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Sliding collapse in masonry structures: experimental tests

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ABSTRACT

Thirty-three static load tests were carried out in dry masonry walls. These walls have been subjected to their self-weight and to a horizontal load to promote a sliding failure between the blocks. The point of application of the load has been unchanged. All the walls have been constructed with the same ninety eight blocks. The disposition of the blocks have been done randomly in each of the walls to place the imperfections randomly too.

The two objectives of this work have been: firstly, to obtain plenty of sliding tests which could enable to form a statistical judgment of the results, and secondly, to compare them with the results from several numerical methods commonly used, especially with the non Standard Limit Analysis (nSLA) ones.

Keywords: sliding collapse, masonry structures, load test.

1. INTRODUCTION

Safety assessment of historical masonry structures, especially dry masonry and those in which the condition and even the presence of joint material is unknown, it is still a matter of discussion [1].

These structures can be modelled as an Unilateral Contact Problem between bodies. From the 80s, these kinds of problems have been solved as Complementarity Problems (CP) [2,3]. These problems have multiple solutions when the collapse is produced with sliding. The author’s numeric simulations [4,5] show that these solutions could have a wide dispersion degree and that not all of them are equally probable.

Even though a large number of masonry structures have been tested [6,7,8,9,10,11,12], in most of the cases rocking was the principal collapse mechanism, resulting in a small dispersion in the results. The number of tests in which the collapse is produced by sliding is considerably lower [13].

Our will is to study the effect of sliding in the collapse of masonry, which means that our tests will be carried out on specimens only subjected to their self-weight composed with a relatively high horizontal external force, as a simulation of the mechanical behaviour of upper parts of buttresses, the

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upper bands of masonry shear walls under thrust of roofs or transverse walls, or the anchorage zones for tension ties.

Here we propose an experimental test with a dry masonry wall subjected to a horizontal point load and in its same plane. The interest of this test is that, with the right selection of the piece's form and the right point of application of the load, it is possible to achieve a quasi-static way to collapse by pure-sliding.

2. EXPERIMENTAL TESTS

A wall of dry masonry was subjected to a series of load tests, where the actions were the self-weight and a horizontal load. The objective was to obtain plenty of sliding tests which could enable to form a statistical judgment of the results and compare them with the results from several numerical methods commonly used. The experimental tests were done in the Building Structures Department laboratory, ETSAM, Technical University of Madrid. All tests were performed under controlled environmental conditions both for temperature (20ºC+-2) and for relative humidity (R.H. 40%+-10), measured by means of a Hydromette HT-85-T hygrometer.

2.1 Materials

All the tests have been carried out on dry brickwork masonry walls. Brick pieces were chosen as base material due to its geometrical consistency, Its geometrical features can be found on Table 1, where %Min stands for the difference in percentage between minimum and mean values. Min stands for the minimum value, Max for its maximum, SD for the standard deviation, CV for the coefficient of variation (standard deviation / mean) and %Max for the difference in percentage between the maximum and mean values.

Table 1. Features of the brick HD R-20 used in experimental tests

	%Min	Min	Mean	Max	%Max	SD	CV %
length mm.	0.42	239	240	24.1	0.42	0.50	0.20
width mm.	0.35	115	115.4	116.0	0.51	0.51	0.43
height mm.	1.05	49.8	50.3	50.8	0.94	0.21	0.41
weight N	0.63	16.42	16.52	16.76	1.43	0.07	0.42

Friction coefficients have been obtained by means of the same methods and apparatuses used in the tests described below, and under those same conditions, obtaining a mean value of 0.52 and a standard deviation of 0.03.

2.2 Test description

The experiment was repeated 33 times, with the same general layout: the same point of application of the horizontal load and the same procedure (Fig.1), varying the position of the pieces in each test. Brickwork walls are 15 rows in height for a total number of 98 pieces (82 full-sized bricks and 8 of them split in two halves.

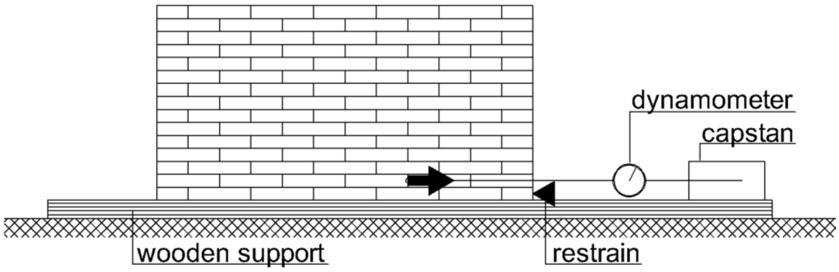

Figure 1. *Diagram of the test.*

With all the bricks numbered, the method known as Fisher-Yates-Durstenfeld shuffle [14] has been used to ensure the randomness in the position of the pieces. (Fig. 2)

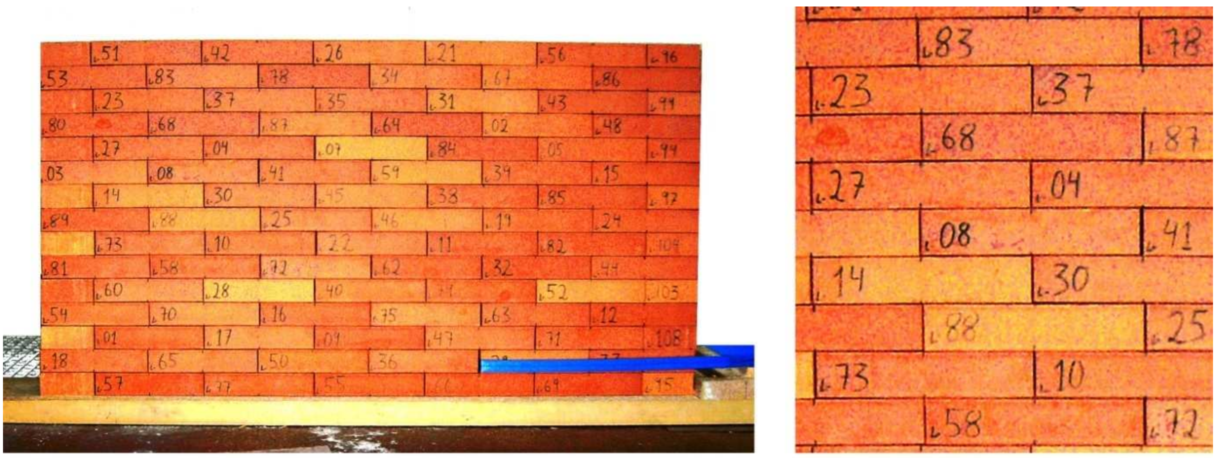

Figure 2. *Application of Fisher-Yates-Durstenfeld shuffle.*

The test procedure consists in applying an increasing horizontal load at the second lower row of the specimen, being the displacements of the first row restricted at the edge.

The application of the load begins immediately after the construction of the wall. Load is introduced on the specimen by means of a Imnasa-350 capstan, and using a Sauter FA-500 dynamometer the load data is measured.

Once load starts to be applied, as soon as sliding opposition intensity decreases the horizontal load is forced to vanish. Then the gap that appears on the point of the brick where load was applied, is measured and recorded.

Finally, this same process is repeated several times, and the yield line progression data are retrieved and recorded.

2.3 Test results

The obtained results have been tabulated, statistically treated and compared with the results obtained by numerical methods.

In Table 2 there are shown the results for the load that promotes the beginning of sliding at the initiation of each experimental test.

Table 2. Results of test (load in N).

309.5	324.1	329.1	334.4	339.1	339.4	354.3	359.1	364.4	379.0	384.2
388.9	389.0	389.0	389.3	398.9	398.9	404.3	404.3	418.9	424.2	424.2
433.8	433.8	453.8	459.2	463.8	469.2	474.2	479.0	508.6	509.1	533.6

Using the same abbreviations as shown on Table 1, some descriptive statistics for the previous values are shown on Table 3.

Table 3. Statistics of tests (load in N).

Nº	%Min	Min	Mean	Max	%Max	SD	CV %
33	24.20	309.5	408.3	533.6	30.68	58.03	13.99

The implementation of several goodness of fit tests and normality tests allows to conclude that a Normal (Gaussian) distribution seems to be the best-fit option. A most likely range of values for the most relevant statistic parameters has to be found. Hence, as a conclusion, confidence intervals are obtained only for case D, for the 5% percentile and other parameters, for a 99% confidence level after using resampling methods [15] applied on the best-fit normal distribution (parametric bootstrap).

In Figure 3, values for tests having a zero initial gap and functions are shown: a histogram scaled to 0'50, the frequency distribution, the best-fit normal distribution, maximum and minimum values retrieved from tests and the 5% percentile confidence interval of those values for a 99% confidence level.

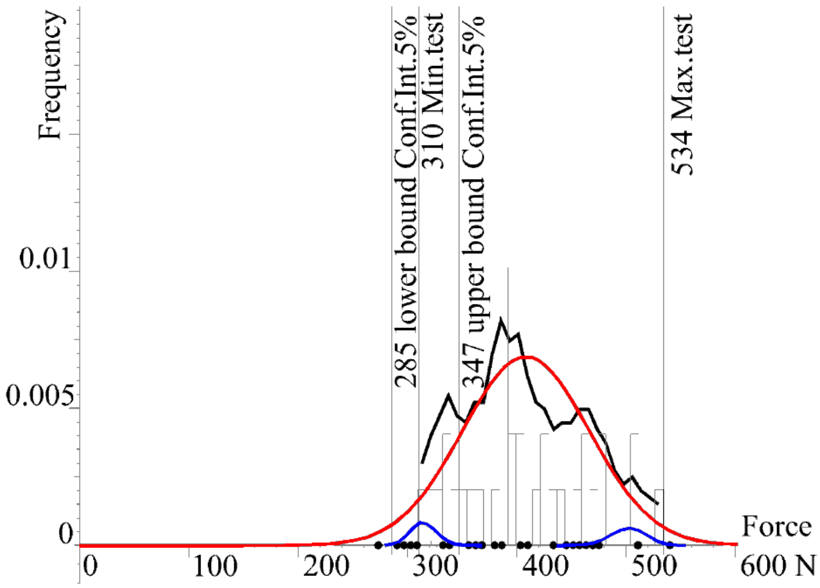

Figure 3. *Graphic of experimental results.*

Numerical results for confidence intervals are shown on Table 4.

Table 4. Confidence intervals (load in N).

Confidence intervals at 99% confidence level	5% percentile	Mean	95% percentile
	285-347	383-435	460-538

All the values shown correspond to the loads that promotes the beginning of sliding in each experimental test.

The behaviour after the beginning of sliding is not uniform. In some cases, small changes due to gaps, promotes sharp increases or decreases in the sliding resistance.

In Figure 4 the initial gap vs load (force) points are represented. These points correspond to couples of values obtained for all tests. Those belonging to the same test are linked by straight lines

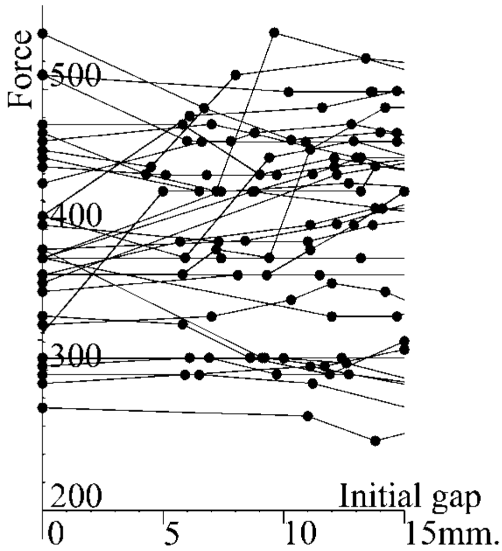

Figure 4. *Evolution of sliding resistance during the experimental tests.*

This non-uniform behaviour provokes that during the experimental tests, different yield lines could appear giving complex breaking patterns.

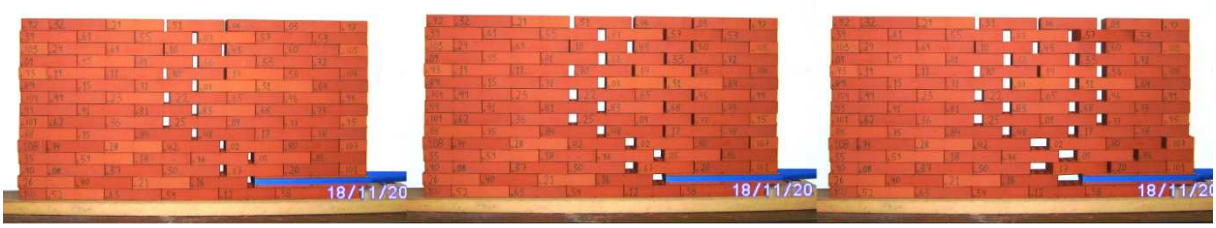

Figure 5. *Different collapse mechanisms examples during the same test.*

There has been a variety of collapse mechanisms with one or more yield lines (Fig. 6). Not all of them have been equally probable. In some cases the collapse mechanism has been the same as in case 1, with small variations.

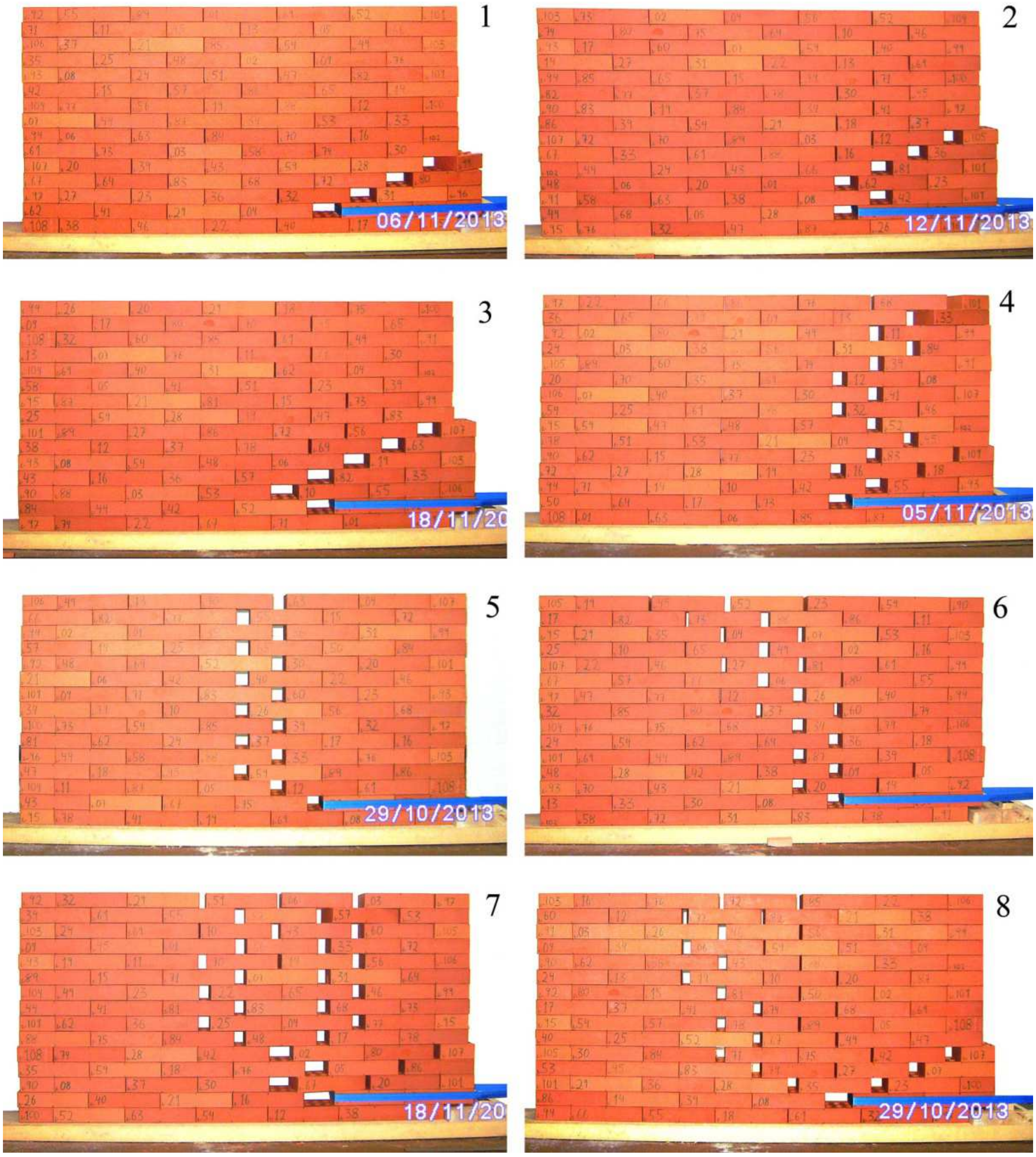

Figure 6. *Different collapse mechanisms in different tests.*

3. COMPARISON WITH SOME NUMERICAL METHODS

3.1 Applied methods

The numerical methods here used are:

min nSLA: minimum value of non-Standard Limit Analysis (without dilatancy), as described in [2,3,5].

min USD: minimum value of Uniform Stress Distribution, following Rankine theory about frictional tenacity [16].

max SLA: maximum value of Standard Limit Analysis, obtained by Limit Analysis by Linear Programming [17,18].

This previous selection does not involve any preliminary judgement on the suitability that these methods may bring to our purposes.

In addition, a calculation has been done using linear FEM and contact elements using the commercial software ANSYS. The results are not shown here since they are exactly the same as the obtained by min USD. The use of non-linear finite elements with non-associative friction laws is beyond of the scope of this work. None of the compared results take into account the material deformation, although the min USD do it indirectly by assuming a uniform distribution of the stresses (and strains) in each bed joint.

The max SLA (maximum value of Standard Limit Analysis) obtains the maximum of all the possible values, not considering the strength of the joint material.

The min nSLA (absolute minimum value of non-Standard Limit Analysis - without dilatancy) obtains the minimum of all the possible values not taking into account the strength of the joint material.

Any other method that does not consider the strength of the joint material will give an intermediate result between both sides; this is what happens with min USD (minimum value of Uniform Stress Distribution).

Regarding to min nSLA it has to be mentioned that: although the simplest formulation for the non-standard Limit Analysis is posed as a Linear Complementarity Problem and, therefore, it stands as a great difficulty [19,20,21], in our case, once a yield line has been selected and the corresponding limit conditions are substituted in the original problem, it turns out a linear problem and the global minimum can be obtained by means of linear programming. In the present work once we test a number of yield lines , it is proved that the one represented is the minimum value. (Fig. 7)

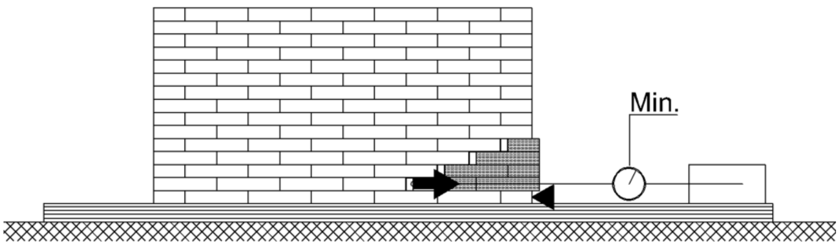

Figure 7. *Collapse mechanism corresponding to min nSLA*

In the described case it is possible that the only load that takes part in the resistance to sliding is the self-weight of moving blocks, since it exist an equilibrium solution for the blocks that have remained in their position (Fig. 8).

Figure 8. *The wall after collapse.*

3.2 Comparison of the results

In Table 5 and in Figure 9 values for tests having a zero initial gap and functions are shown again. All values are compared with those retrieved from numerical methods.

Table 5. Comparison of numerical methods and experimental results. (force in N).

Min. nSLA	99% confidence interval 5% percentile		Min.USD	Max. SLA
45 N	285 N	347 N	455 N	589 N

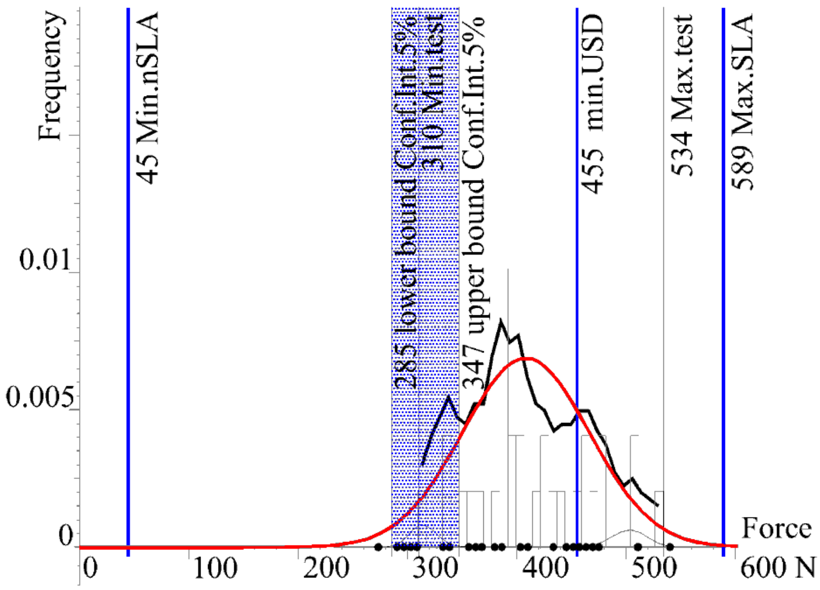

Figure 9. *Comparison of numerical and experimental results.*

4. DISCUSSION AND CONCLUSIONS

The solution for the onset of collapse, and hence its load factor, is not always unique. It is not possible to explain the experimental data dispersion from the material properties dispersion, since the value of the first one is much greater. Comparing the results of several numerical methods - Minimum of non-Standard Limit Analysis [2], Uniform Stress Distribution [16], Maximum of Standard Limit Analysis [17] - which take into account the discontinuity of the material giving just a single value, it can be seen that this value is quite far from the test characteristic value, namely the 5% percentile.

Moreover, the second and the third methods are unsafe and the first method [2] gives an excessively conservative result (Table 5). Other authors [22,23] have suggested that this last method is excessively conservative, the obtained results confirm this idea. For the cases we have studied, the search for the global minimum by non-Standard Limit Analysis does not seem to prove efficient, either in terms of computational costs or for its accuracy in approximating the actual minimum.

As a conclusion, it is worth to notice that in cases as the one treated, when the contribution of the mortar cannot be taken into account for the strength of the structure and when the collapse is produced by sliding and due to point loads, the dispersion of the results is wide, implying that those methods that do not take into account the randomness effect, could give results far from the characteristic value of the experimental results. Therefore, a larger research in this field is required, both from the theoretical and the experimental points of view.

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