a more accurate understanding of shear resistance mechanisms, thereby enhancing numerical modeling accuracy and improving the structural assessment of terraced masonry buildings in seismic regions.

EXPERIMENTAL APPROACHES

Shear properties at the masonry interface are commonly assessed through both standardized testing methods and custom experimental setups. The most widely utilized techniques are illustrated in Figure 1, while a comparative evaluation of their advantages and limitations is presented in Table 1. Among the various testing configurations, the shear triplet test, as depicted in Figure 1(d), was selected as the most suitable method for the experimental campaign.

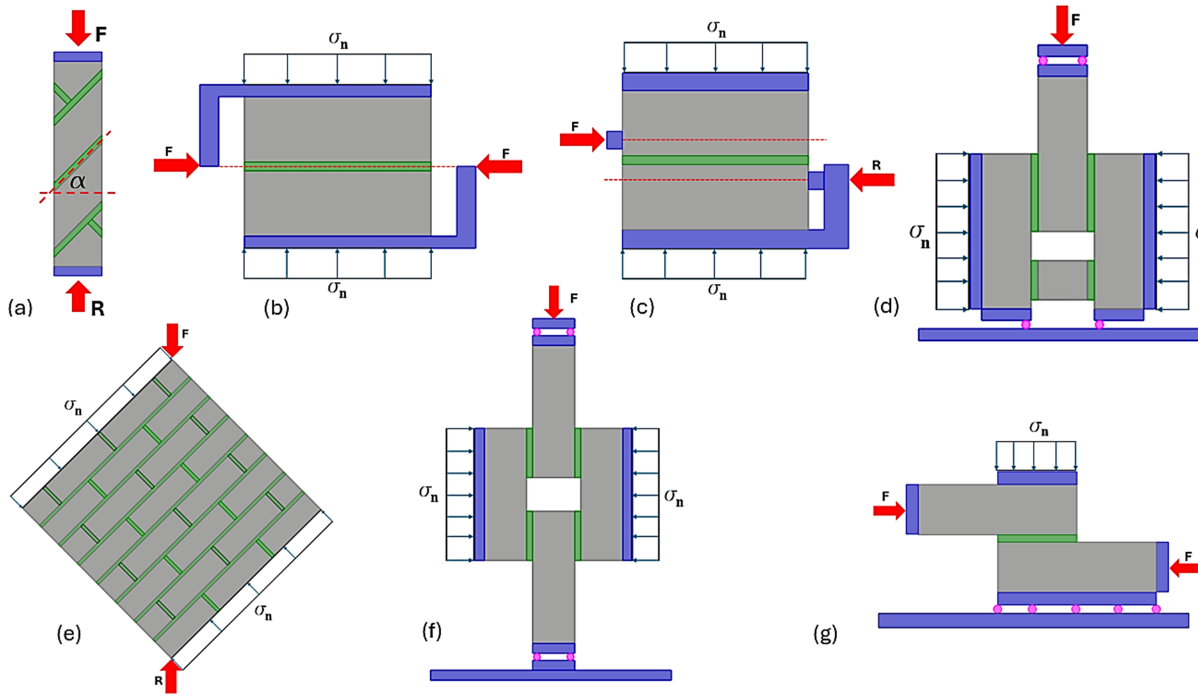


Figure 1: Common test setups for shear testing.

Table 1: Advantages and limitations of shear test

Test Name	Description	Advantages	Limitations	Applications
Nuss Shear Test (a)	Evaluates bond strength between clay masonry units and mortar using shear along bed joints.	Provides detailed bond strength parameters; useful for clay masonry research.	Not widely standardized or adopted; focused on clay masonry.	Research on bond strength for clay masonry systems.
Van der Pluijm's Test (b)	Uses a triplet configuration to analyze shear strength under varying normal stresses.	Widely used for numerical model calibration; systematic and controlled.	Limited to laboratory conditions; does not represent full-scale behavior.	Calibrating numerical models; studying interface mechanics.
Lourenço's Test (c)	Compact shear box test focusing on single mortar joints.	Simple, compact, and effective for single-joint analysis.	Focuses only on single joints; excludes multi-joint behavior.	Investigating bond-slip behavior and cohesion-friction analysis.
Shear Triplet Test (EN 1052-3) (d)	Standardized test with shear applied to the central unit in a triplet under precompression.	Standardized and reliable; provides robust shear strength and friction data.	Does not represent full-scale masonry behavior.	Design and research in compliance with Eurocode 6.

Table 1: Continued

Diagonal Tension Test (e)	Evaluates in-plane shear strength of walls by inducing failure along a diagonal plane.	Simulates realistic in-plane forces; captures combined stress states.	Results influenced by both units and mortar; difficult to isolate interface properties.	Evaluating shear capacity and seismic performance of masonry walls.
Meli's Test (f)	Simulates in-plane shear behavior of larger masonry assemblies under controlled conditions.	Captures overall system behavior; effective for seismic performance analysis.	Resource-intensive and complex; not suitable for isolating interface properties.	Structural behavior analysis under shear loads, especially seismic conditions.
Direct Shear Test (g)	Applies horizontal shear force to a single interface under constant normal load.	Easy setup; isolates interface behavior with direct shear strength measurements.	May not represent real-world masonry wall conditions.	Basic research on shear properties of masonry joints.

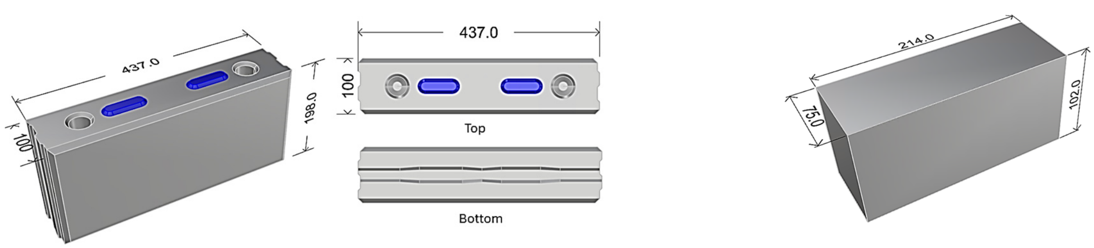
MATERIALS AND METHODS

Material

The materials used in this study include calcium silicate bricks and blocks, as detailed below:

1- Calcium Silicate Brick (CS-Brick): These bricks have dimensions of 214 × 102 × 75 mm and are laid using a 10 mm cementitious mortar with a mix ratio of cement, lime, and sand as 1:0:3. The compressive strength of the mortar is 6.6 MPa.
2- Calcium Silicate Block (CS-Block): The blocks have original dimensions of 437 × 198 × 100 mm and are bonded using a 3 mm adhesive mortar, commercially known as Lijmmortel in the Netherlands. The adhesive mortar is a premixed product with a compressive strength of 16 MPa.

The 3D view of CS-block and brick are presented in Figure 2. Both the calcium silicate bricks and blocks used in this study were sourced from the same manufacturer, Malk Kalkzandsteen, based in the Netherlands. These masonry units are widely utilized in construction across the Groningen region, particularly in terraced buildings with cavity walls. The mechanical properties of the materials are summarized in Table 2.



(a) Block (b) Brick

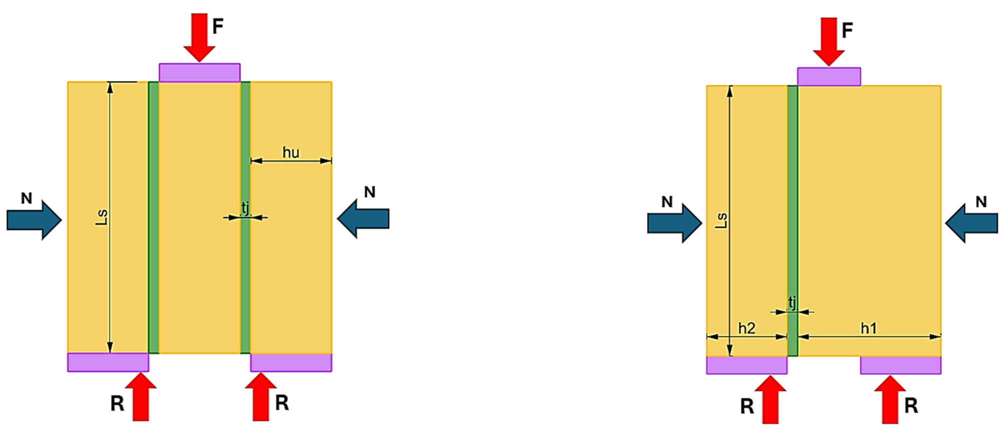
Figure 2: Dimensions of the units.

Table 2: Mechanical properties of the material.

Material	Compressive Strength (MPa)	Tensile Strength (MPa)	Density (kg/m^3)
CS-Brick	18.8	2.7	1780
CS-Block	12	2.2	1755
Mortar(1-C:0-L:3-S)	6.6	2.8	1700
Adhesive	16	2	1650

Specimen Preparation

The specimens were constructed in the Stevin II Laboratory at TU Delft University in the Netherlands, within a controlled indoor environment where temperature and humidity were carefully regulated to ensure consistent curing conditions and minimize environmental influences on the material properties. During the construction process, all bricks and blocks were thoroughly soaked in water to minimize their rate of water absorption from the mortar or adhesive. However, it is noteworthy that in practical construction, many masons tend to skip this step to maintain faster construction speeds. All specimens were cured for over two months to ensure full material stabilization, despite the adhesive mortar reaching its structural load-bearing capacity within 10 days. This extended curing period was implemented to eliminate any potential time-dependent effects on the shear interface behavior. All samples were prepared in accordance with the guidelines specified in EN 1052-3 [10]. For the calcium silicate blocks, modifications were necessary due to their larger dimensions compared to the bricks. The EN 1052-3 standard [10] outlines two types of specimens for conducting shear triplet tests, as illustrated in Figure 3. The selection of the specimen type is determined by the geometry of the masonry units, as specified in Table 3. Here, Lu represents the length of the unit, Ls denotes the recommended specimen length, and hu refers to the height of the unit. According to the standard, if the unit height (hu) exceeds 200 mm, Type II specimens are recommended.



Type 1 **Type 2**

Figure 3: Specimen type and Dimensions based on EN 1052-3[10]

For calcium silicate blocks, where the unit length (Lu) exceeds 300 mm and the height (hu) is less than 200 mm, Type I was selected as the reference specimen. This classification ensures compliance with the code requirements while maintaining consistency in specimen preparation.

Table 3: Dimensions and type of shear test specimen [3]

Unit Length	Specimen type and dimension	
Lu (mm)	Type	Dimensions
≤ 300	1	Ls= Lu
>300	1	300<Ls<350
≤ 300	2	h1= 200, Ls= Lu
>300	2	h1= 200, 300<Ls<350

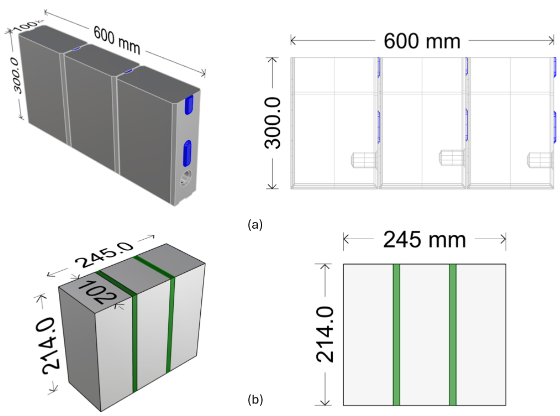


Figure 4: Geometry of samples, (a) CS-Block, (b) CS-Brick.

EXPERIMENTAL SETUP

Several configurations exist for the shear triplet test as shown in Figure 1, each offering specific advantages depending on the testing objectives. In this study, a setup has been designed as illustrated in Figure 5 in alignment with EN1052-3 [10]. This configuration allows for convenient placement of the sample, ensuring ease of operation. Additionally, it provides an unobstructed view in front of the sample, which is particularly beneficial for the application of Digital Image Correlation (DIC). In this arrangement, the left and right columns are securely fixed to the base rigid beam, providing stable support for the horizontal actuator and firmly holding the sample in place, as depicted in Figure 5.

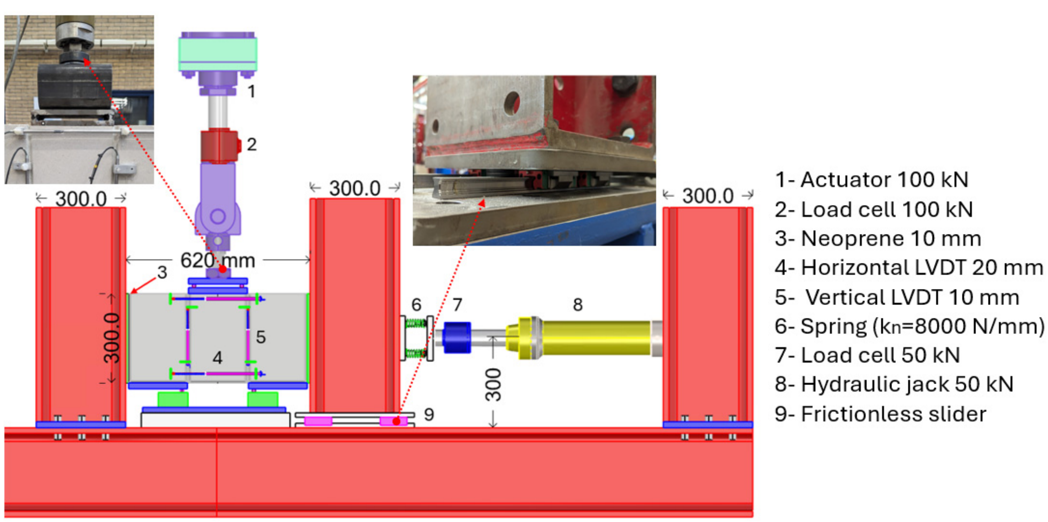


Figure 5: Shear test setup.

The middle column is positioned on frictionless support, ensuring that the total force applied by the horizontal hydraulic jack is fully transferred to the sample without dissipation. This setup also facilitates uniform stress distribution along the height of the sample by preventing localized force concentration. The horizontal hydraulic actuator has a capacity of 50 kN, and a 50 kN load cell is installed at the actuator head to precisely monitor the applied force.

To mitigate confinement effects due to mortar dilation, a spring was placed between the middle column and the horizontal hydraulic jack, allowing controlled movement and preventing artificial increases in normal stress at the interface. Without this adjustment, the system could overestimate shear resistance, introducing errors in the experimental results. Additionally, for larger specimens, such as calcium silicate blocks, non-uniform stress distribution may lead to localized bending effects, further affecting shear measurements. The middle column in this setup prevents it from resisting horizontal forces while maintaining bending resistance, ensuring accurate shear evaluation. These refinements help minimize error propagation in shear strength assessments. To ensure precise displacement tracking, LVDT supports were positioned based on unit dimensions, with 95 mm and 235 mm for CS-Block and 80 mm and 100 mm for CS-Brick, aligning with experimental requirements.

TESTING PROTOCOL

The experiment was conducted under displacement-controlled conditions, with the loading rate of the vertical actuator standardized at 0.002 mm/sec for all samples. During the precompression stage, considering that both masonry units exhibit a compressive strength exceeding 10 MPa, three distinct levels of precompression stress were applied: 0.2 MPa, 0.6 MPa, and 0.8 MPa. The pre-compression force was first introduced to the specimen, ensuring uniform stress distribution. Following this, the loading plates were carefully positioned on top of the middle unit, as illustrated in Figure 5. To further ensure uniform force transmission and eliminate any unintended bending moments, a ball hinge was placed at the center of the middle unit, allowing for proper load alignment and minimizing secondary stress effects on the sample. During the preparation phase, samples were precisely positioned on their designated supports, ensuring that the top surface of the middle unit remained horizontally level and that the vertical joints were perpendicular to this plane. This alignment was verified using a spirit level, as depicted in Figure 6 , to prevent any unintended eccentricities that could alter the test results.

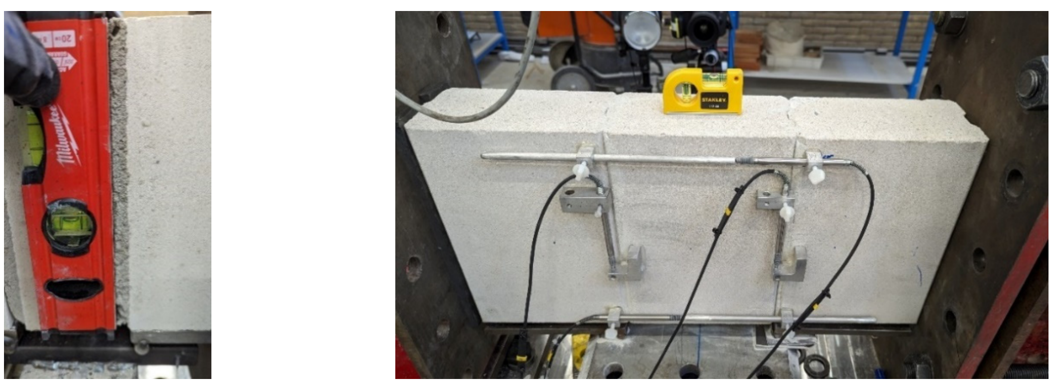


Figure 6: Levelling check by spirit level

RESULTS AND DISCUSSION

Failure modes

The shear strength of masonry joints depends on failure mechanisms that occur when applied forces exceed system resistance. Failure manifests as brick failure, mortar failure, or interface failure, with brick cracking in weak units, mortar crushing under stress, or joint slippage due to weak adhesion. CS-Block specimens primarily failed at the interface, indicating adhesion failure, while CS-Brick exhibited a combination of sliding and diagonal shear cracking, highlighting differences in shear resistance. Digital Image Correlation (DIC) effectively captured crack propagation and displacement fields, as shown in Figure 10.

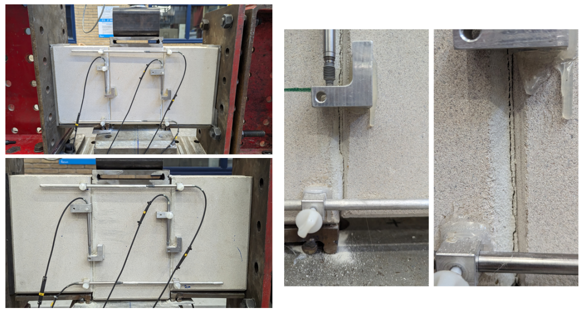


Figure 7: Failure mode in CS-Block.

Figure 8: Failure surface in CS-Block.

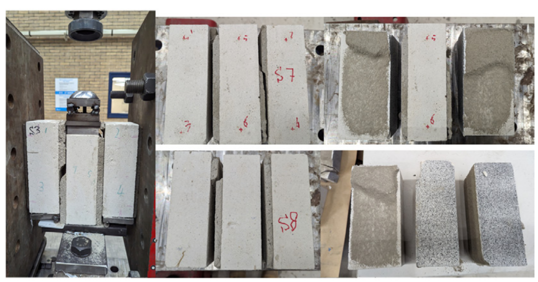
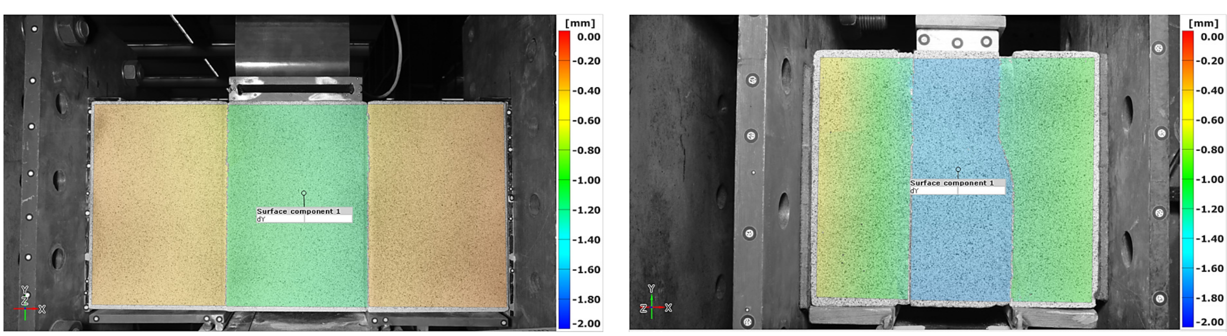


Figure 9: Failure mode and surfaces in CS-Brick



(a) (b)

Figure 10: Vertical deformation of samples: (a) CS-Block, (b) CS-Brick

Friction, Cohesion, Dilation and Residual friction

This section provides a deeper analysis of the shear behavior of CS-Brick and CS-Block samples under shear loading. As illustrated in Figure 11, the shear-sliding behavior reveals that CS-Blocks exhibit more brittle characteristics compared to CS-Bricks. Additionally, the reduction in normal stress observed at the peak shear stress in Figure 12 indicates that both materials generate a similar push-off force due to dilation expansion, despite differences in their mechanical responses. Sample 3 in Figure 11, shows a unique response due to asymmetric shear failure, with one joint failing before the other. The second peak in the load-displacement curve results from sample rotation following the initiation of the first crack.

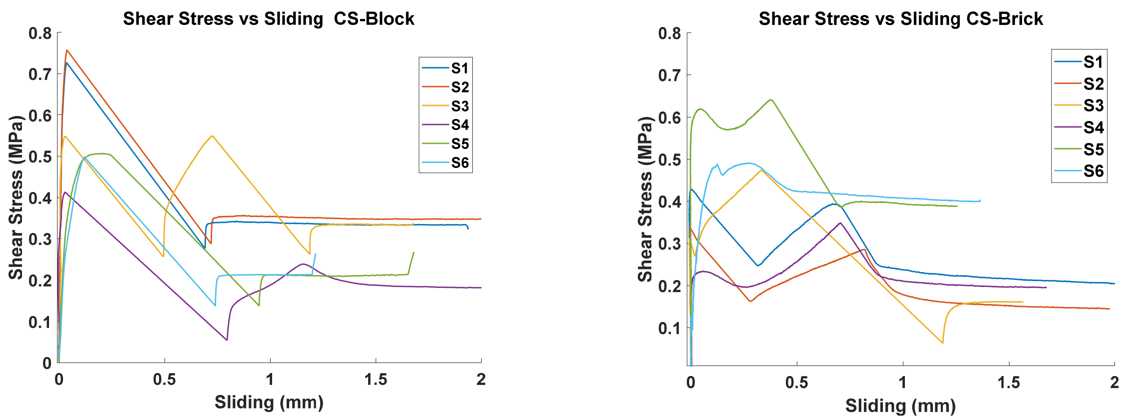


Figure 11: Shear-sliding behaviour

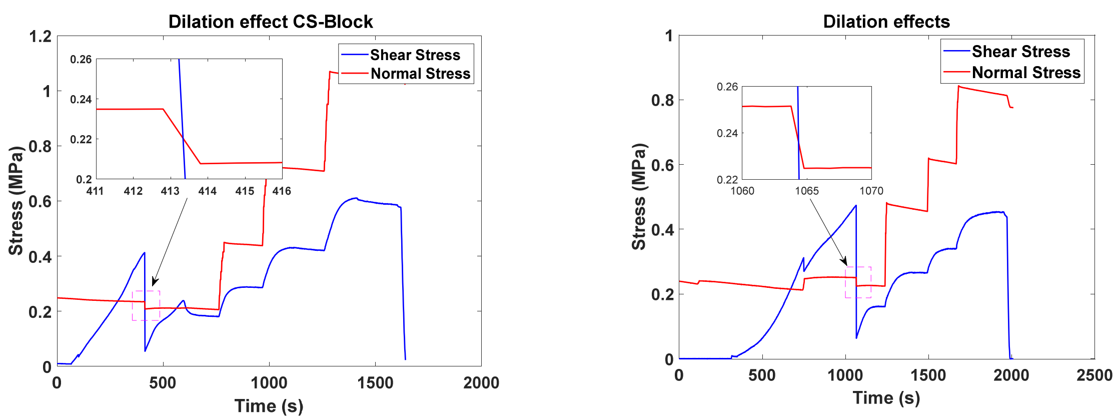


Figure 12: Dilation effects

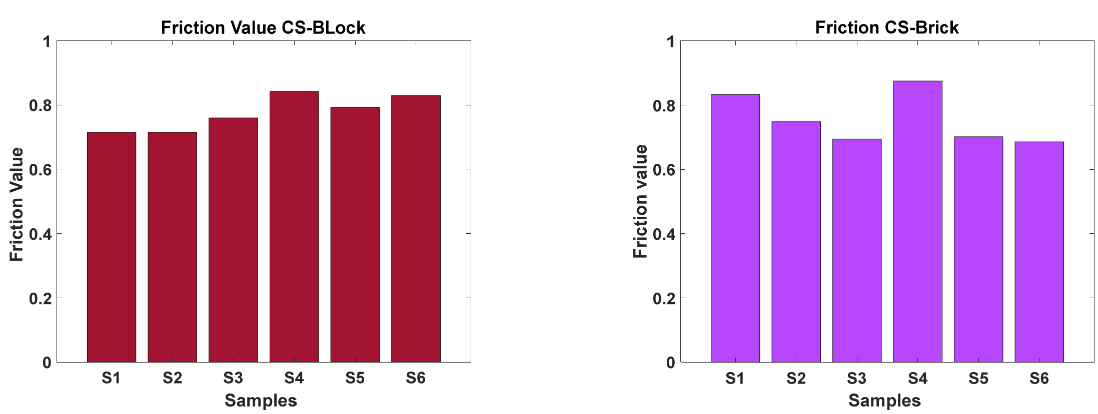


Figure 13: Friction value for the CS-Brick and Block

As illustrated in Figure 13, the average friction coefficient for the CS-Block interface is 0.8, whereas for the CS-Brick, it is slightly lower at 0.73. Furthermore, Figure 14 shows that the residual friction coefficient is 0.65 for the CS-Block and 0.6 for the CS-Brick, indicating subtle yet important differences in their frictional behavior under shear loading.

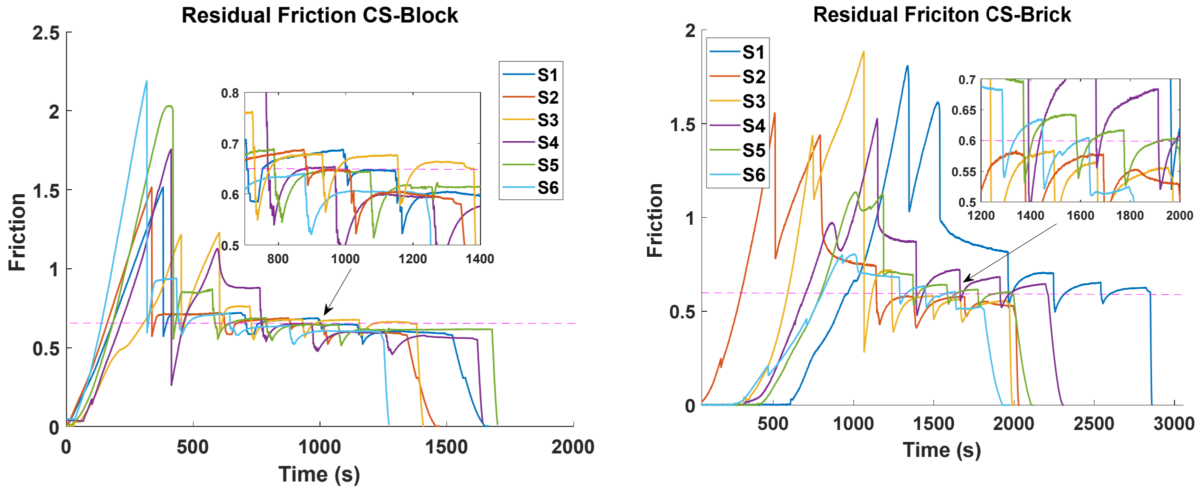


Figure 14: Residual Friction value for CS-Brick and Block

Figure 15 illustrates two key parameters; friction angle, and cohesion; that define the shear behavior at the masonry interface and are essential for the reliable modeling of masonry walls under lateral loading. In this study, these parameters were derived using the Mohr-Coulomb criterion, with cohesion represented by the intercept at zero normal stress (red star mark). The results reveal that CS-Brick exhibits higher cohesion than CS-Block, while the friction angle for CS-Block is nearly twice that of CS-Brick, underscoring significant differences in their shear response. Additional samples incorporating variations in normal stress will be tested to enhance the robustness of our findings, which will be detailed in a forthcoming study on the calibration of numerical models.

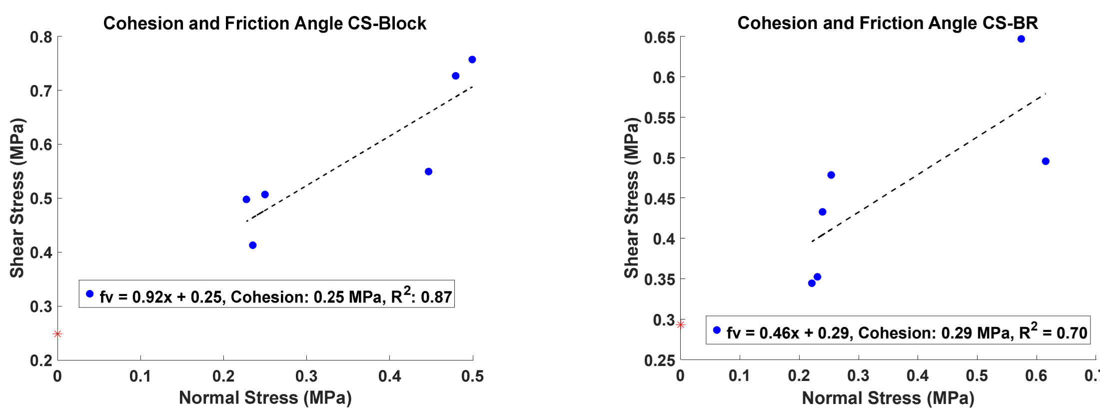


Figure 15: Cohesion and friction angle for CS-Brick and Block

Conclusion and Future Work

This study compared the shear behavior of calcium silicate bricks (CS-Brick) with thick mortar joints and calcium silicate blocks (CS-Block) with thin adhesive joints using shear triplet testing. The results showed that CS-Blocks exhibit more brittle behavior, with failure occurring primarily at the adhesive-block interface, indicating limited adhesion strength. In contrast, CS-Brick specimens displayed a combination of joint sliding and mortar shear failure, suggesting that mortar cohesion played a greater role in resisting shear forces. Additionally, CS-Blocks had a higher friction angle, nearly twice that of CS-Bricks, while CS-Bricks exhibited greater cohesion, making them more resistant under shear loading.

Future research should explore cyclic shear testing to assess seismic performance, investigate higher precompression levels, and conduct microstructural analysis to better understand interface adhesion mechanisms. Numerical modeling can further refine shear strength predictions, while testing improved adhesive mortars may enhance the performance of CS-Block masonry. These findings contribute to a deeper understanding of masonry shear behavior, aiding in the design, retrofitting, and seismic assessment of structures, particularly in regions prone to induced seismicity, such as Groningen.

ACKNOWLEDGMENTS

The support and funding provided by Instituut Mijnbouwschade Groningen (IMG) is gratefully acknowledged. Appreciation is also extended to the technicians at the Stevin II Laboratory of TU Delft for their assistance in conducting the experimental work.

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