Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Bachelorarbeit FS14

SHEAR TESTS ON MASONRY TRIPLETS WITH DIFFERENT SOFT LAYER MEMBRANES

Tests Report

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Contents

Abstract

Shear tests on pre-compressed masonry triplets with a soft layer membrane place in the middle of the mortar joint have been performed. The main objective of the present project was to assess the mechanical characteristics of masonry elements (triplets) with different types of soft layer membranes built-in on the joints. These soft layer membranes were placed in between two layers of elastomer to avoid degradation of the middle soft layer. Both monotonic and static-cyclic tests were performed in order to obtain values of the friction coefficient and to observe the mechanical behavior of the triplets in these two types of experiments.

Four different types of soft layer membranes were used in the tests. The materials chosen, often used in masonry constructions, were: bitumen, rubber-granulate, cork and a mixture of rubber-granulate and cork. In addition, some triplets without soft layer were also tested and served as control specimens.

Moreover, three levels of pre-compression were applied in order to observe the influence of it and to be able to obtain values for the mechanical properties. The shear strength was highly influenced by the pre-compression, giving higher values for higher levels of pre-compression. Furthermore, the relative displacement (slip) between each outer brick and the middle brick was measured at the same time.

The failure criterion used in the post-processing of the results was the Mohr-Coulomb failure criterion which appeared to describe it very precisely. Hence, the cohesion and friction coefficient could be obtained by a linear regression between the shear stress and the compressive stress.

Other issues taken into account were the degradation of the soft layer, the sliding behavior and the relationship between the results of the two types of tests. By the static-cyclic tests large energy dissipation could be observed in the triplets with built-in soft layer membrane. The soft layers allowed sliding in the joint and therefore helped the dissipation of energy. However, for the specimens with only mortar in the joints less energy dissipation could have place. On the other hand, mortar specimens showed much higher shear force resistance than the other triplets.

Foreword

This research project was held on ETH Zürich during the spring semester of 2014. As an exchange student of UPC Barcelona this Bachelor Thesis was the final degree project for my studies of Civil Engineering. The work lasted for 4 months including the preparation and execution of the tests, writing of a report and the final discussion and conclusion of the project.

The main goal of the thesis was to assess the mechanical behavior of a set of masonry triplets with different soft layer membranes. In order to obtain a wide range of results and be able to determine some structural parameters, both monotonic and static-cyclic tests were performed in the laboratory.

A complete preparation of the set-up took place during the first week. 28 days after the specimens were build, tests began. While testing, some parameters were controlled, such as the pre-compression and all data was registered by a computer.

I would like to thank Prof. Nebojša Mojsilović for giving me the opportunity to participate in such an interesting research project and let me inquire into this exciting field. Moreover, I would also like to acknowledge him for the support and help given throughout the project. In addition, I would like to thank my advisor Miloš Petrović for helping me understand the basic concepts of the project and introducing me to the laboratory work.

1. Introduction

1.1 Soft layer membranes in masonry

Soft layer membranes are often used in masonry as a moisture barrier or to allow differential displacements in the joints. They are often placed in the bed joint or between the wall and the concrete slab. Therefore, it is important to determine the influence of the implementation of a soft layer in a wall to its mechanical properties, specially its behavior when shear force is applied. Obviously the maximum shear force resistance is lower with a soft layer in the bed joint, despite this, other advantages can be found.

Soft layer membranes can influence highly the resistance of a masonry wall in the event of an earthquake. As it allows relative displacement, the energy is dissipated by sliding in the joint without causing damage to the structure. On the other hand, a wall without soft layer would have to dissipate the same energy, but instead of doing it so by relative displacement it would dissipate the energy moving the whole wall and causing cracks and damage to the it. If the damage was too high, the wall could eventually break and fall. Fig. 1 shows how masonry buildings are usually damaged due to earthquake loads.

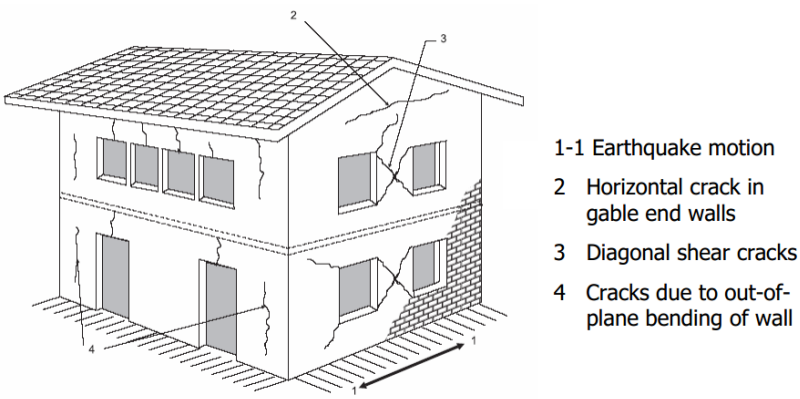


Fig. 1 Typical type of damage to structural walls subjected to seismic loads.

Fig. 2 Dinar Afyon earthquake (1995) M = 6.1.

As it can be seen, the in plane shear stresses cause x-shaped cracks in the walls. The energy is dissipated through these cracks as in the wall from Fig. 2. These types of cracks are often generated when the wall is in the same plane as the direction of the momentary movement of the earthquake. The seismic impulse can be considered as a lateral force in the whole building, as the movement is very quick and sudden there is relative displacement between the upper and lower part of the wall. As shown in Fig. 3 if there is no soft layer in the bed joint the upper part of the wall would move in one direction relatively to the lower part. This would case that one of the internal diagonals would get shorter and the other one longer. A shorter diagonal means compression in its direction and so a longer one means tension. As it is known masonry does not resist well tension and therefore cracks would appear perpendicular to the longer diagonal. In conclusion, the cracks would appear in both directions as the earthquake moves fast in all directions.

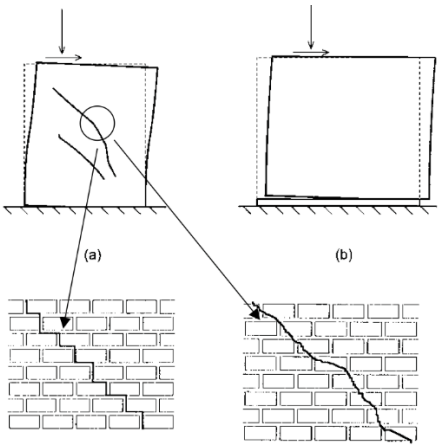


Fig. 3 Earthquake behavior of a masonry wall. (a) Without soft layer. (b) With soft layer.

Having a soft layer membrane in the bed joint of the wall would allow the whole structure to dissipate the energy through differential movement. The upper part of the wall would move relatively to the lower part. This type of behavior can be observed in Fig.4. If the whole part above the joint moves together less internal stresses take place and then no tension needs to be resisted by the wall. Finally, no cracks would appear.

Fig. 4 Typical soft layer earthquake performance.

To sum up, by implementing soft layers in masonry walls we would increase the resistance and reliability of the whole unreinforced masonry structure. This would be much cheaper and easier to implement than reinforcing the structure. Finally, the soft layer membrane could serve not only as a moisture barrier but also as a method to resist and behave better in the event of possible earthquakes.

1.2 Objectives of the tests

The main goal of the tests is to assess the main mechanical parameters of different soft layer membranes under shear loads. Four types of soft layers will be used in both monotonic and static-cyclic tests and in light of the results the cohesion and friction coefficient will be determined for each material. In that sense, the results for both types of tests will be compared in order to obtain a relationship between them. The objective is to conclude if there is any relationship between both results. If one was to be found, monotonic tests would be more often performed as they are less time consuming and present less difficulties while testing.

Furthermore, another main objective is to observe and compare the degradation of the different soft layers. If a membrane is easily degraded it could become a problem as it would have to be substituted or repaired more often. Therefore, a more physically resistive material is preferred and the deterioration of the materials will be taken into account for each level of pre-compression.

For the static-cyclic tests the energy dissipation is going to be observed. In that sense, the results will have to show the amount of energy dissipated and this will be observed and considered for each material. Nearly no dissipation of energy is expected for the triplets without soft layers and the goal is to see which triplet with soft layers can resist more shear load with same differential displacements.

In any case, this project is a first step to a much greater and more ambitious long-term objective. If the results are positive the final goal of the investigations would be to implement a type of soft layer in the bed joint of masonry walls so that they could resist better earthquakes. After having assessed all the characteristics of the chosen materials, one or some of them will be considered as suitable for masonry constructions in real life.

1.3 Theoretical basis

As considered in previous investigations, a classical Mohr-Coulomb failure criterion will be used in order to describe the sliding failure of the tests. The criterion states that failure will occur as soon as the following equation is not fulfilled:

$$\tau \leq c + \sigma * \tan(\varphi)$$

Where τ stands for the shear stress in the joint, c for the cohesion, σ stands for the pre-compression level (normal stress), φ for the angle of internal friction and $\tan(\varphi)$ for the friction coefficient. For each level of pre-compression the triplet will resist a different maximum shear force. Once all the results are gathered a linear regression will be done in order to obtain the value of the cohesion and the friction coefficient.

The Mohr-Coulomb failure criterion can also be described graphically as in Fig. 5:

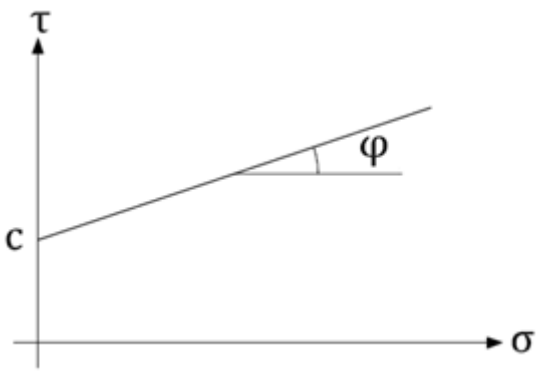


Fig. 5 Failure criterion by Mohr-Coulomb.

If the stress state is under the line, the material will not fail. However, if it reaches the line failure will eventually occur. As it can be easily observed from the graphic, the higher the normal stress, higher will be the maximum shear force. The cohesion is the initial resistance that a material has when no tension force is applied. For the triplets with soft layers this cohesion could be considered as 0, as the bricks can actually be separated; there is no cohesion between soft layer and mortar, except for the specimens with bitumen soft layer.

1.4 Previous investigations

Not much has been investigated about the behavior of soft layer membranes under shear loads within the joints of masonry walls. Therefore, this field of research is nowadays poorly assessed and few contributions can be found. More are the questions raised than the investigation going on to answer them. However, some papers and works have already opened

the door to this new and young research field. Despite this, the possibilities are still numerous and very little is known about the mechanical characteristics of the different types of soft layers such as the ones being used in this project.

Nevertheless, Mojsilović N in [1] assessed the mentioned mechanical parameters for three types of materials: elastomer, bitumen and polyester. These results can be then used to compare the ones obtain in this project and to see any similarities or improvements as bitumen will also be used as a soft layer membrane. Furthermore, Mojsilović N et al. in [2] performed cyclic tests on wallettes as an experimental study to observe the behavior of the soft layer in the bed joint. The results lead to the conclusion that the soft layer helped to dissipate energy and encouraged further investigations to determine the most suitable material.

Similar tests as the ones in this project were previously performed. However, they all required further assessment of materials in this matter in order to get a final conclusion to the issue. In [3] and [4] similar tests as the ones in the present work took place. In that sense, this project is based in some assumptions and conjectures that appeared to be right in previous investigations, such as the consideration of the Mohr-Coulomb failure criterion.

Some slides from masonry structures lectures as in [6] and [7] were used in order to learn the basic concepts and the theoretical basis of masonry structures and to obtain an overall view of this previously fairly known field of study. The slides helped to learn about the mechanical characteristics and earthquake behavior of masonry structures.

2. Masonry materials

Each triplet was built by a professional mason so as to represent real life masonry. For the specimens with soft layer, the soft layer was incorporated between two layers of elastomer. Between each brick and these three layers, a layer of mortar was placed. Fig. 6 shows the procedure followed by the mason. The maximum thickness of each joint was 10 mm. for the specimens with soft layer.

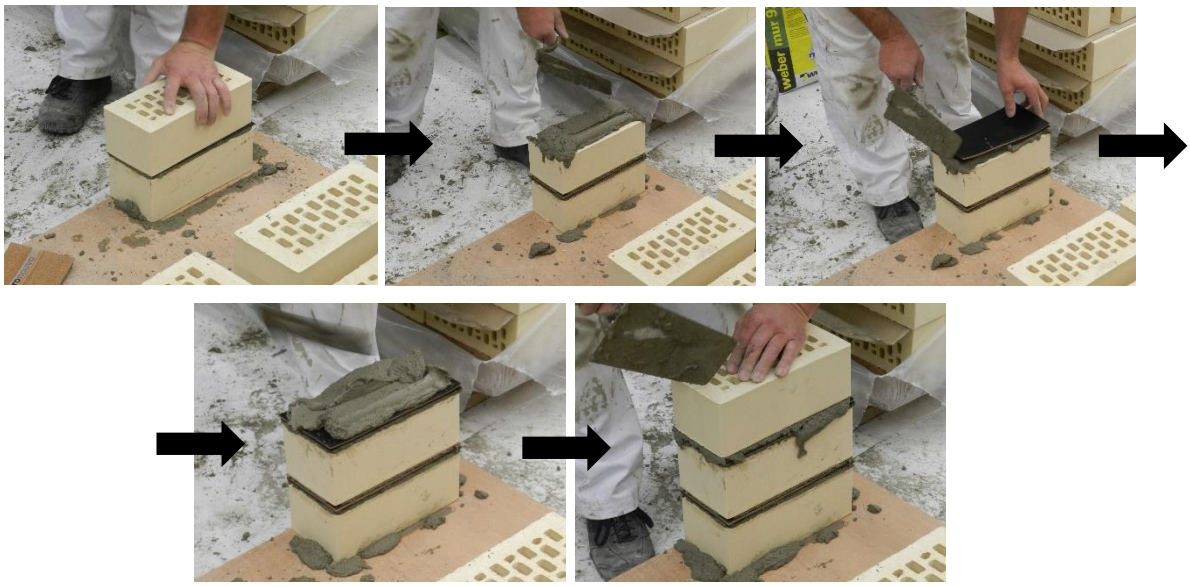


Fig. 6 Building sequence of a specimen.

Fig. 7 is an oversized representation of the disposition of the layers in the joints. Besides, a picture of a real specimen is also shown in order to compare. As explained before, mortar layers (grey) were between the bricks (brown) and the "sandwich", where the elastomer layers (black), were on top and below the soft layer (orange).

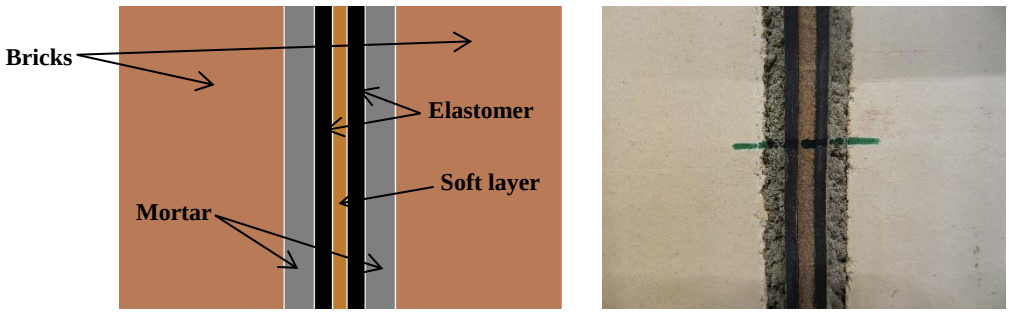


Fig. 7 Joint disposal in specimens with soft layer. Representation (left) and reality (right).

2.1 Bricks

The bricks used were extruded clay bricks and the main dimensions and properties are shown in Tab. 1:

Measure	Value	Units
Length*width*height	250*120*90	[mm]
Weight per unit	3.6	[kg]
Compression resistance	19.4	[MPa]
Void percentage	30.3	[%]

Tab. 1 Dimensions and properties of the bricks.

It is important to mention that most of the bricks used during testing got many cracks and did not resist very well the stresses. Especially for higher levels of pre-compression some bricks were even completely destroyed. In any case, cracks due to bending stresses appeared in most of the specimens once the pre-compression was applied. The theoretical compression resistance of the bricks was 35 MPa., as found in the product quality characteristics. However, compression tests were performed and the average value obtained was 19.4 MPa.

2.2 Mortar

A typical standard cement mortar was used for building the triplets. Everything was prepared in the laboratory under standard conditions. At the time of building the specimens, six mortar prisms with nominal dimensions of 160 x 40 x 40 mm were casted. Three prisms were stored next to the specimens until the day of testing and the other three were stored in a special chamber. Prisms 1-3 were the ones from the making site and prisms 4-6 were the ones from the chamber.

The Prisms were tested according to EN 196-1:2005 at the laboratories of the ETH Zurich by the author of this project.

The prisms were tested according to the following test protocol:

1. Firstly, the elastic modulus of Prism 1 was determined assuming that a third of its compressive strength would be 2 MPa. Then, the bending strength of Prism 1 was determined with a standard three-point bending test.

2. On each of the two resulting halves of Prism 1, the compressive strength was determined with a force controlled compression test.
3. With the assumption of having approximately the same compressive strength for all mortar Prisms, the elastic modulus of Prisms 2 and 6 was determined at 30% of the initially measured compressive strength. However, the compressive strength for the Prisms from the chamber was much higher and a new value for the stress in the elastic modulus test was used.
4. The bending strength of Prisms 2 to 6 was determined analogue to Prism 1.
5. The compressive strength of both halves of Prisms 2 to 6 was determined.

This procedure gives a total of 6 results for the bending strength, 6 for the elastic modulus and 12 values for the compressive strength. Tab. 2 shows the results.

Prism	Compressive strength [MPa]	Bending strength [MPa]	Elastic modulus [MPa]
1	7.035	1.97	7177
2	6.30	1.87	6330
3	6.70	2.01	6595
4	15.00	4.29	12727
5	16.17	4.49	12925
6	14.85	4.69	12410

Tab. 2 Mortar tests results.

2.3 Soft layer membranes

As commented in previous sections, the materials used for the soft layer membranes were elastomer, bitumen, cork, rubber granulate and a mixture of cork and rubber granulate. The elastomer was always placed above and under the soft layer tested. That is because the purpose of the elastomer was to protect the inside layer from degradation, as it appears to have a good resistance against it.

Nonetheless, degradation could be observed in many cases. As it will be later described, not all the layers could resist the tests properly. Some layers got even totally destroyed, mainly in the static-cyclic tests.

2.3.1 Elastomer

2.3.2 Bitumen

2.3.3 Cork

2.3.4 Rubber granulate

2.3.5 Mixture of cork and rubber granulate

A Table (Tab.3) with the thickness of each soft layer is added below.

Soft layer	Elastomer	Bitumen	Cork	Rubber-granulate	Mixture of cork and rubber-granulate
Thickness (mm)	2.0	2.0	3.2	3.0	3.5

Tab. 3 Thicknesses of soft layers.

3. Test procedure

3.1 Triplets

As mentioned before, a professional bricklayer built all the triplets in the laboratory. In total, 32 specimens were built for this project. After at least 28 days of curing time the tests began.

3.2 Test set-up and measurements

The same set-up was used for both types of tests during the laboratory work. However, some elements had to be incorporated for the static-cyclic phase. As the displacement in the monotonic tests was only in one direction, the set up was much simpler and easier to mount than the one for the static-cyclic tests. Fig. 8 shows the main elements of the set-up for the static-cyclic phase of experiments. The same figure will be used to describe the set-up for the monotonic tests as the only difference is that some elements were not needed.

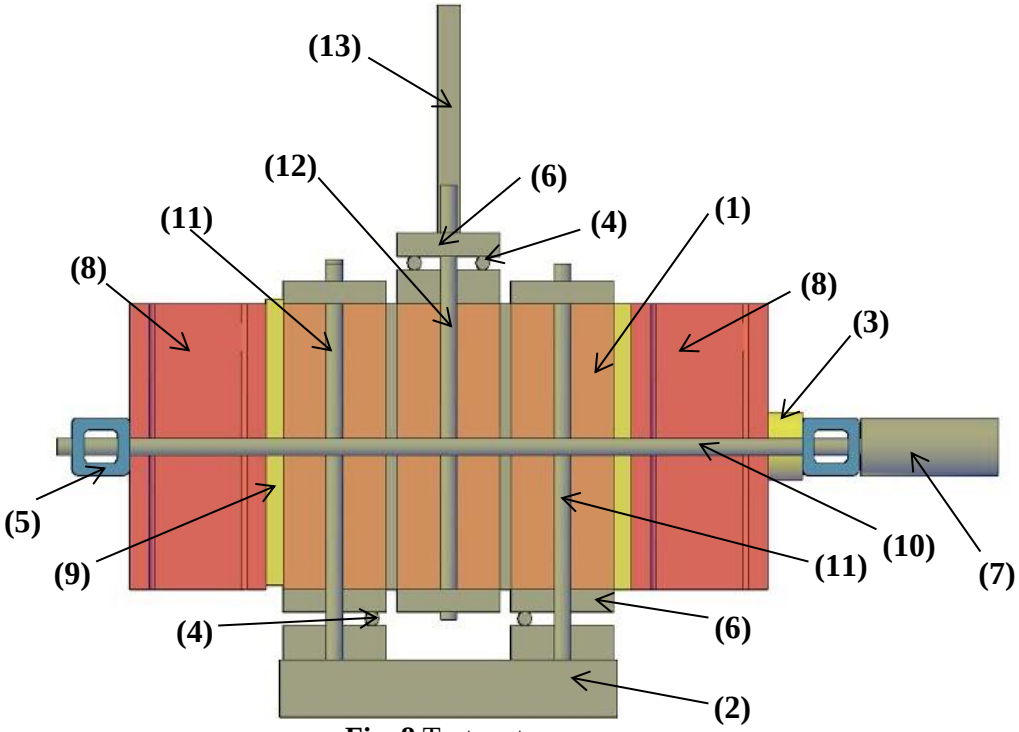


Fig. 8 Tests set-up.

For the monotonic tests, the specimen (1) was placed in the universal testing machine after being clamped between two red steel profiles, represented in Fig. 8 by (8). In order to introduce properly the compressive force, two wooden sheets (9) were placed between the brick and the steel profile in each side. The machine had two load transmission elements, lower element represented by (2). The upper element stayed static while the lower one pushed upwards during the test. Steel cylinders (4) were used to introduce the shear force as close as

possible to the joints. This arrangement ensured a proper transmission of the load. Three steel plates also helped this transmission between specimen and machine (6).

Moreover, the whole specimen was held together by means of two rods (10) attached to a jack (3) that introduced the pre-compressive force. The jack was placed in the center of the brick and two blue beams (5) attached to the rods. Two load cells (7) were also placed in these rods in order to register in real time the pre-compression level.

Finally, the displacement was also measured and three LVDT's were used for it. They registered the displacement of each brick and sent the data to the computer.

For the static-cyclic tests a more complex set-up was required. Some elements were incorporated to the monotonic set-up.

Using a clamp to hold it together, the specimen (1) was placed in the universal testing machine between two load transmission elements. However, only the bottom element (2) moved upwards (firstly) and downwards (push cycle), while the upper element remained static. That is how the shear force was transmitted. The steel cylinders (4) helped to transmit the shear load as close as possible to the joint. Also, steel plates (6) were placed between the cylinders and the specimen. Both outer bricks were kept in place by means of four steel rods (11). These were needed during the push cycle (pushing downwards). These rods were anchored to the upper static element by a massive steel plate (13). Fig. 9 shows two pictures of both versions of the set-up.

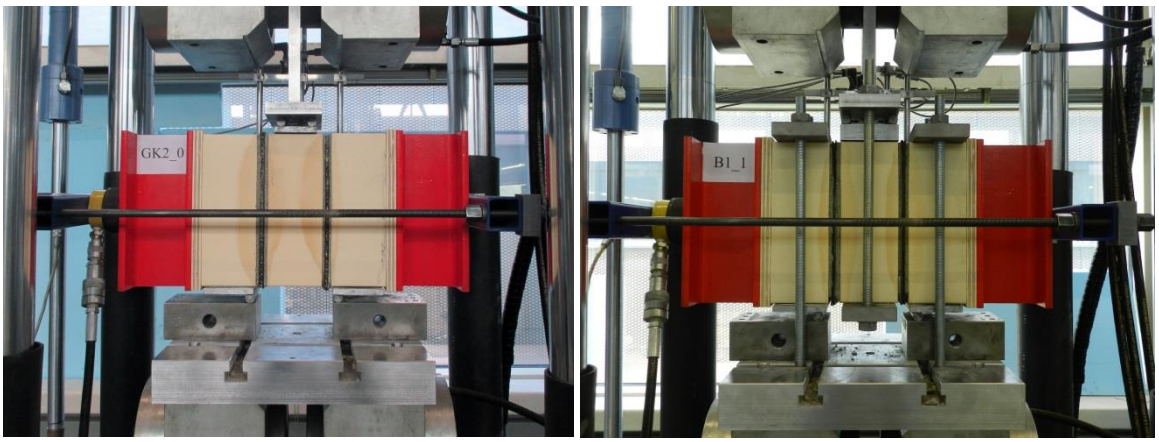


Fig. 9 Monotonic set-up (left) and cyclic-static set-up (right).

The whole specimen had been previously placed between two red steel profiles (8). In order to apply properly the pre-compression force two wood sheets (9) were placed in between each steel profile and the specimen. A hydraulic jack (3) applied the pre-compression force, and remained constant during the tests. The jack was kept in position by means of two rods (10)

and two blue steel profiles (5). In the same rods, two load cells (7) registered the compressive force and sent the information to the computer.

The relative displacement or slip was also measured during the test. In order to do so, three LVDTs were employed. The force applied by the machine was also recorded and all measuring devices were connected to a personal computer which processed the data in real time. Showing the pre-compression, the force applied at every moment, the relative displacements and the position of each LVDT. Fig. 10 shows this part of the set-up.

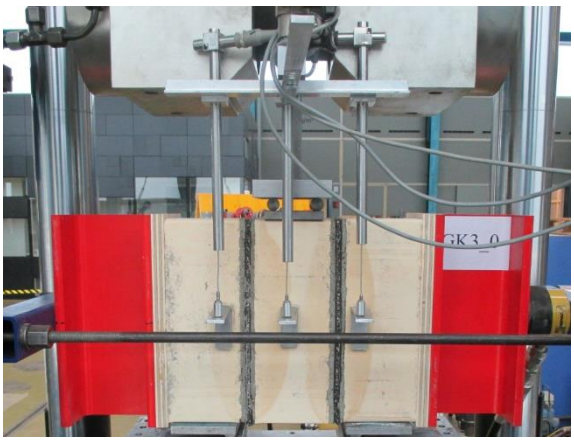


Fig. 10 LVDT's in the set-up.

3.3 Test procedure

Monotonic tests

The experiments were displacement controlled. In that sense, the shear load was applied by an upwards movement of the lower element of the machine at a constant speed of 0.25 mm/min. Once it reached the maximum resistance force, the force started to drop and when the deformation was significant the test was stopped. The pre-compression force stayed stable during the whole test at the required level. A computer recorded at real time all the variables and values from the measurement items and those could be watched in a screen in order to follow the advance of the test.

Static-cyclic tests

The procedure of this type of experiments was much more complex. Shear load was applied using computer controlled displacement steps. Each step was repeated twice in a form of a sinusoidal wave. The speed of each step was gradually increased, being much lower for small displacements. Tab. 4 gives information on the speed and the duration of each step. The total

duration of the experiment was of 161.34 min. However, tests were often stopped before the end as the deterioration of the specimen was making the experiment too harsh and it was nonsense to continue.

Travel [mm]	0.5	1	2	3	5	10	15	20	30	Total Duration [min]
Loading speed [mm/min]	0.5	0.5	0.5	1	3	5	10	10	10	
Period [min]	4.00	8.00	16.00	12.00	6.67	8.00	6.00	8.00	12.00	161.34

Tab. 4 Loading history for static-cyclic tests.

Fig. 11 shows the displacement over time, a sinusoidal wave can be easily recognized and two repetitions for each step can also be seen. Usually, experiments were finished once the displacement reached 15 or 20 mm. At that point, some specimens were already considerably deteriorated and in some cases we were forced to stop as it will be explained below.

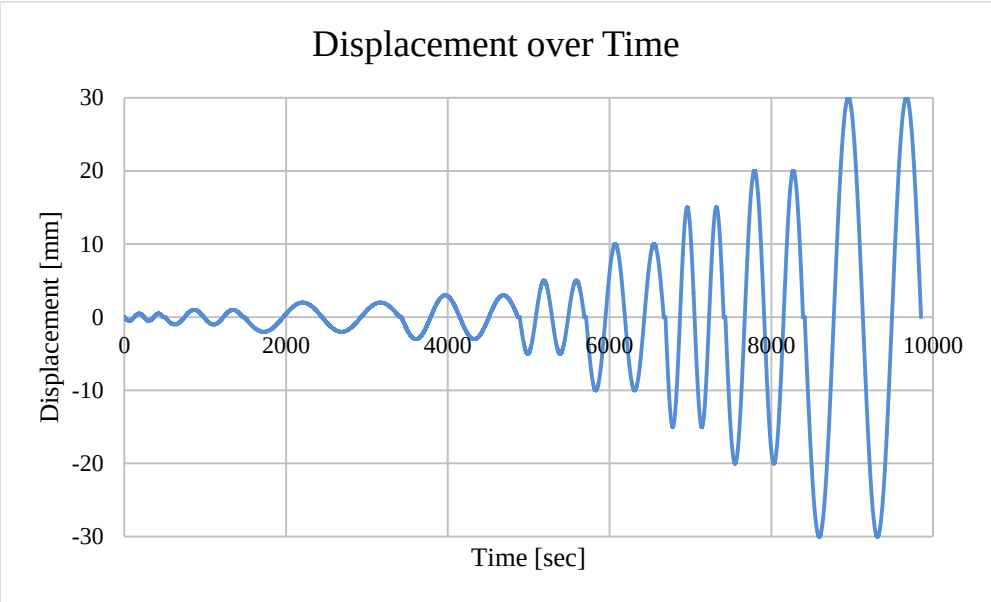


Fig. 11 Typical displacement history.

In this type of tests, the pre-compression was also observed and looked after during the whole experiment. Fig. 12 is an example of how the force previously applied oscillated over time. At the beginning, the force is pretty stable as the displacements were not big enough to have an influence on it. However, once the displacements started to be considerably high the pre-compression dropped and raised a lot, getting away from the value it had to be. In order to maintain the value required, readjustments were necessary the whole time. By means of the jack we applied or released pressure when needed.

Once the displacement got to 20 mm. the specimen was highly deteriorated and many cracks had already appeared. Then the pre-compression dropped to 22 kN and despite the attempt to

raise it again, it dropped back to less than 15 kN. That was when the experiment had to be stopped as the pre-compression could not be regained and hence, it did not make any sense to continue. This type of ending could be observed in other tests, mainly for high levels of pre-compression; the joints were too degraded and the capacity of the jack was then exceeded.

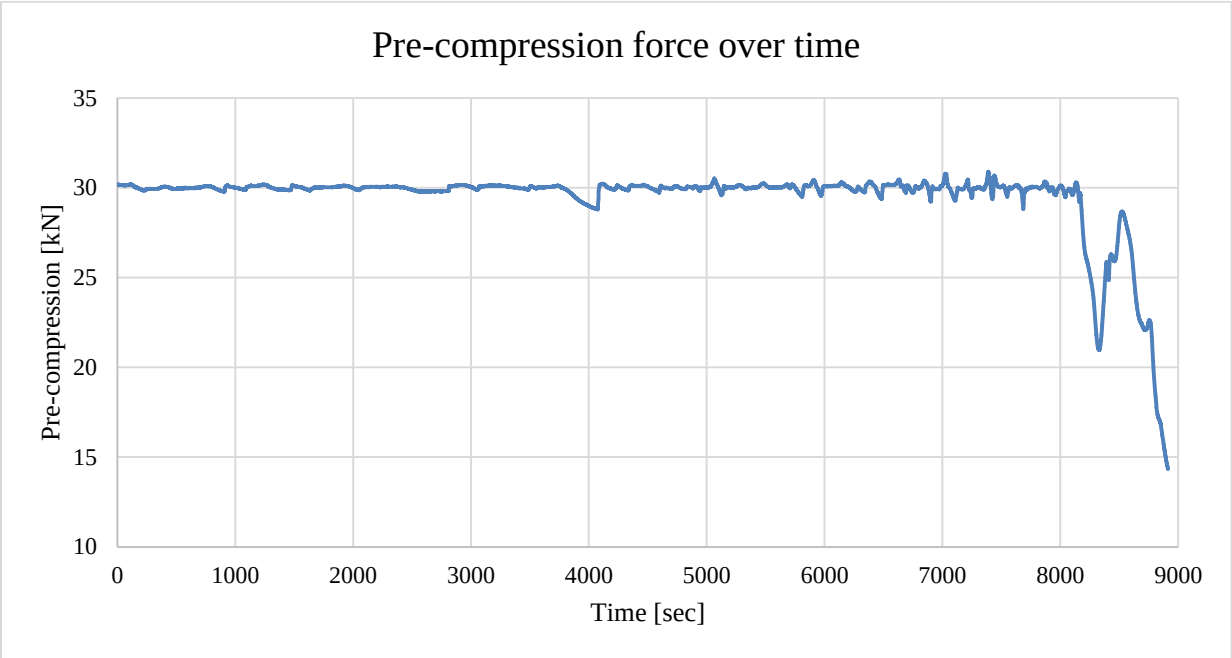


Fig. 12 Pre-compression force over time for G3_1.

3.4 Tests plan

In the current study, both monotonic and static-cyclic tests were performed. First of all, the monotonic tests were done and in the second phase of the laboratory work the static-cyclic tests took place. During the initial phase of the program, three triplets for each type of triplet were tested. One for every level of pre-compression. Once all the specimens with soft layers were tested, static-cyclic tests started. This order was followed as the set-up for each type of test was different and therefore it was easier and more efficient to do first one type of tests and after the other one.

An alphanumerical code was used to label the specimens. Fig. 13 explains the meaning of each element from the code.

$$\mathbf{XN_1\_N_2}$$

Fig. 13 Alphanumerical code.

- The letter X stands for the type of triplet used in the test. The possible meanings of X are: M (only mortar), G (rubber granulate), K (cork), GK (mixture of rubber granulate and cork) and B (bitumen).
- For N_1 three values could be taken 1, 2 or 3. One for each level of pre-compression: 0.2 MPa, 0.6 MPa and 1 MPa correspondingly.
- N_2 was used to differentiate between monotonic and static-cyclic tests. 0 meant monotonic and 1 stood for static-cyclic.

A total of 15 experiments took place during the first phase. These are shown in Tab. 5.

Monotonic	**0.2 MPa**	**0.6 MPa**	**1 MPa**
Mortar (M)	M1_0	M2_0	M3_0
Rubber granulate (G)	G1_0	G2_0	G3_0
Cork (K)	K1_0	K2_0	K3_0
Mixture (GK)	GK1_0	GK2_0	GK3_0
Bitumen (B)	B1_0	B2_0	B3_0

Tab. 5 Monotonic tests program.

Once the set-up was changed and prepared for the static-cyclic tests, the same procedure was used for the rest of the program. For each type of triplet three tests were performed, one for each level of pre-compression. Also 15 experiments took place and they can be seen in Tab 6.

Static-cyclic	**0.2 MPa**	**0.6 MPa**	**1 MPa**
Mortar (M)	M1_1	M2_1	M3_1
Rubber granulate (G)	G1_1	G2_1	G3_1
Cork (K)	K1_1	K2_1	K3_1
Mixture (GK)	GK1_1	GK2_1	GK3_1
Bitumen (B)	B1_1	B2_1	B3_1

Tab. 6 Static-cyclic tests program.

The whole preparation and procedure of the tests lasted for several weeks. At the beginning, some problems were faced regarding the set-up which delayed the start of the actual experiments. Once the preparation of all the elements and the machine was finished, tests could begin. This happened after one week of work.

The first monotonic tests did not give the results expected and some re-adjustments had to be made which was also difficult and time consuming. However, after a few experiments results started to fulfill the expectations and even 2 or 3 tests could be performed per day.

Nevertheless, the static-cyclic tests were much slower and only up to 2 tests were done every day. At the end, 5 weeks were invested in all the experiments and after that, data could be post-processed and evaluated.

4. Tests results

4.1 Monotonic series

All monotonic tests were firstly performed in the universal machine with the procedure previously explained. For each experiment a graph was obtained showing the relationship between the force and the slip. As there were three levels of pre-compression, all graphs are shown together for each level in order to be able to compare the types of specimens used. The slip between the middle brick and both outer bricks was measured during the test and the mean value of them was simultaneously calculated. Fig. 14-16 are representations of all the experiments for the same value of pre-compression. The discussion of the results and the conclusions extracted from them are later explained in the corresponding chapters. This part is only the exposure of the actual results.

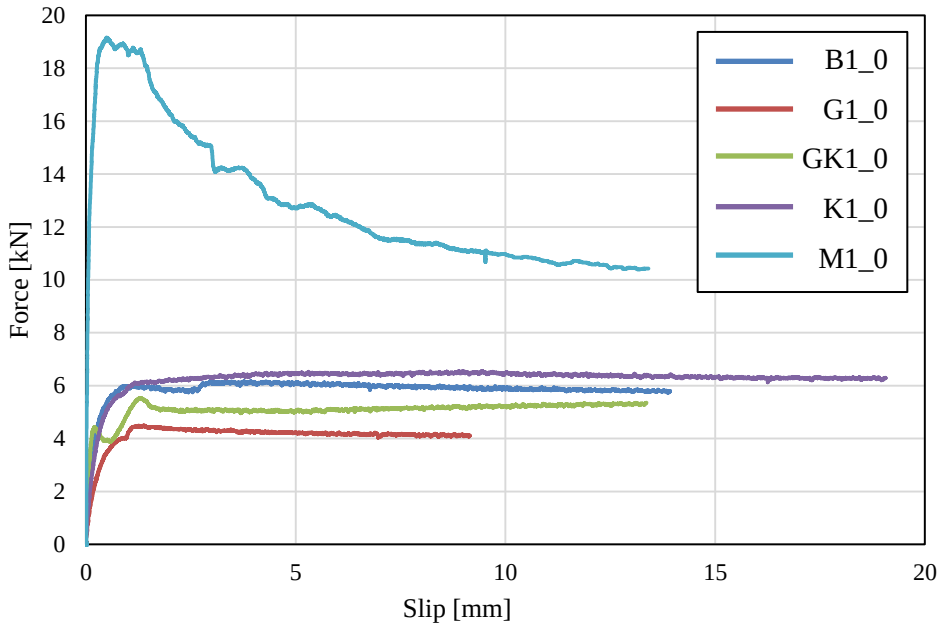


Fig. 14 Tests with 0.2 MPa of pre-compression.

The graphic above (Fig. 14) shows the evolution of the force in relation with the slip. As it can be seen, the tests were stopped at different times depending on the actual deterioration of the specimen at every time. A huge difference can be noticed between the M specimen and the rest. It is clear that its maximum force is much higher than the other ones. This will be seen in all cases as the M specimens, without soft layers, had a greater shear resistance. For the other cases the behavior was approximately similar and it will be explained later on.

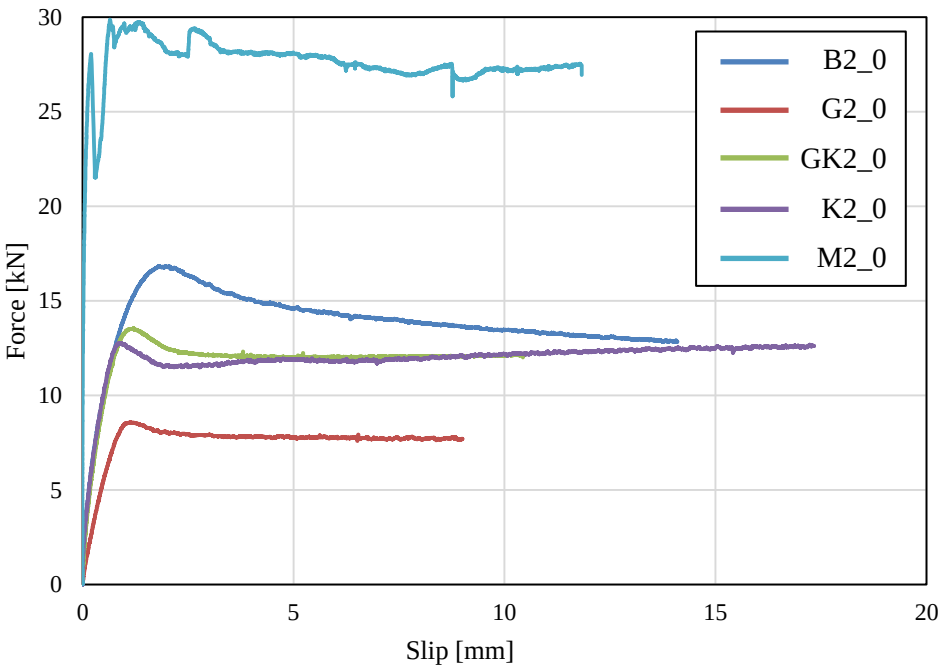


Fig. 15 Tests with 0.6 MPa of pre-compression.

Fig. 15 represents the experiments for the second level of pre-compression. The maximum value for the M specimen is again much higher than the others but its behavior requires some brief explanation. At the beginning, the force rises quickly but there is a sudden drop from which it recovers shortly after. This drop on the force is due to a sudden crack occurred during testing. The other series followed an expected pattern and reached the maximum force approximately in the same moment.

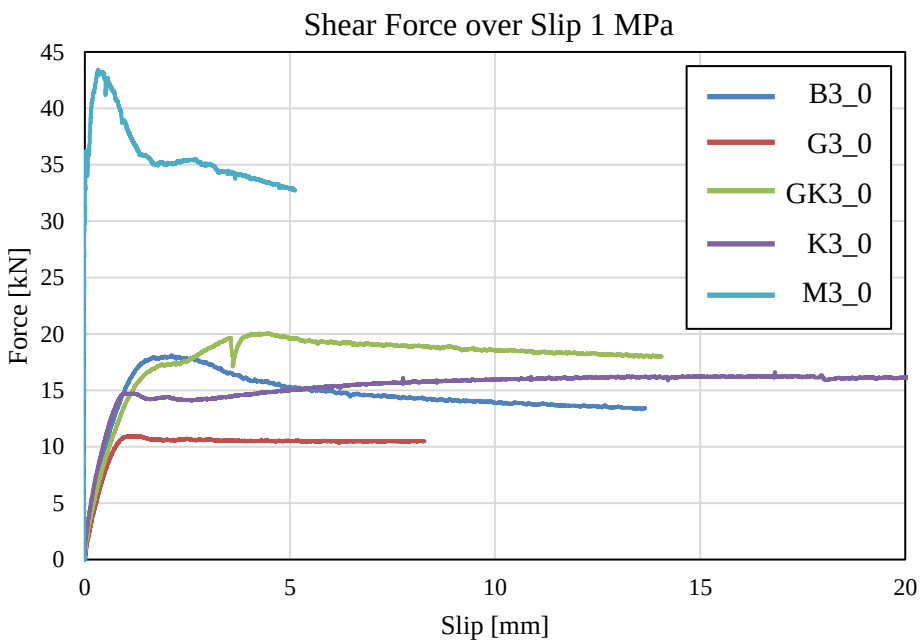


Fig. 16 Tests with 1 MPa of pre-compression.

Fig. 16 summarizes the results for the tests with 1 Mpa of pre-compression. For this level of pre-compression the specimens suffered some cracks even before starting the tests. As the pre-compression force was considerably high, the stress in the brick was also quite high. In some cases, the accumulation of stress in the brick provoked cracks. However these did not influence the results as the joints remained intact.

In addition, Table 7 summarizes the maximum forces for all the tests performed. For each type of specimen three different values are shown. For all series, there is an observable increase in the force as the pre-compression rises (as it was expected). The interesting fact to consider is how important is this increase, quantitatively speaking, and how good was the performance of the material in comparison to the others.

Series	**Maximum shear force [kN]**		
	σ_{pc} = 0.2 [MPa]	σ_{pc} = 0.6 [MPa]	σ_{pc} = [1 MPa]
B	6.163	16.838	18.086
G	4.493	8.582	10.925
GK	5.53	13.555	20.045
K	6.547	12.768	14.726
M	19.161	29.875	43.43

Tab. 7 Maximum shear force for monotonic tests.

Some post-processing of the data is required, which will be done and explained in the next chapter. It will be needed to assess the mechanical characteristics (friction coefficient) of the materials used.

4.2 Static-cyclic series

This type of tests are much more time consuming but at the same time the procedure is much more similar to an actual earthquake. Therefore, its results can be more useful as the specimens may behave as they would do in reality. Important differences could be noticed in comparison to the monotonic tests, as the maximum forces were much higher.

As in the monotonic tests, three levels of pre-compression were considered. In the next page some of the experiments performed are shown, in order to exhibit them as examples. All these specimens had a soft layer. Later the specimens without soft layer will be exposed. It is

important to take into account that the same scale is used for all of them. That is useful when comparing the performance of each type of specimen.

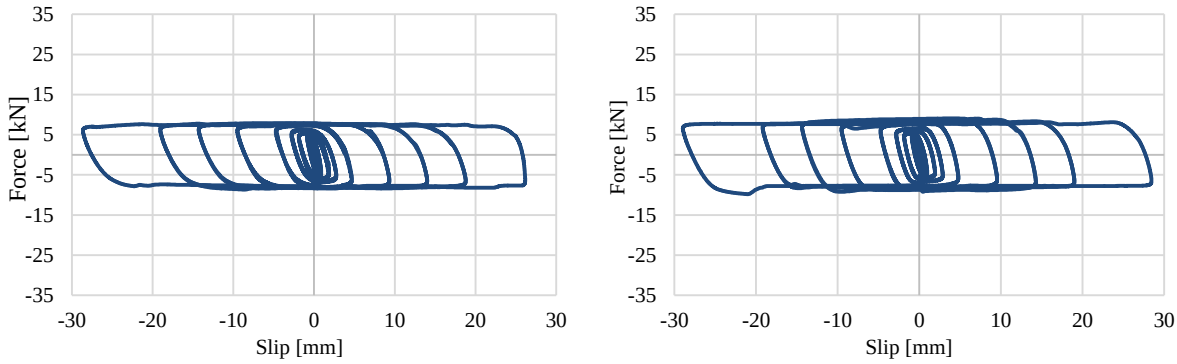


Fig. 17 Shear force-deformation characteristics for K1_1 (left) and GK1_1 (right).

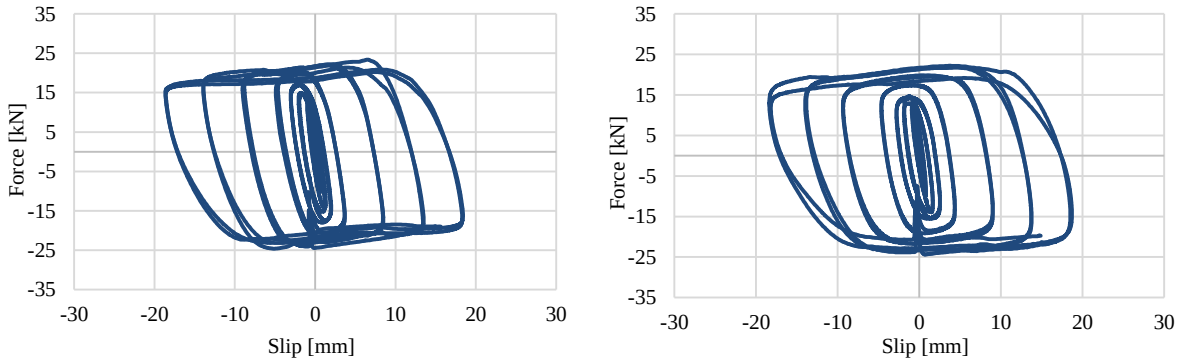


Fig. 18 Shear force-deformation characteristics for GK2_1 (left) and B2_1 (right).

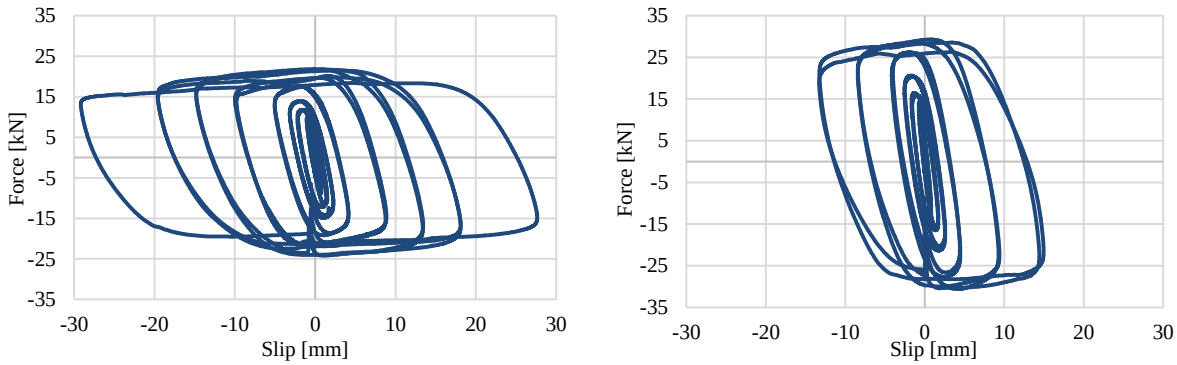


Fig. 19 Shear force-deformation characteristics for G2_1 (left) and K3_1 (right).

It can be clearly observed that the higher the level of pre-compression the higher the maximum force that the specimen could resist. Moreover, for lower levels the specimen could reach larger displacements without deteriorating too much. That means that the pre-compression had a huge influence on the degradation of the triplets, sometimes destroying completely the middle brick due to too high stresses.

Regardless of the type of material used, all specimens presented a considerably high energy dissipation. As it can be seen from Figs. 17-19, the hysteresis curves encased a large area, which could be translated as the energy dissipated by displacement.

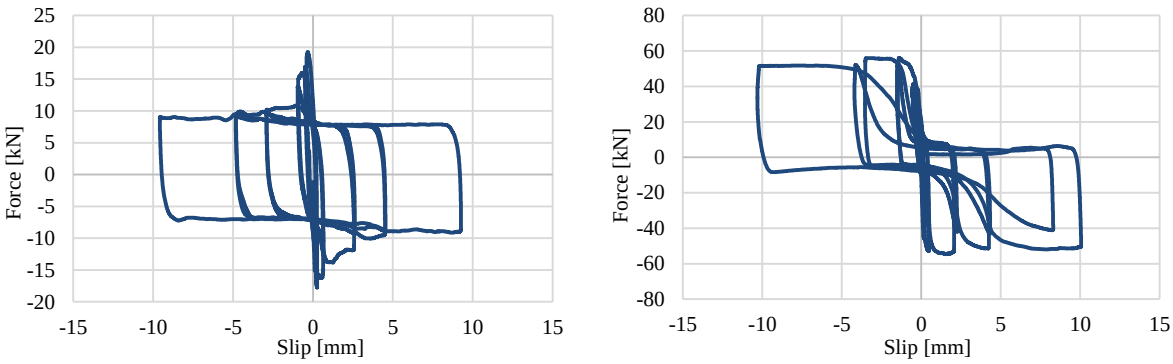


Fig. 20 Shear force-deformation characteristics for M1_1 (left) and M3_1 (right).

The behavior for the specimens without soft layer was much different as it can be concluded from Fig. 20. In contrast to the specimens with soft layer, the maximum force was registered during the first phases of the test, while the displacements were still small (0.5-2.0 mm.). Once sliding failure appeared in the joint between the mortar and the brick the shear force was much lower. The hysteresis pattern is very different to the others and it will be discussed in following chapters.

Series	**Minimum/maximum shear force [kN]**		
	σ_{pc} = 0.2 [MPa]	σ_{pc} = 0.6 [MPa]	σ_{pc} = [1 MPa]
B	-9.754/9.216	-24.365/22.195	-35.059/31.046
G	-9.638/8.909	-24.211/21.85	-27.859/26.746
GK	-9.792/9.082	-24.614/23.405	-35.75/35.002
K	-8.678/7.853	-23.021/20.333	-30.586/29.318
M	-17.741/19.277	-32.198/36.365	-54.605/56.122

Tab. 8 Maximum and minimum shear force for all specimens.

Tab. 8 is an overview of all the minimum and maximum values of the force for the static-cyclic tests. As noticed previously in the monotonic tests there is clear relationship between the increase of the level of pre-compression and the maximum values observed. The higher the pre-compression, the higher the force. For the two first levels, the performance of the materials was very similar, giving more or less the same maximum values. However, for the last level of pre-compression, some materials behaved much better than others.

5. Discussion

Monotonic tests

In the following section the presented tests results will be discussed and some preliminary conclusions will also be inferred. The first part will discuss the results from the monotonic experiments and the second part will focus on the static-cyclic tests. However, some conclusions are shared and are common for both types of experiments. Nonetheless, all possible final statements will be summarized in the conclusions chapter.

Mohr-Coulomb's friction law is used to interpret both set of results. The linear relationship between shear stress and normal stress can be clearly seen in both graphs. In that sense, the results from the experiments adjust very well to the regression line calculated once the actual results were post-processed. Thereafter, and as seen in previous works, Mohr-Coulomb's law applicability can be ensured for both types of tests.

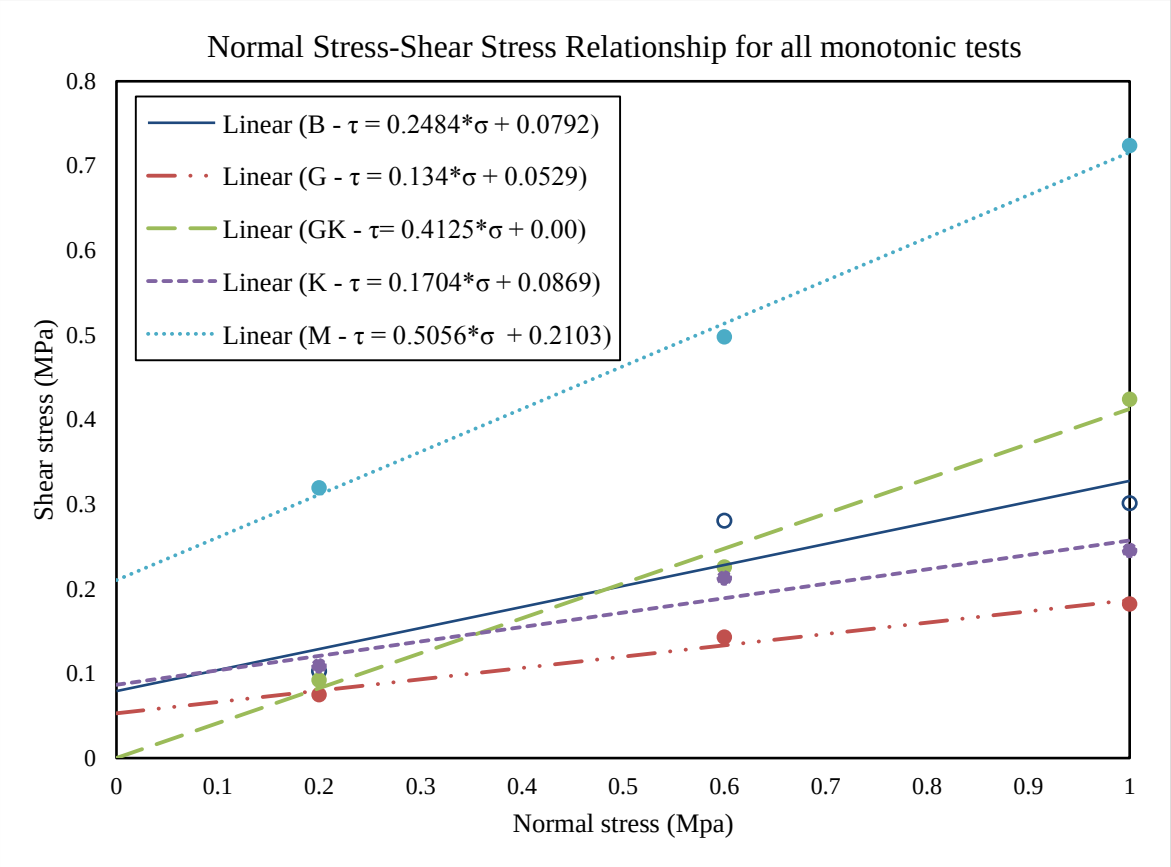


Fig. 21 Stresses relationship for monotonic tests.

Fig. 21 exhibits the regression lines for all types of specimens in monotonic tests. An interpretation of the graph will follow next:

First of all, there is a noticeable relationship between the shear stress and the normal stress. The higher the previous normal stress applied, the higher the shear stress that it can resist until it fails. The slope of this linear relationship is the so called friction coefficient and it is written in the top left of the graph for each type of specimen. Secondly, the highest values of shear stress were registered with the only mortar specimens, they showed a considerable higher resistance to failure than any other specimen. This can be seen clearly in the graph. In addition to this, it must be emphasized that while these specimens showed high resistance the rest of the tests gave lower results and much more similar to each other.

Besides, the mechanical parameters (cohesion and friction coefficient) were calculated for all types of tests. As explained before the slope of the linear regression is the friction coefficient and the y-intercept is the cohesion. At that point, it is important to take into account that the specimens with soft layer do not present any cohesion in the joints. Except for the bitumen specimens, as the bitumen induces some cohesion due to the pre-compression applied. In spite of these, the equations show some apparent cohesion which should be neglected. Mechanical parameters were also much higher for only mortar tests than for the rest.

Two different failure behaviors could be observed. For the specimens without soft layer (M series) failure occurred due to sliding in the joint between the brick and the mortar. On the other hand, all specimens with soft layer (B, G, GK and K series) failed also by sliding but between the soft layer and the elastomer, also for all levels of pre-compression. Failure occurred approximately simultaneously in both joints. Fig. 22 shows these two types of failure with two examples. As it is observable in the right picture, the mortar and elastomer layers stayed in its initial relative position, while the soft layer slide.

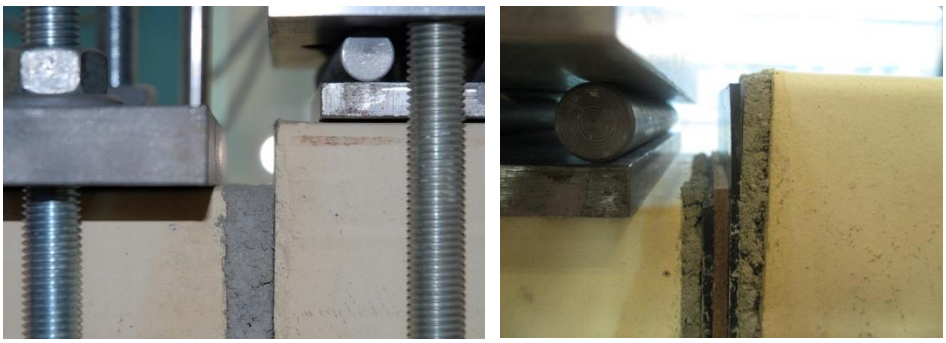


Fig. 22 Sliding failure in test M1_0 (left) and in test K2_0 (right).

Triplets without soft layer behaved linear-elastically until the maximum shear force, when failure occurred. After that, softening behavior was observed and once the slip was large enough the test was finished. This can be concluded from Fig. 14-16 paying special attention

to the tests without soft layer. On the other hand, specimens with soft layer showed very different patterns. Nevertheless, an overall conclusion can be made. Firstly, non-linear behavior was observed for all soft layer specimens, however the response after the break was different for each type. The force remained constant in some cases (GK series), decreased linearly for others (B series) and even increased in some cases (K series). For all monotonic tests no degradation from the soft layers was observed.

To sum up, there is a big difference in the behavior of the triplet when using one soft layer material or another. Taking into account the different parameters and considerations one material can be chosen as the most suitable for masonry walls. However, only with an overall picture a conclusion can be made. Important issues are the degradation of the material, the maximum shear force that it can resist and its friction coefficient. A final conclusion considering all that will be made in the next chapter.

Static-cyclic tests

Some of the conclusions inferred from the static-cyclic test results are very similar or even identical to the ones from the previous section. However, due to some substantial differences on the type of experiment, other interpretations and discussions are extracted in the following paragraphs.

To begin with, and as mentioned previously, the Mohr-Coulomb's failure law was used and showed some good results, validating its applicability. Fig. 23 is a graph with all the results for each type of specimen that is used to compare them.

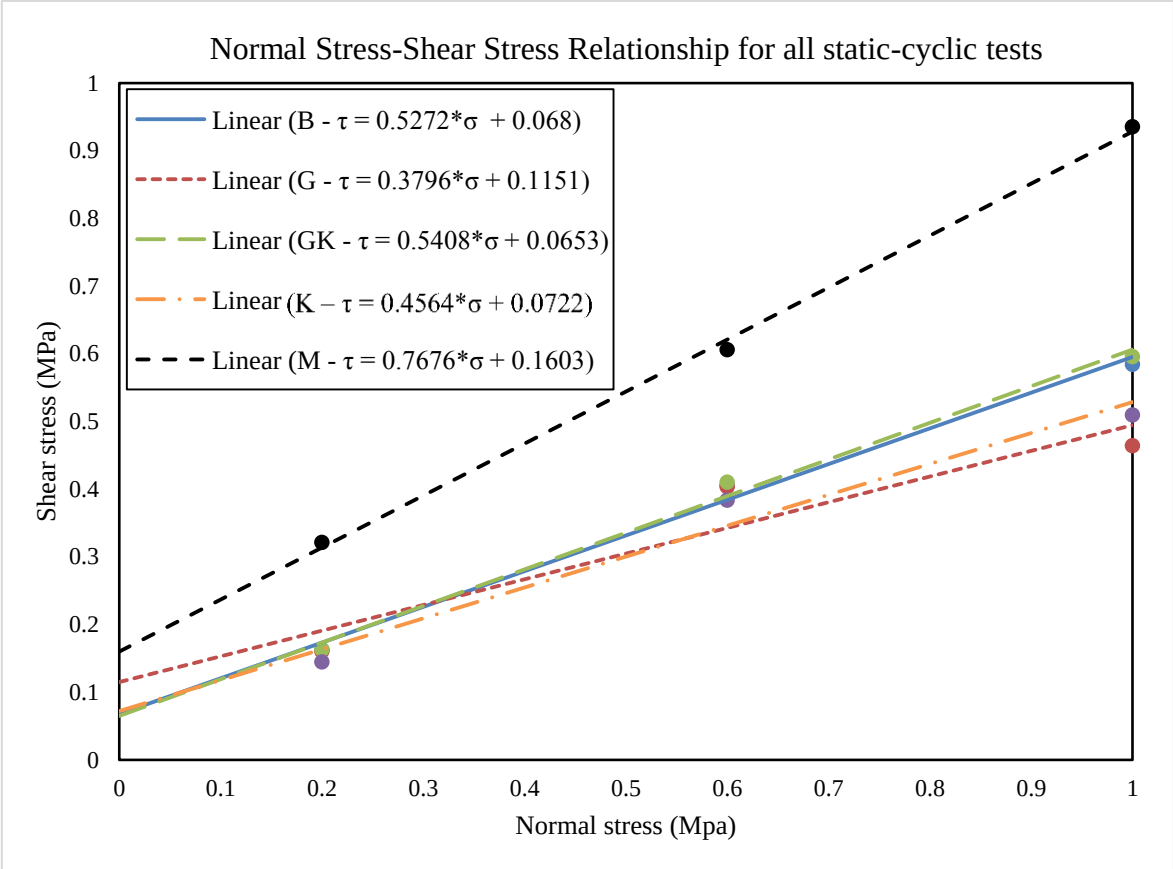


Fig. 23 Stresses relationship for static-cyclic tests.

As for the monotonic tests, the linear relationship between stresses was clear. The higher the pre-compression level, the higher the shear force it could resist. This applies to all types of specimens. Again, specimens without soft layer presented the highest shear force values and also its mechanical parameters were greater. As seen in the graph, triplets with soft layer showed some apparent cohesion but, as said before, this should be neglected as there is no cohesion what so ever for these types of specimens. Except for the specimens with bitumen layer.

As it can be seen in the graphic and in Tab. 8, the values of the maximum shear force for the specimens with soft layer were very similar, mainly in the first and second level of pre-compression. More specifically, GK and B series had nearly the same behavior and therefore their mechanical parameters are nearly identical. The main difference then, was the degradation of the materials, which will be later discussed.

Furthermore, these maximum shear force values were also much higher than the ones obtained in the monotonic tests. They were actually more than double sometimes, results can be compared between Tab. 7 and 8. Therefore, no relationship in the results between the two types of experiments was found. It was concluded that this happened due to a difference in

the velocity of displacement for the two types of experiments. While the initial speed in the monotonic tests was from 0.25 mm/min. the initial velocity in the static-cyclic experiments was from 0.5 mm/min. It seems that the maximum resistance force is velocity dependent and because of that, there is a great difference between both set of results. To investigate this in detail, further monotonic tests were performed, changing the initial displacement speed. These results are not considered in the present work.

Regarding the failure behavior, the specimens failed the same way as they did in the monotonic tests. On the one hand, specimens without soft layer failed when sliding between the mortar and the brick occurred. This happened for all three levels of pre-compression. On the other hand, specimens with soft layer also failed due to sliding, but in this case the sliding was between the soft layer and the elastomer. This behavior was exactly as the one observed for the monotonic tests.

Fig. 17-20 are considered now in order to compare the energy dissipation. For the specimens with soft layer all graphs show hysteresis curves surrounding a large area, therefore the dissipation of the energy was due to sliding in the joints. In contrast, the pattern for the specimens without soft layer was much different. They reached high shear forces without much sliding, nearly no sliding was observed which would be less suitable for seismic movements.

In order to compare the degradation of the specimens for the static-cyclic tests Tab. 9 expresses qualitatively how degraded were the soft layers after the test. Four levels of degradation are considered:

- None: soft layer was perfect.
- Few: soft layer showed some signs of degradation.
- Considerable: soft layer had several holes and degradation but stayed as a single piece.
- Total: soft layer was completely destroyed and only very small parts held together.

Series	**Degradation of the soft layer**		
	σ_{pc} = 0.2 [MPa]	σ_{pc} = 0.6 [MPa]	σ_{pc} = [1 MPa]
B	Considerable	Total	Total
G	None	Considerable	Total
GK	None	Few	None
K	None	None	Few

Tab. 9 Level of degradation of the soft layer after the test.

There is an obvious relationship between the level of pre-compression and the degradation of the layer. The higher the normal stress applied, the more degraded the material was at the end. In addition, it is important to emphasize that some soft layers got more degraded than others, making them, in some sense, less suitable. GK and K series had the best responses and resisted quite well the tests. On the other hand, G and B series behaved differently. Bitumen layers got completely destroyed and in some cases they were not even visible after the test, as the layer had merged into the elastomer layer. Fig. 23 shows some examples of the damage observed in the soft layers during the test.

Fig. 24 Degradation during testing; B2_1 (left and middle) and G3_1 (right).

The tables below (Tab. 10-11) summarize the mechanical parameters of each series of tests. The letter c stands for cohesion and μ is the friction coefficient. From the tables, it is clear that the results of the monotonic tests and the ones from the static-cyclic tests are not similar. However, the mechanical properties of the different soft layers can still be compared. In both types of tests, M series obtained the highest friction coefficient followed by GK series.

Series	B_0	G_0	GK_0	K_0	M_0
c	0.0792	0.0529	0.00	0.0869	0.2103
μ	0.2484	0.134	0.4125	0.1704	0.5056

Tab. 10 Mechanical characteristics for monotonic tests.

Series	B_1	G_1	GK_1	K_1	M_1
c	0.068	0.1151	0.0653	0.0722	0.1603
μ	0.5272	0.3796	0.5408	0.4564	0.7676

Tab. 11 Mechanical characteristics for static-cyclic tests.

Pictures of the triplets and the soft layers were taken after the tests. In order to compare them, some of the pictures are shown in the next page. The differences between the final states of the triplets can be clearly seen in these images. Furthermore, the degradation of the soft layers explained before is also visible.

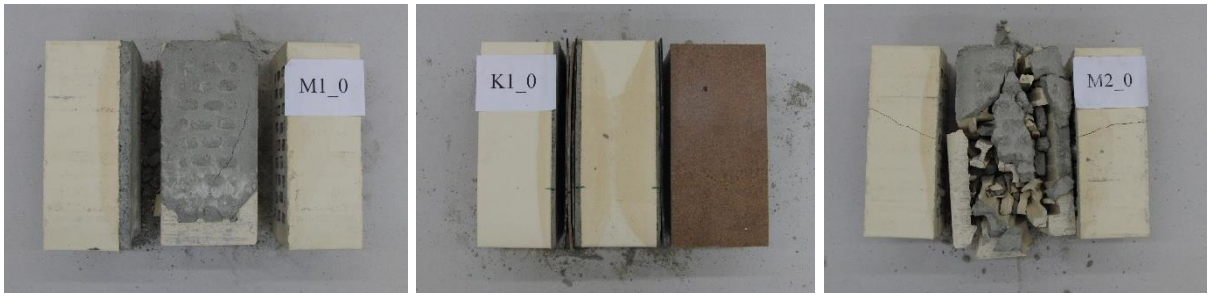


Fig. 25 Typical failure of monotonic test specimens (first and second level of pre-compression).

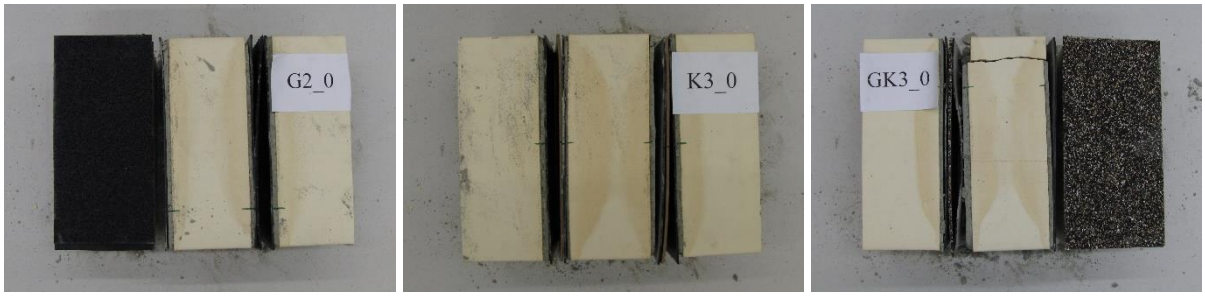


Fig. 26 Typical failure of monotonic test specimens (second and third level of pre-compression).

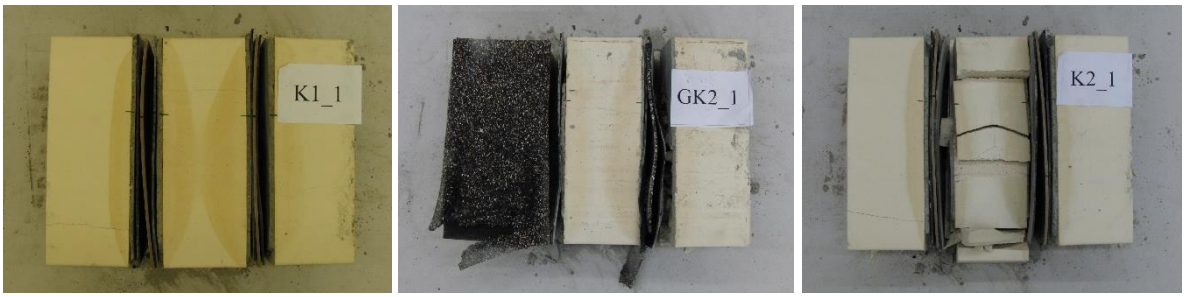
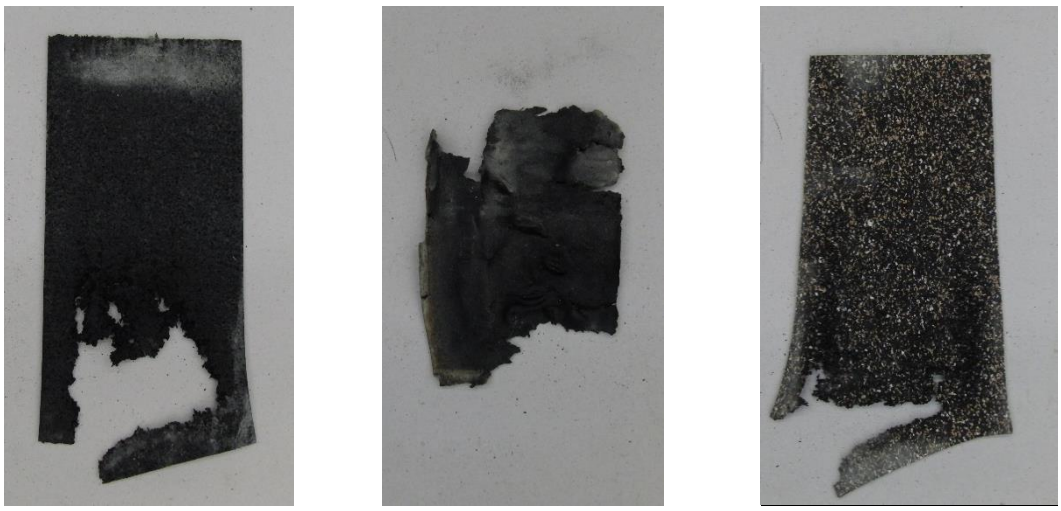


Fig. 27 Typical failure of static-cyclic test specimens (first and second level of pre-compression).

Fig. 28 Typical failure of static-cyclic test specimens (second and third level of pre-compression).

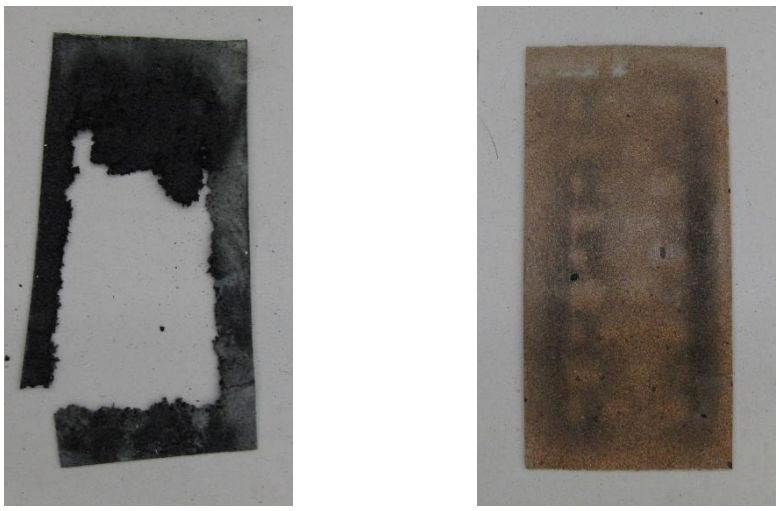
B2_0 **K3_0** **G3_0**

Fig. 29 Soft layers after monotonic tests.



G2_1 **B2_1** **GK2_1**

Fig. 30 Soft layers after static-cyclic tests (second level of pre-compression).



G3_1 **K3_1**

Fig. 31 Soft layers after static-cyclic tests (third level of pre-compression).

As mentioned before, to extract final conclusions many different matters should be taken into account. On the one hand, energy dissipation is an important issue to be considered, so the specimens with higher shear force resistance would be in better consideration. However, the degradation of the material should also be regarded, as low resistance to degradation induces shorter useful-life of the material. Moreover, greater friction coefficients would as well be better if the normal stress was to be high, but this will vary depending on the situation.

6. Conclusions

An experimental study was conducted to investigate the structural behavior of masonry elements subjected to shear and having a soft layer placed in the joints. Both monotonic and static-cyclic tests were performed and the test results have been discussed and evaluated. From the results following conclusions can be drawn:

- The shear resistance was highly influenced by the level of pre-compression: the higher the pre-compression force applied, the higher the maximum shear force. A Mohr Coulomb failure criterion was used in order to obtain the cohesion and friction coefficient of the materials.
- Specimens without soft layer showed consistently higher shear strength than the ones with soft layer. Furthermore, its mechanical parameters (cohesion and friction coefficient) were also greater.
- No correlation was found between the results from the monotonic tests and the ones from the static-cyclic tests. The failure loads were much higher for the static-cyclic tests. It seems that the shear strength is dependent on the velocity of the displacement during the test. As different speeds were used for both types of tests further tests should be performed with same speed.
- All specimens had the same failure behavior. When the maximum shear force was reached, sliding occurred. However, the slip plane was not always the same. For the specimens without soft layer, the sliding was between the mortar and the brick. On the other hand, the slip occurred between the soft layer and the elastomer for the specimens with soft layer.
- From the static-cyclic tests it was concluded that due to sliding behavior, i.e. quasi ductile behavior, large energy dissipation was observed for the specimens with soft layer. Such behavior would be desirable for seismic performance. However, only mortar specimens did not exhibit such behavior.
- During the monotonic tests no degradation of the soft layers was observed. However, for the static cyclic tests some materials were considerably degraded. Cork and rubber granulate-cork layers resisted very well the tests and were nearly never deteriorated. On the other hand, bitumen and rubber-granulate layers showed high degradation.
- Comparing the mechanical characteristics of the materials, rubber granulate-cork showed the highest value of friction coefficient, followed by bitumen, cork and rubber-granulate. The apparent cohesion seen in the results should be neglected as

there is not such cohesion in reality for the specimens with incorporated soft layer. Except for the ones with bitumen layer, as the bitumen gets some cohesion due to the pre-compression applied.

In order to determine which material should be more suitable to implement as a soft layer in masonry walls many issues must be taken into account. The mechanical characteristics, the failure behavior or the degradation of the layer are important matters that should always be considered. This project yields some preliminary conclusions about this issues for the materials used.

References

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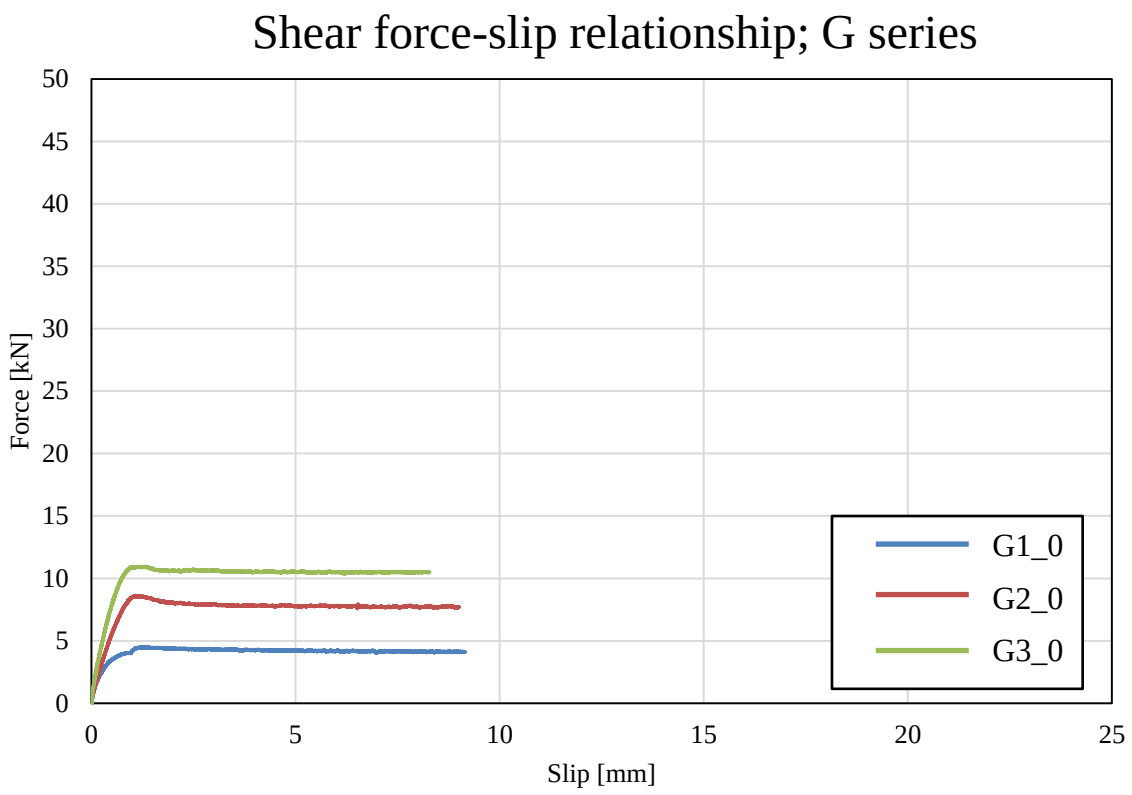
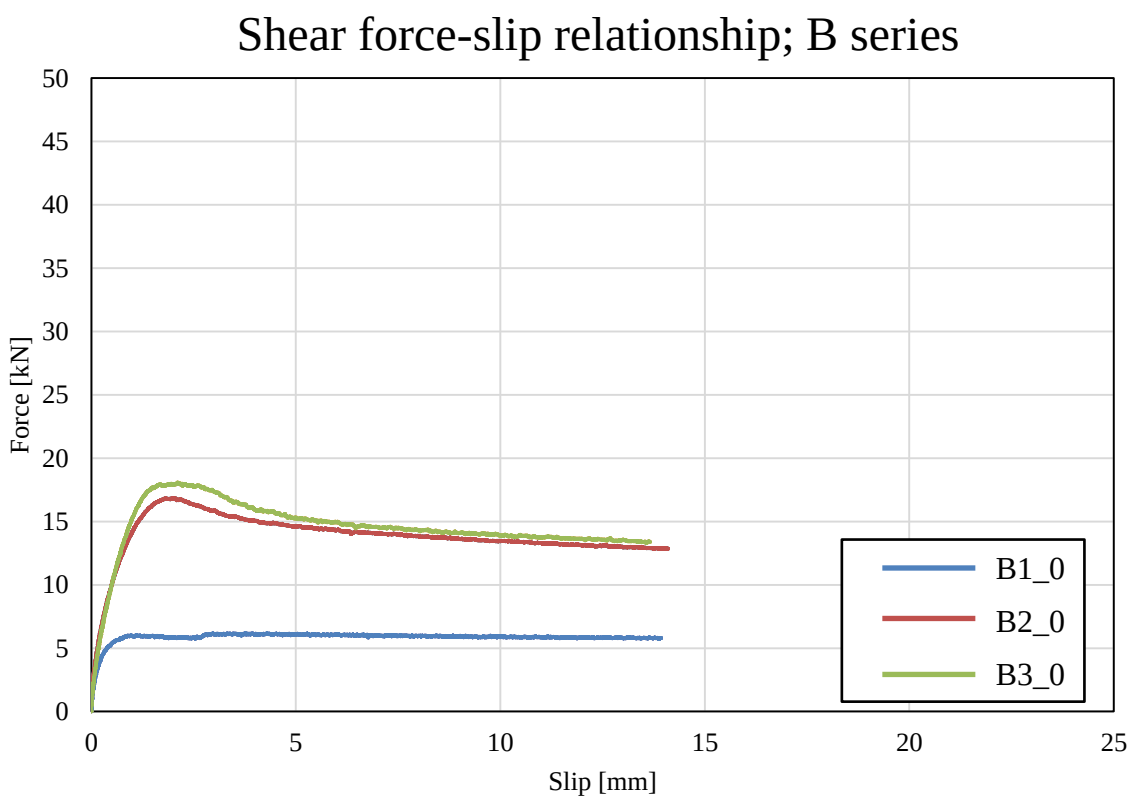
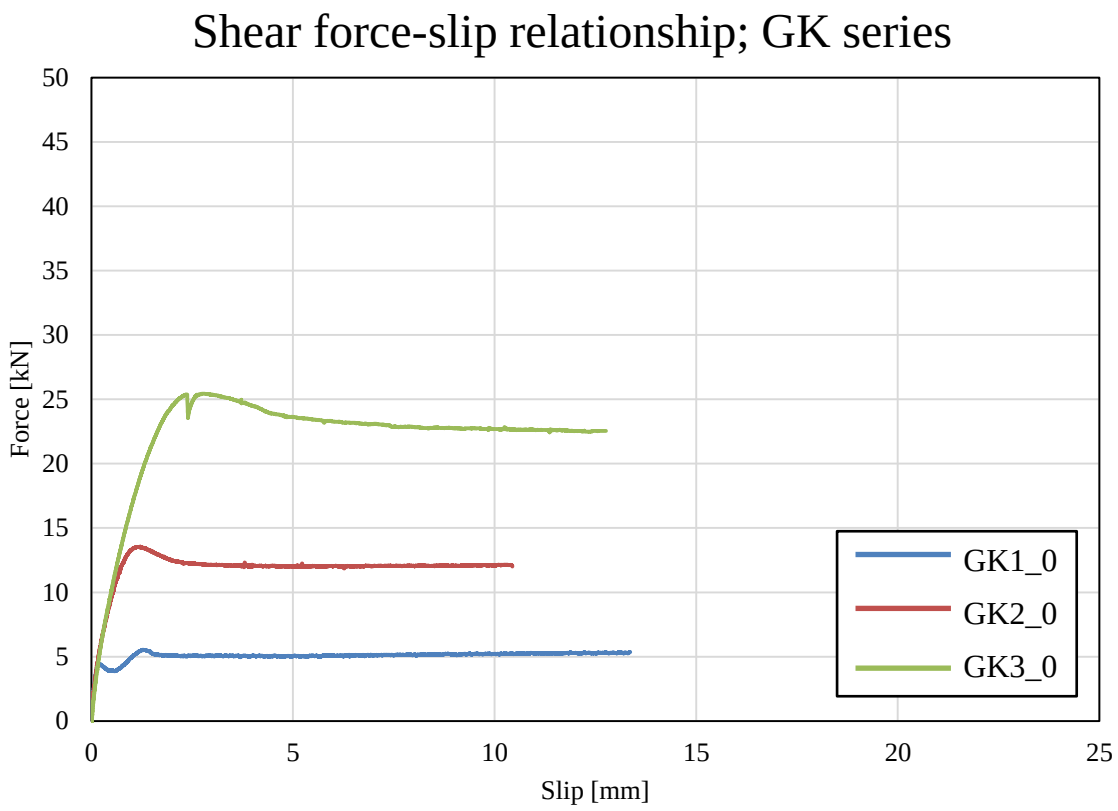
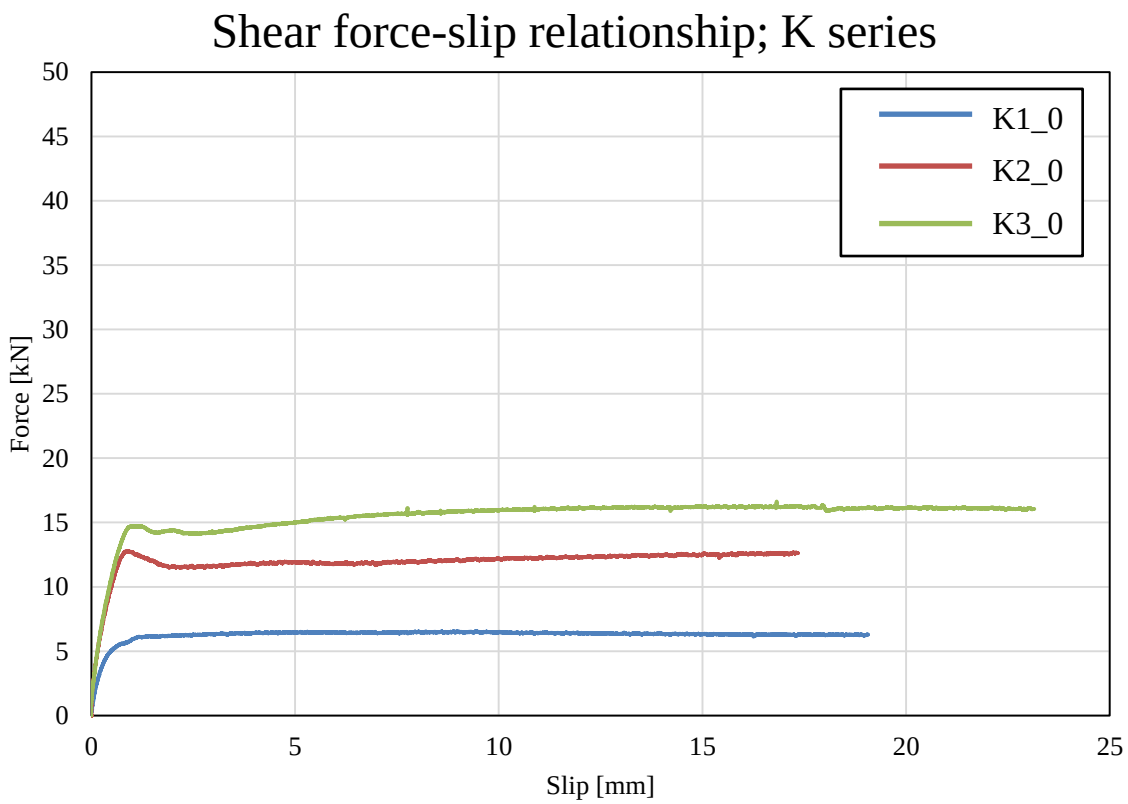
Annexes

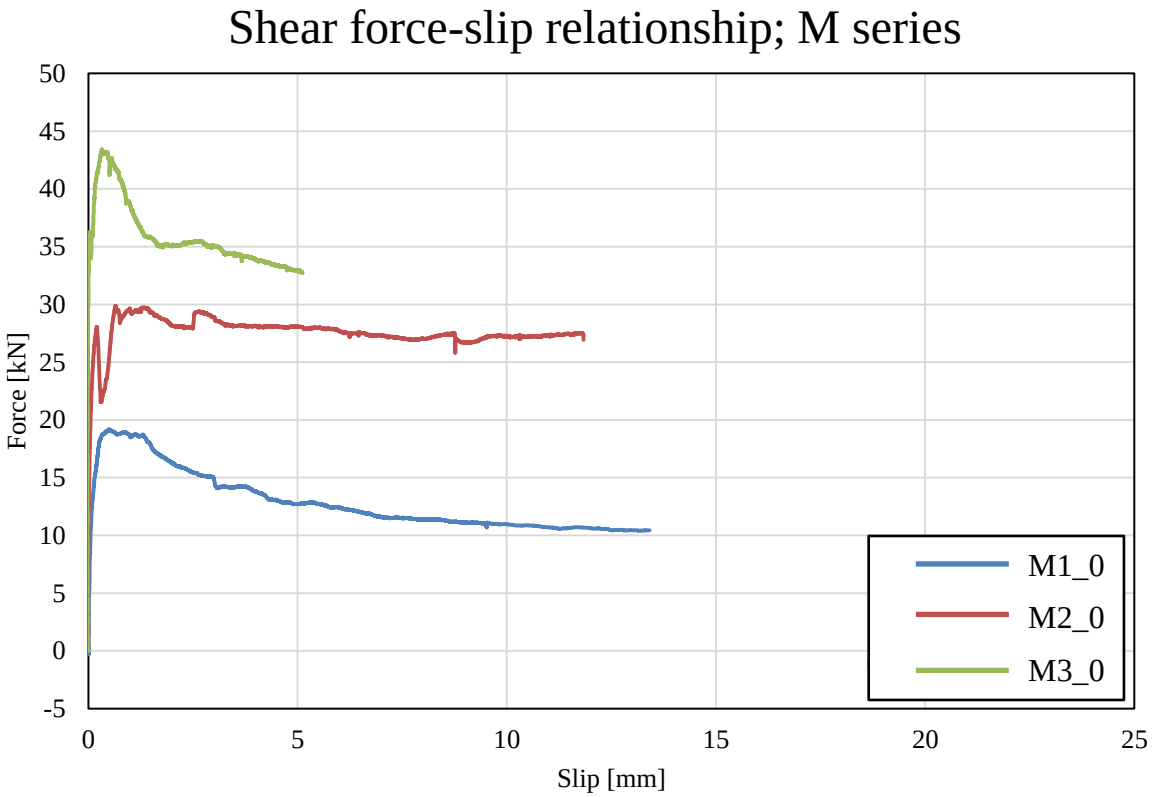
A1 Monotonic tests graphics for each type of specimen





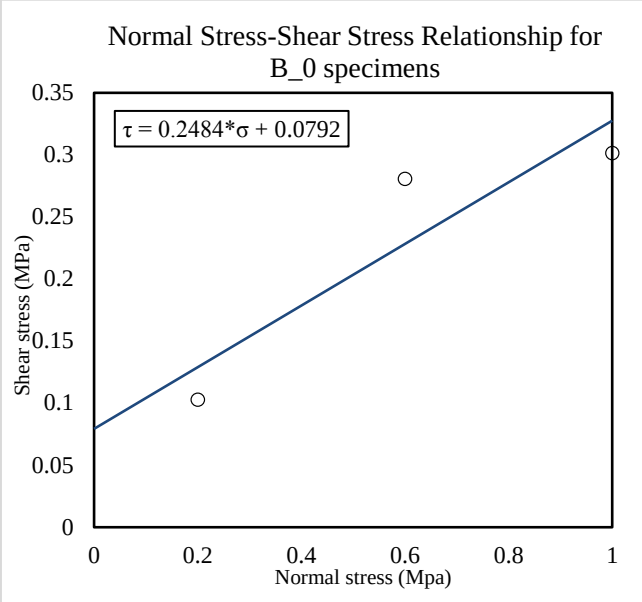

Shear force-slip relationship; GK series
Force [kN]
Slip [mm]
0
5
10
15
20
25
30
35
40
45
50
GK1_0
GK2_0
GK3_0


Shear force-slip relationship; K series
Force [kN]
Slip [mm]
0
5
10
15
20
25
30
35
40
45
50
K1_0
K2_0
K3_0

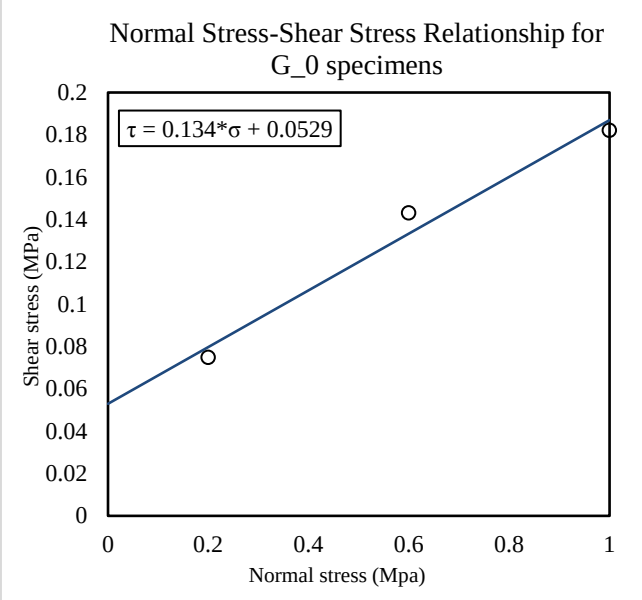

Shear force-slip relationship; M series
Force [kN]
50
45
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
Slip [mm]
M1_0
M2_0
M3_0

A2 Monotonic linear regressions

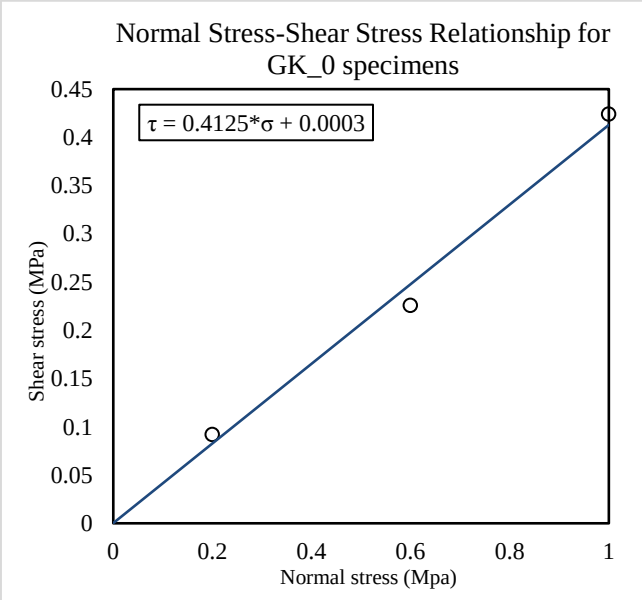
B_0



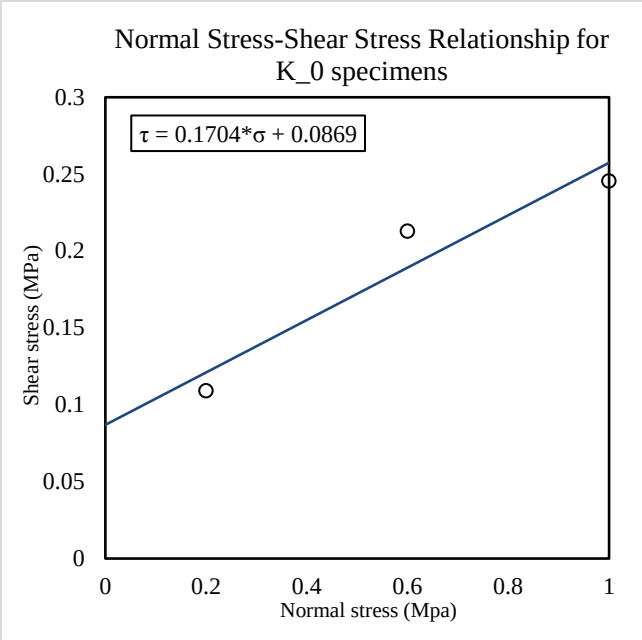
G_0



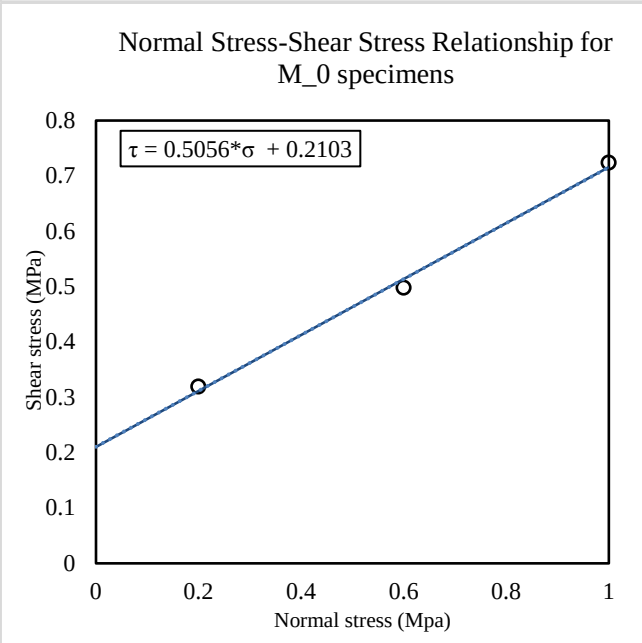
GK_0



K_0

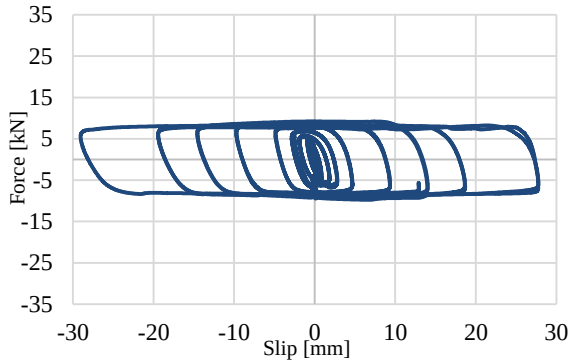

Normal Stress-Shear Stress Relationship for K_0 specimens
τ = 0.1704*σ + 0.0869
Shear stress (MPa)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
Normal stress (Mpa)

M_0

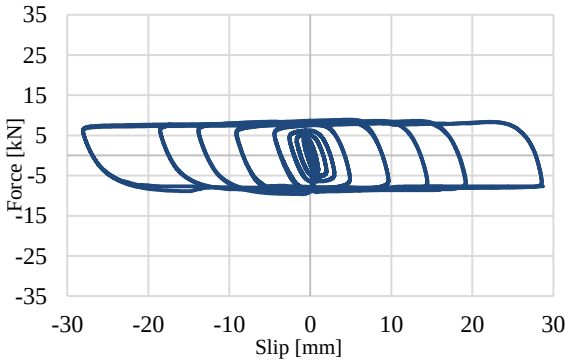

Normal Stress-Shear Stress Relationship for M_0 specimens
τ = 0.5056*σ + 0.2103
Shear stress (MPa)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
Normal stress (Mpa)

A3 Static-cyclic tests graphics for each type of specimen

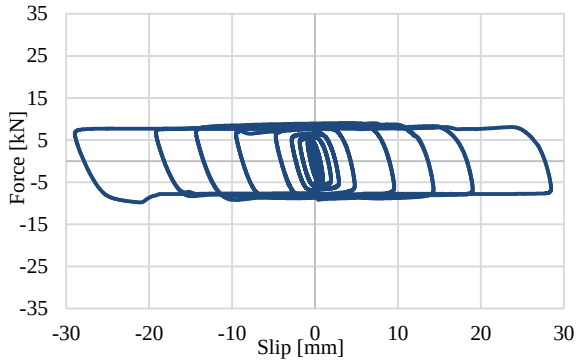
Shear force-deformation characteristics for B, G, GK and K series.



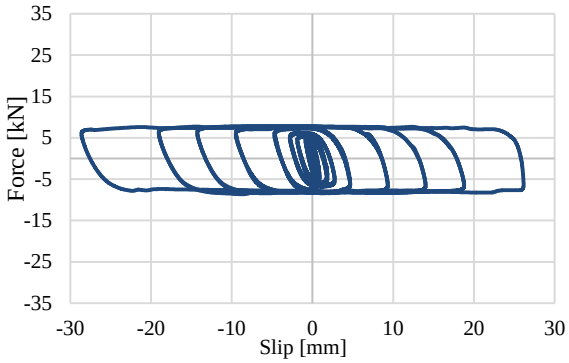
B1_1



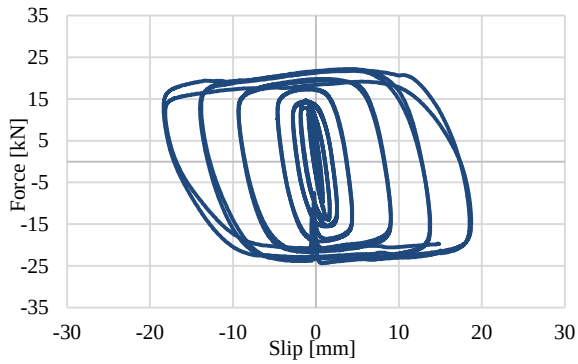
G1_1



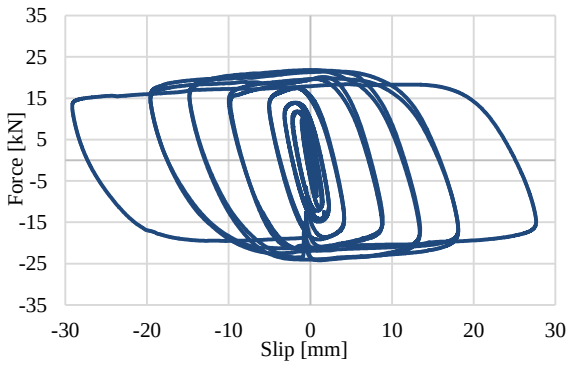
GK1_1



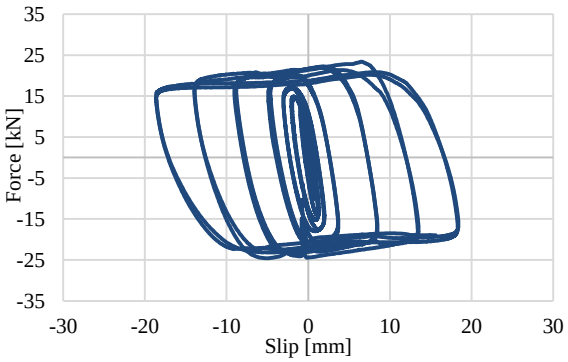
K1_1



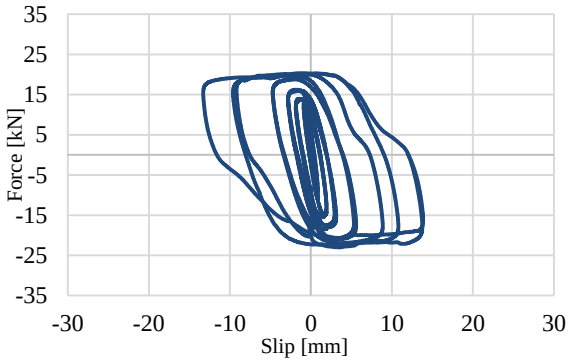
B2_1



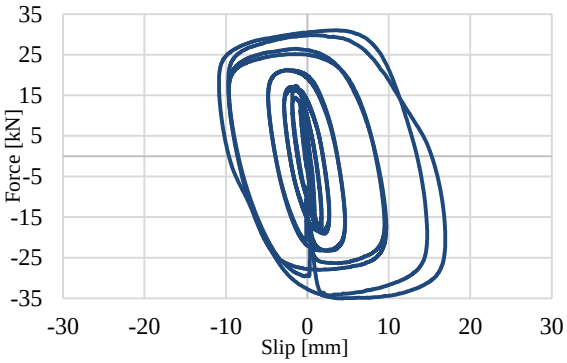
G2_1



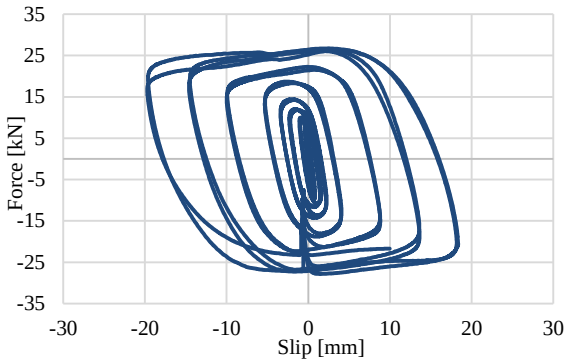
GK2_1



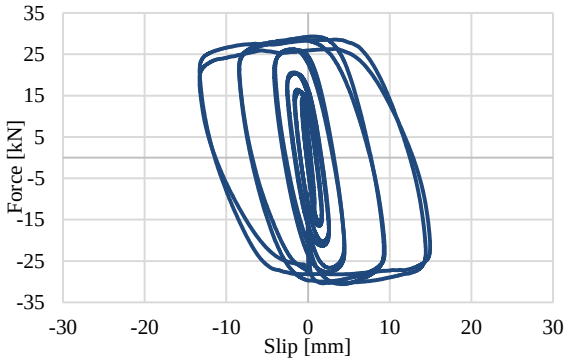
K2_1



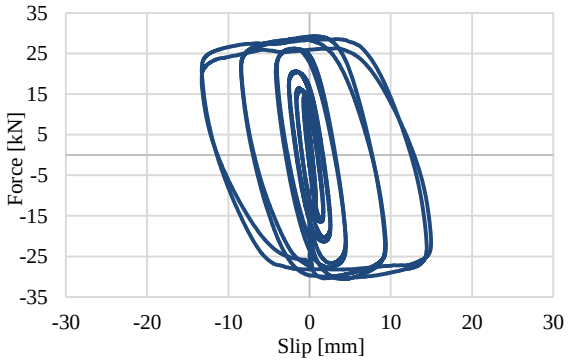
B3_1



G3_1

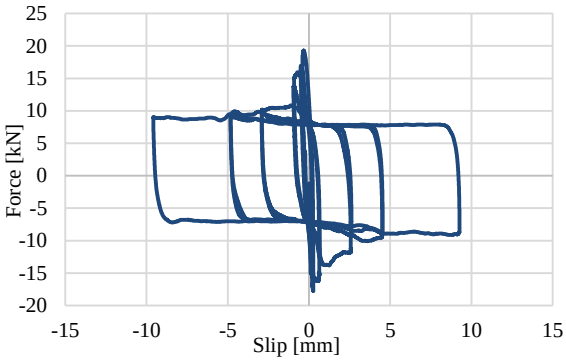


GK3_1

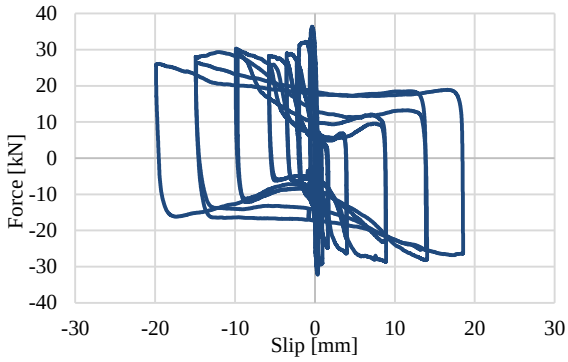


K3_1

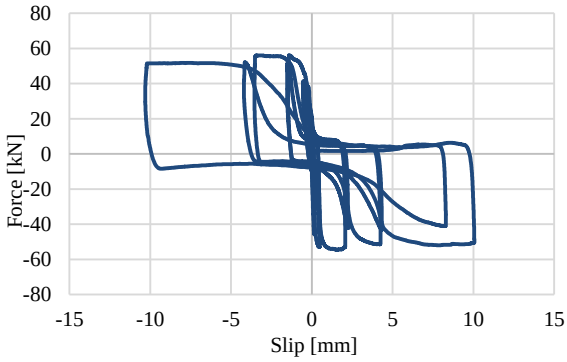
Shear force-deformation characteristics for M series.



M1_1



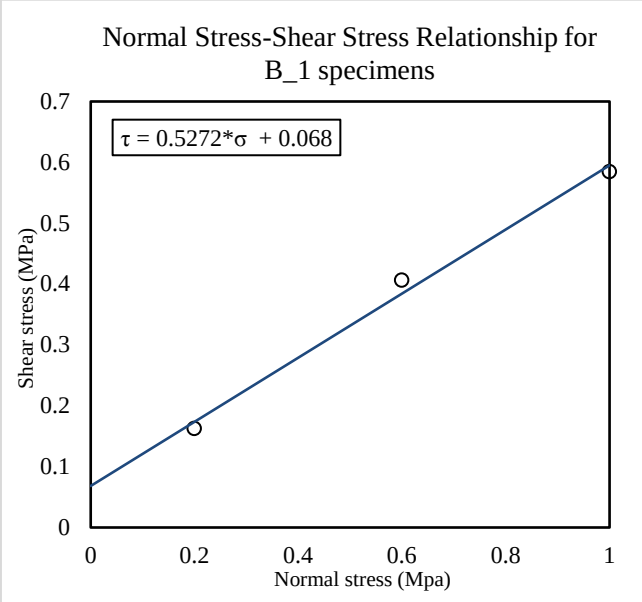
M2_1



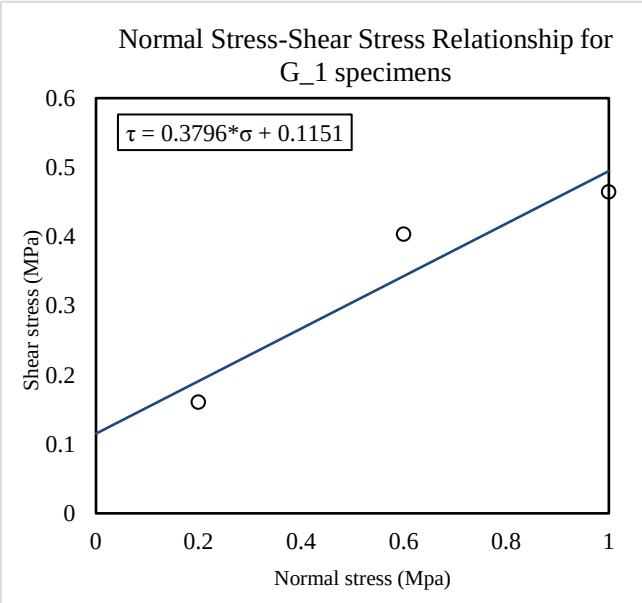
M3_1

A4 Static-cyclic linear regressions

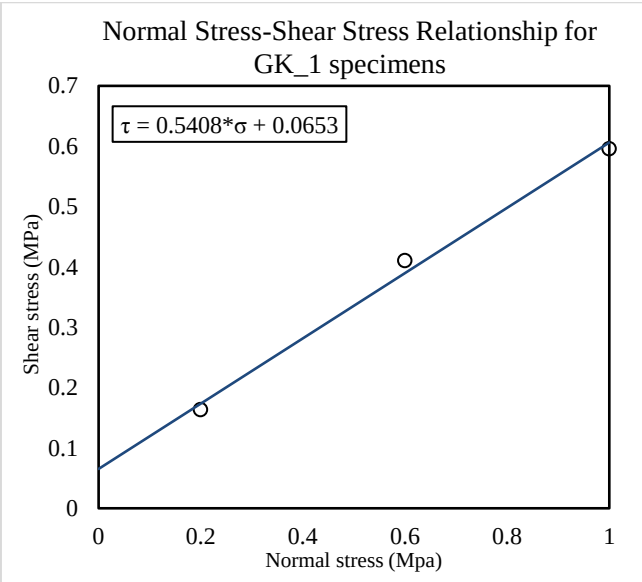
B_1



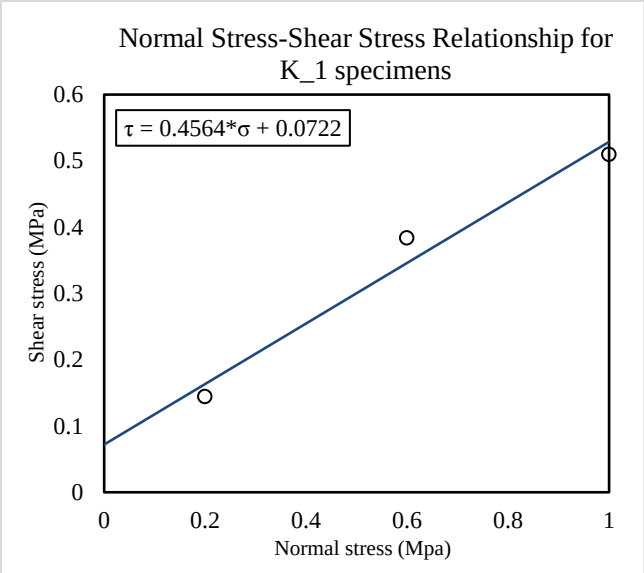
G_1



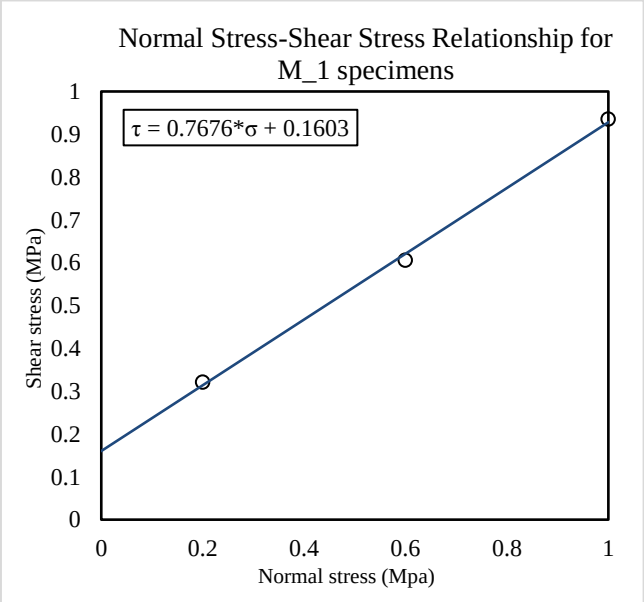
GK_1



K_1


Normal Stress-Shear Stress Relationship for K_1 specimens
τ = 0.4564*σ + 0.0722
Shear stress (MPa)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.2
0.4
0.6
0.8
1
Normal stress (Mpa)

M_1


Normal Stress-Shear Stress Relationship for M_1 specimens
τ = 0.7676*σ + 0.1603
Shear stress (MPa)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
Normal stress (Mpa)