STATIC-CYCLIC SHEAR TESTS ON MASONRY TRIPLETS WITH A DAMP-PROOF COURSE MEMBRANE

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ABSTRACT

A joint research project between ETH Zurich and University of Newcastle on the shear behaviour of masonry elements (triplets) with damp-proof course (DPC) membrane placed in the bed joints is underway. The main goal of the research project is to investigate the influence of DPC on masonry behaviour under static-cyclic shear load and to assess the shear mechanical characteristics. Load tests on four series of masonry triplets have been completed. The specimens consisted of three bricks and two bed joints with the DPC membrane being placed in the middle of the bed joints (Series A) or between the bed joints and the brick unit (Series B). For the test series typical Australian extruded clay bricks and embossed polythene DPC membrane have been used. Each series consisted of 9 specimens and a standard cement-lime mortar has been used to produce 10 mm thick bed joints. After at least 28 days of curing time the specimens were firstly subjected to a given pre-compression load and subsequently subjected to the cyclic shear load which was applied using computer controlled displacement steps. Each step was repeated twice in the form of a sinusoidal wave. Three different levels of pre-compression were considered (0.2 MPa, 0.6 MPa and 1.0 MPa) and for each level and for each specimen of both series A and B three replicates were tested. In addition, two Series, C and D (each consisted of three specimens), which corresponded to Series A and B, respectively, were tested under static loading. This paper presents preliminary results and discusses their significance in relation to current design practice.

KEYWORDS: clay brick, damp-proof course, shear, static-cyclic tests, unreinforced masonry

INTRODUCTION

The effective seismic design of unreinforced masonry structures is of prime importance, as they are susceptible to major damage and possible collapse under earthquake loading. In this context, the scientific significance of the establishing the basis for evaluating the seismic performance of structural masonry with an incorporated DPC membrane is very high. At a fundamental level, very little research in this area has been reported in the literature, thus leaving numerous questions unanswered. Possible advances established within the present project would improve this situation considerably. Static-cyclic tests were performed on a total of 24 specimens and provided data on the mechanical properties of the masonry with DPC (cohesion and friction coefficient), on the energy dissipation and on overall behaviour under static-cyclic loading.

Experimental work has been carried out using masonry materials produced in Australia, the findings, however, are generally applicable.

In previous investigations, a series of static, static-cyclic and dynamic tests on small masonry specimens with different types of damp-proof courses were performed and indicated that shear load can be transmitted through a joint containing a DPC. Griffith and Page [1] performed monotonic, static-cyclic and dynamic shear tests on small masonry elements (triplets) with different types of damp-proof course membranes: bitumen coated aluminium; polythene/bitumen coated aluminium and embossed polythene and reported the corresponding friction coefficients. The DPC membranes were placed in both mortar joints of the brick triplet; in one series the middle brick was made of concrete in order to simulate the concrete slab. Test specimens were initially subjected to a given level of pre-compression, which was kept constant during the test. The shear load was applied in the out-of-plane direction and the masonry materials used were typical extruded clay bricks with standard 1:1:6 (cement:lime:sand) mortar. Similar results were reported by Suter and Ibrahim [2], Zhuge and Mills [3], Simundic et al. [4], Totoev et al. [5] and Totoev and Simundic [6]. Recently, static-cyclic tests were performed on masonry wallettes subjected to static-cyclic shear loading with embossed polythene DPC incorporated either in a mortar joint or at the masonry-concrete slab interface, see Mojsilović et al. [7, 8]. Results from this investigation also confirmed good performance of the DPC subjected to cyclic loading. Finally, within the framework of the recently finished research project at ETH in Zurich on the shear behaviour of masonry elements (triplets) with DPC membrane placed in the bed joints, load tests on ten series of masonry triplets with three different DPC membranes (elastomer-, bitumen- and polythene-based membranes) have been completed. As a result of this project, the shear strength parameters, namely the cohesion and friction coefficient, of masonry elements with DPC placed in the bed joint subjected to in-plane shear force have been assessed and the overall structural behaviour has been investigated. The shear behaviour of the specimens was highly influenced by the applied pre-compression level with much less influence from the position of the DPC. For the prediction of the failure shear force a Mohr–Coulomb failure criterion can be applied. A considerable energy dissipation and large deformation capacity could be expected in masonry structures with such DPC incorporated in the bed joints, see also Mojsilović [9].

TEST PROGRAM AND MASONRY MATERIALS

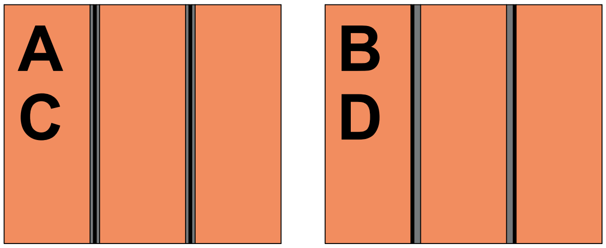

Figure 1: DPC Position within Test Specimen

The aim of the testing program was to obtain the above mentioned characteristics, namely mechanical properties, energy dissipation capacity and overall structural behaviour of the masonry with DPC by performing two test series on small masonry specimens (triplets). These specimens consisted of three bricks and two bed joints with the DPC being placed in the middle of the bed joints (Series A) or between the bed joints and the brick unit (Series B), see Figure 1. Both series have been tested in accordance with the European Testing Standard EN 1052-3 [10]. For both test series typical Australian extruded clay bricks with nominal dimensions 230x110x76 mm (25% void area) and embossed polythene DPC membrane have been used, see Figure 2. Tests were performed in the Civil Engineering Laboratory of the University of Newcastle.

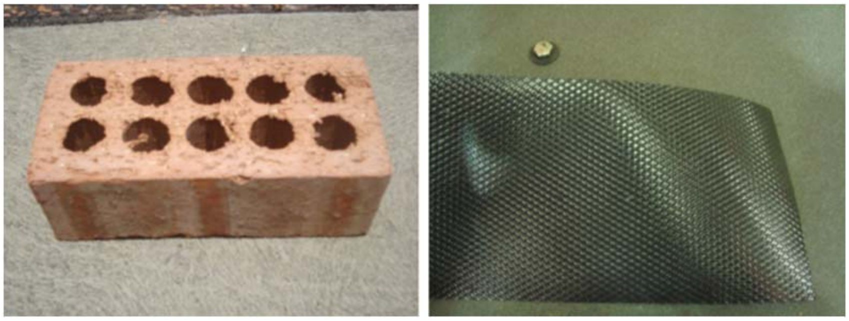

Figure 2: Clay Brick and DPC Membrane used in Tests

Each series consisted of 9 specimens and a standard 1:1:6 (cement:lime:sand) mortar was used to produce 10 mm thick bed joints. All specimens were built by a professional mason and were air cured at the testing site. After preparation and prescribed curing time (28 days) the elements were placed in the universal testing machine, firstly subjected to a given pre-compression and subsequently subjected to shear loading. The cyclic shear load was applied using computer controlled displacement steps. Three different levels of pre-compression were considered (0.2 MPa, 0.6 MPa and 1.0 MPa) and for each specimen of both series three replicates were tested for each level. In addition, two Test Series, C and D (each consisted of three specimens), which corresponded to the above mentioned Series A and B, respectively, were tested under static loading. A summary of the test program is given in Table 1.

Table 1: Sample Designation for Test Program

Series	**Pre-compression σ_{pc} [MPa]**		
	0.2	0.6	1.0
A	A1	A2	A3
B	B1	B2	B3
C	C1	C2	C3
D	D1	D2	D3

TEST SET-UP

Figures 3 and 4 show the test set-up. After preparation, the specimens, (1), were placed in the universal testing machine, between two load transmission elements, (2) and (3), and centred to avoid any bending influence. The shear load was applied by means of the upper (spherical-cap hinged) load transmission element, (2), which moved (firstly) downwards (push cycle) and subsequently upwards (pull cycle) during the test, whilst the lower load transmission element, (3), was static. The steel cylinders, (4), together with the upper and lower sets of steel plates, (5) and (6), ensured a proper shear load introduction into the specimen. The distance between the support cylinder centreline and the brick edge, i.e. bed joint, was 19 mm which was 1/4 of the height of the clay brick. To achieve a good contact between the steel plates, (6), and the specimen, thin dental plaster layers were applied on the upper and the lower edges of the specimen, cf. Figure 4. Both outer bricks were kept in position by means of four steel rods, (7), which were anchored in the static load transmission element, (3). Cyclic movement of the middle brick was ensured by means of the steel rods, (8), on both opposite sides of the specimen, which were fixed to the massive steel plate, (9).

In order to achieve a good contact between the specimen and the steel profiles, (11), used for the introduction of the pre-compression force, two plywood sheets, (10), were employed. The pre-compression force was introduced and kept constant by means of hydraulic jack, (12). Hydraulic jack, (12) and load cell, (13), which was used to monitor the applied pre-compression force, were kept in position by means of two rods, (14), on both opposite sides of the specimen. These rods were, in turn, kept in position by two steel profiles, (15).

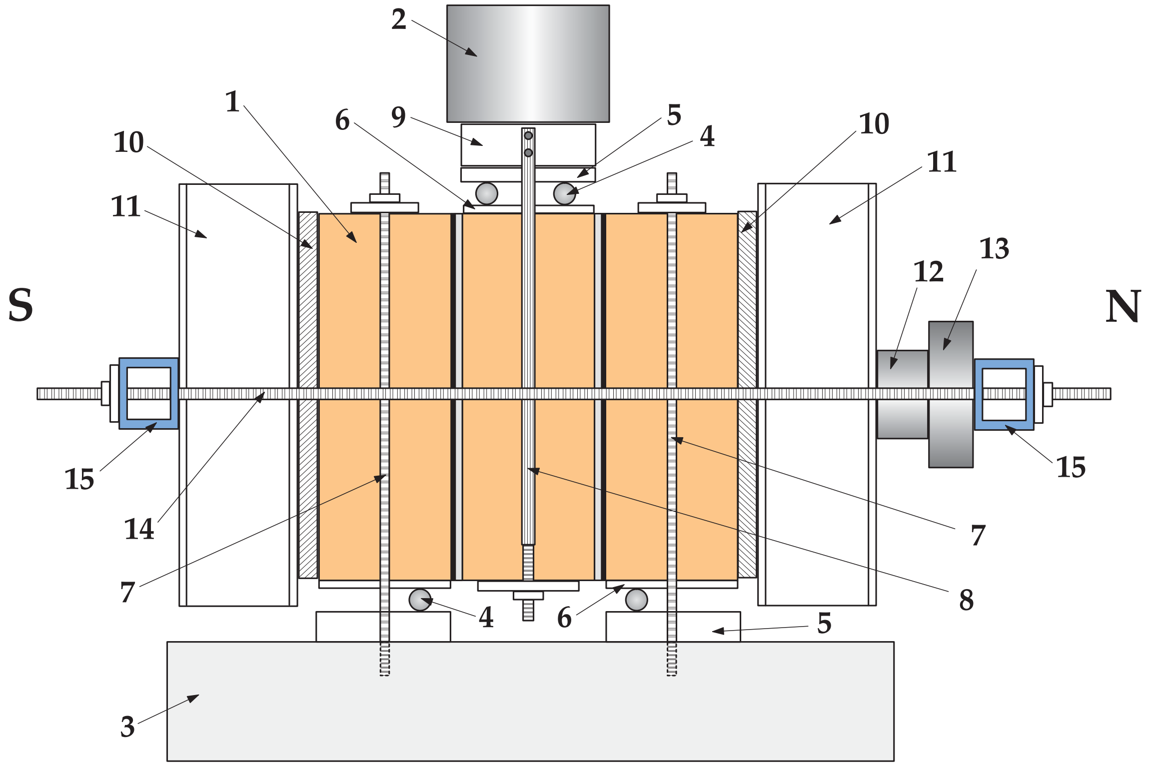

Figure 3: Test Set-up

Apart from the applied shear load, measurements included the difference of the vertical displacements (slip) between the outer and middle bricks of the specimen. These differential displacements were measured by means of two potentiometers, each on both east and west surface of the specimen, resting on the aluminium plates, which in turn were glued to the bricks, see Figure 4 (a). The pre-compression force was monitored during the test by means of the load cell (13) on the north side of the specimen, see Figure 4 (b). All measuring devices were connected to a personal computer, which processed the data in real time.

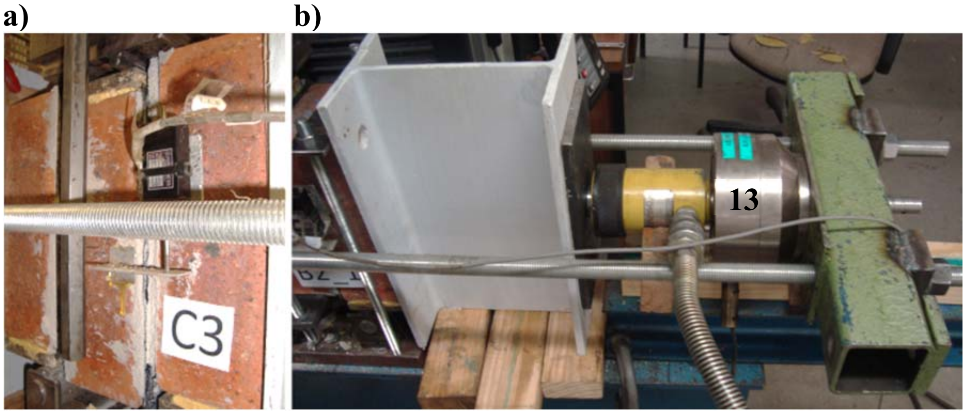

Figure 4: Measurements

The cyclic shear load was applied using computer controlled displacement steps. Each step was repeated twice in a form of a sinusoidal wave. At the beginning of the test, i.e. for small displacements, the loading speed was only 1 mm/min. For the larger displacement steps the loading speed was gradually increased up to 3 mm/min for the maximum applied displacement of 10 mm, see Table 2. This Table gives information on the duration (period length) of each load stage. Using this procedure, the test duration equalled 128 minutes.

Table 2: Loading History for Series A and B

Travel [mm]	0.5	1	1.5	2	3	5	7.5	10
Loading speed [mm/min]	1	1	1	1	2	2	2	3
Period [min]	2	4	6	8	6	10	15	13.3

TEST RESULTS

Table 3 shows the values of the minimum (push cycle) and maximum (pull cycle) recorded shear force obtained from the tests. Note that all tests, namely static-cyclic (Series A and B) and pure static tests (Series C and D) were started with the push cycle (negative value of the shear force in Table 3 and on Figures 5 and 6). The (absolute) recorded values for the specimens loaded statically (Series C and D) were clearly higher than those of the Series A and B, which were loaded cyclically. Figure 5 shows the shear force-deformation characteristics of selected specimens (showing one each of the three replicates per test) subjected to cyclic loading. The deformation value shown in the diagram is the relative displacement (slip), s, between the middle and the outer (on the north and south sides of the specimen) bricks. The graphs show an average of both values on the south and north sides.

Table 3: Test Results

Series	**Minimum/Maximum shear force [kN]**		
	σ_{pc} = 0.2 [MPa]	σ_{pc} = 0.6 [MPa]	σ_{pc} = 1.0 [MPa]
A	-9.56/8.02	-21.56/19.82	-31.88/31.74
B	-5.50/5.14	-15.98/15.02	-26.72/24.96
C	-12.58	-24.88	-35.76

D	-6.88	-16.76	-27.34

As can be seen from Figure 5, typical cyclic behaviour (hysteresis curves) has been observed for all levels of pre-compression and for both positions of the DPC membrane. The initial response of the specimens was linear-elastic and with increasing deformation evolved into an ideal-plastic horizontal branch (plateau). Further, all specimens exhibited considerable energy dissipation (area under the hysteresis envelope) and behaved in a quasi-ductile manner.

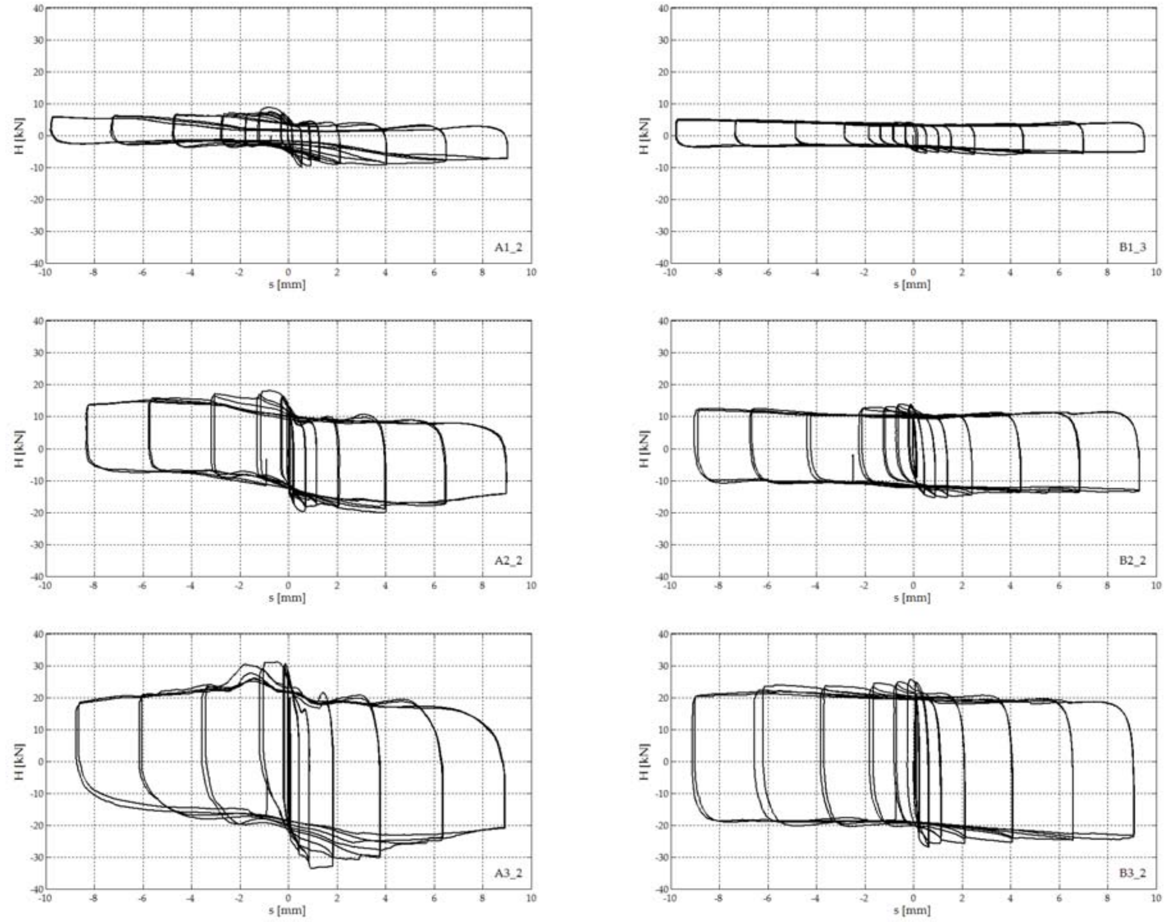

Figure 5: Shear Force-Deformation Characteristics for Series A and B (Cyclic Loading)

From Figure 6 it can be seen that the specimens of Series C (DPC sandwiched in the bed joint) behaved linear-elastically with a high stiffness up to the maximum value of shear force. Thereafter, softening behaviour could be observed. The specimens of the Series D, with DPC membrane placed between the mortar joint and outer brick, exhibited from the beginning a non-linear behaviour. Here, too, after reaching the maximum value the softening behaviour was observed. However, this phase was very short and subsequently the slope in the softening range was constant, except for the specimen D3 (see Figure 6).

During the cycling, a slip in the bed joint of the specimens was observed. Tests were interrupted after reaching a considerable shear deformation, meaning that the effective failure of the specimen was not reached. For the observed failure mode, i.e. sliding along the DPC in the bed joint, the shear deformation is theoretically unlimited. However, during the tests these deformations were limited by the test set-up and the measuring range of the applied potentiometers available. Figure 7 shows, typically, the shear deformation (sliding along the DPC) of the specimens A3_3 and B2_2. The slip planes formed always along the DPC membrane, as expected. For series A and C these planes formed between the bed joint mortar halves and DPC membrane and were evenly distributed between the south and north contact planes in each joint. For Series B and D, however, the slip planes were formed between the DPC membrane and adjoined brick. This means that, during the cycling, the DPC membrane has been moving together with the middle brick and bed joints, see also Figure 7 (Specimen B2_2).

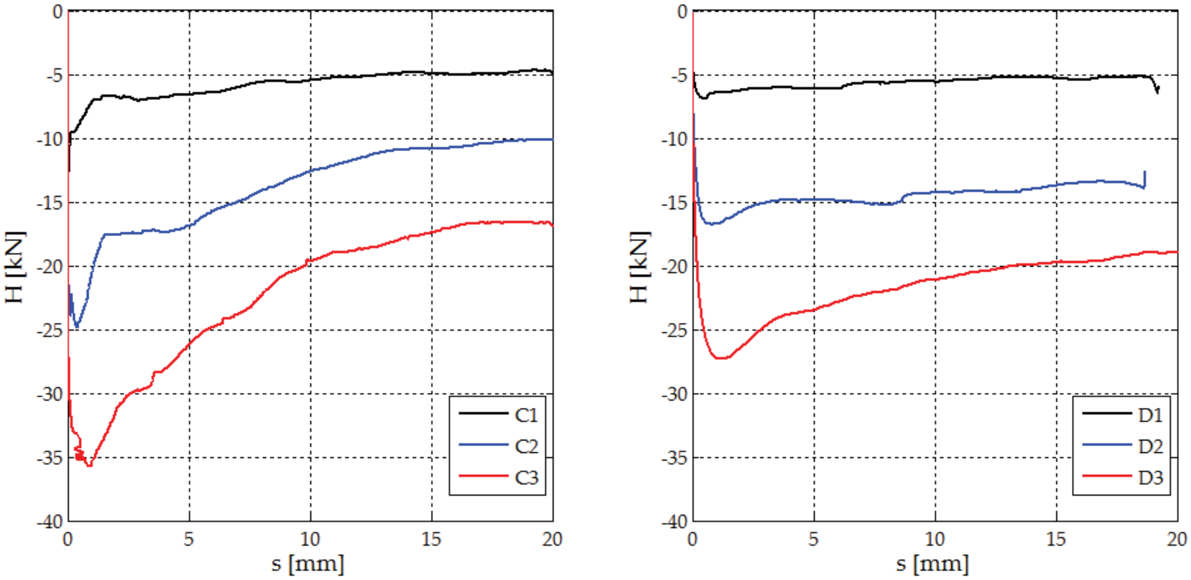

Figure 6: Shear Force-Deformation Characteristics for Series C and D (Static Loading)

Figure 7: Typical Specimen Deformation

The influence of the applied level of the pre-compression is clearly visible from Figures 5 and 6. The shear resistance of the specimens of the Series A and C was higher than for those of Series B and D, respectively, and the difference between the respective values slightly increased with increasing pre-compression level, see Table 3. The difference in stiffness between specimens with different pre-compression levels has not been observed, see Figures 5 and 6.

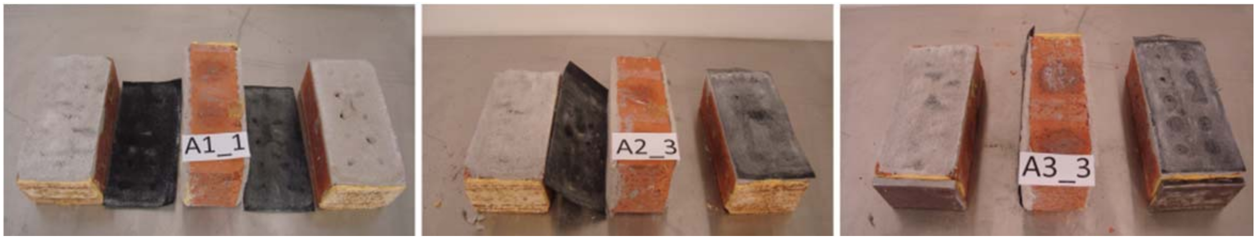

Figure 8: Typical Failure of Specimen of Series A

The failure patterns observed during the tests were characteristic for masonry failing in sliding. Failure of the specimens with DPC sandwiched in the bed joint (Series A and C) occurred due to exceeding of the (very low) bond strength between the DPC membrane and the joint mortar, see e.g. the failure patterns for specimens A1_1, A2_3 and A3_3 shown in Figure 8. For the specimens with DPC membrane placed between the bed joint and outer brick (Series B and D) sliding failure occurred between the brick and the DPC membrane, see e.g. the failure pattern for specimens B1_1, B2_3 and B3_2 shown in Figure 9.

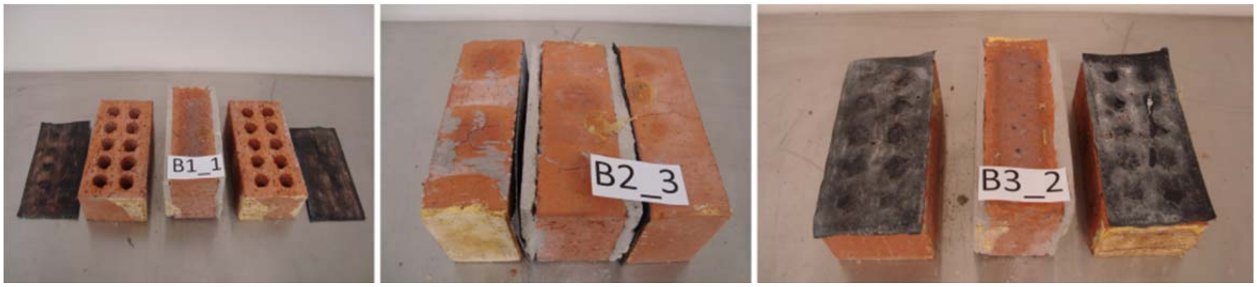

Figure 9: Typical Failure of Specimens of Series B

DISCUSSION

Test data on the mechanical characteristics, energy dissipation and overall behaviour of the masonry elements with DPC subjected to the static-cyclic loading has been obtained. The analysis of the test results delivered values of the mechanical characteristics of the specimens.

Sliding failure of the specimens can be described by the classical Mohr-Coulomb's failure criterion $\tau = c + \sigma \tan\varphi$, where c denotes the cohesion and φ is the angle of internal friction, i.e. $\tan\varphi$ is a friction coefficient. Taking into consideration the tests results, cf. Table 3, a friction coefficient in the bed joint can be estimated from the levels of compression and shear in the joint once sliding has occurred. The resulting shear stress-normal stress graphs are shown in Figure 10 together with the data obtained from the tests. For Series A average cohesion and friction coefficients of 0.04 MPa and 0.28, respectively, were obtained, and for Series B, zero cohesion and an average friction coefficient of 0.26 were determined. As mentioned before two additional Series, C and D, were also performed under static loading. For Series C average cohesion and friction coefficients of 0.07 MPa and 0.29, respectively, were obtained. For Series D average cohesion and friction coefficients of 0.02 MPa and 0.25, respectively, were obtained. A very good agreement between the test results and the theoretical linear relationship (Mohr-Coulomb) is obvious from Figure 10. Furthermore, it can be concluded that the position of the DPC membrane in the bed joint as well as in the masonry wall (placed on the clay brick) has a small influence on the mechanical characteristics obtained (coefficient of friction and cohesion), cf. also graphs in Figure 10.

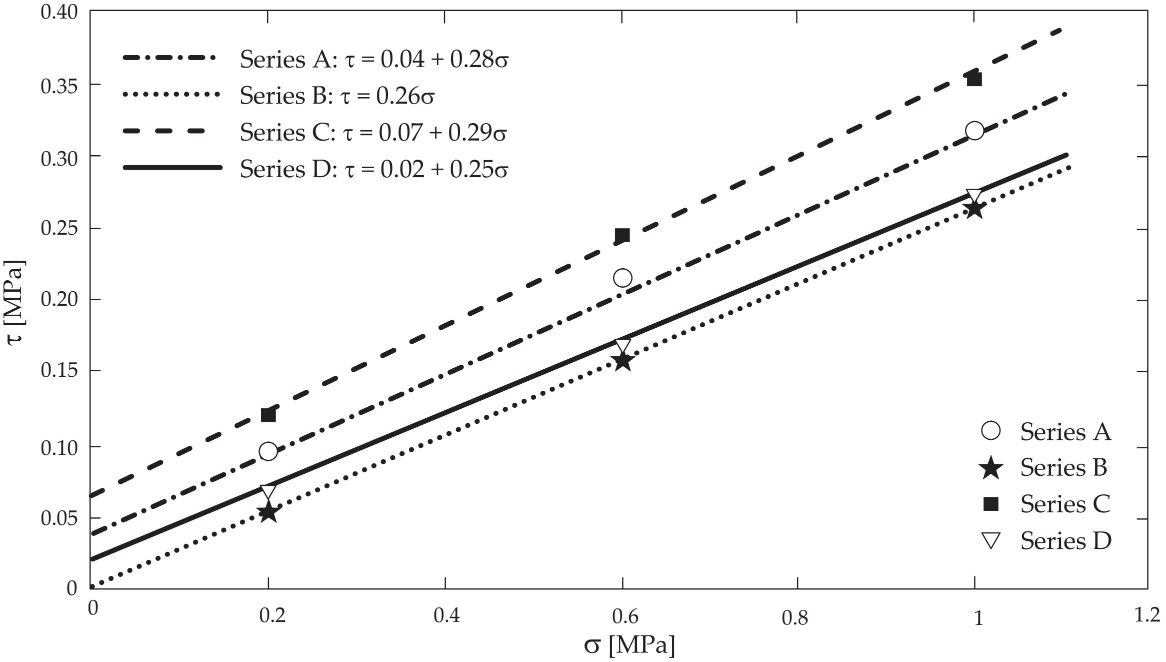

Figure 10: Normal Stress-Shear Stress Relationships for all Series

Based on the results of the present and previous tests, for practical applications, for walls with all levels of compressive loading, the small cohesion value can be neglected and the shear resistance of the masonry with DPC could be defined by the product of friction coefficient and appropriate vertical pre-compression. Furthermore, due to the small difference in the results obtained from tests on static and static-cyclic loading, it can be concluded that shear strength characteristics obtained from static tests can be also used for applications involving static-cyclic loading.

With increasing pre-compression level, the degradation of the DPC membrane also increased. Figure 11 shows the DPC membranes, each one per series, after the completed tests under the highest level of the pre-compression (1.0 MPa). It can be clearly seen that the degradation was larger for specimens of the Series B and D, in which the rupture of the DPC was visible. The deformation (warp) of the DPC under an applied (high) pre-compression level is also visible from this figure. For lower pre-compression levels, however, such a pronounced degradation was not observed. This fact should be taken into account in the case of cyclic (seismic) loading of masonry with such DPC built into the bed joint. Another factor, that leads to the DPC degradation and which should be considered, is the number of the applied cycles.

Figure 11: DPC Degradation under Highest Pre-Compression Level

As expected, the mechanical characteristics progressively degraded with an increasing number of cycles. Additionally, the (qualitative) data on the energy dissipation could be extracted, which is the most crucial design aspect in an earthquake event, since high energy dissipation capacity is the most desirable type of the structural behaviour (particularly for brittle, elastic structural systems such as loadbearing masonry). The obtained hysteresis, i.e. shear force-slip relationships shown in Figure 5, exhibited large area under the hysteresis, thus considerable energy dissipation could be expected in practical applications when the DPC membrane is incorporated in the shear wall. However, the (theoretically) large movements of the shear walls should be limited through constructive detailing and/or other constructive measurements.

CONCLUSIONS

The test results have been evaluated and preliminary analysis has been performed. Further, the test results have been compared to the corresponding analytical model, i.e. Mohr-Coulomb's failure criterion (friction law). It has been found that this analytical model can be used to predict the behaviour of the (tested) masonry with a DPC membrane incorporated in the bed joint. Further, the mechanical characteristics mentioned above and failure loads obtained from the performed static-cyclic test have been compared to the corresponding data obtained from pure static tests. It has been concluded that the values of the failure load were consistently higher for the statically loaded specimens and for those specimens with the DPC membrane placed in the bed joint rather than directly on the brick. For the specimens with the DPC membrane placed between the bed joint mortar and brick almost no difference in the failure loads between the static and static-cyclic tests has been observed. Comparing the mechanical characteristics from static and static-cyclic tests, it could be concluded that there is no large difference between the obtained values of these characteristics. Considering these findings, a correlation could be established, and it would be possible (in future) to use the results of static tests (which are not so time consuming as static-cyclic tests) in the seismic design of shear masonry walls.

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