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# Numerical and Experimental Tests on Three-Leaves Stone Masonry Specimens

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ABSTRACT: Distinct Element SW packages can be devoted to the numerical analysis of masonry structures. This fact has suggested carrying out several numerical tests to check their efficiency in the analysis of the mechanical behavior of three-leaf stone masonries. By means of a Distinct Element Code, numerical models of some physical samples have been performed. The numerical analysis aims to detect the shear transfer capacity of different types of leaves connections: with and without offset.

The comparison between the numerical and experimental results gives indications for the constitutive modeling of the mechanical response for both cases of interface connection. Moreover the effects of stress concentration due to the presence of offsets and its influence on collapse condition have been investigated.

## 1 INTRODUCTION

This paper presents some results of a numerical modeling of the mechanical behavior of three-leaf masonry stone specimens. The modeling was performed taking into account the data of an experimental campaign carried out on full-scale specimens at the testing material laboratory of the department of structural engineering - Politecnico di Milano.

The aim of the campaign was to study the mechanism of stress transfer between the leaves of the walls and to pick out the collapse mode for three-leaf masonry walls subjected to vertical loading on the inner leaf only. This kind of structural elements are quite common in historical buildings in Europe, particularly in Italy. The general shape of the element is a thick wall made by two external leaves of brick or stone block masonry, and an inner leaf of rubble and irregular material with mortar. In most cases the thickness of the inner leaf is equal or larger than that of the external walls. Often the inner leaf is made by irregular elements of the same stone used for the external; the well-cut stones are used for the regular panels, small stone pieces remaining from cutting are used for the infill. The experimental campaign tested this particular condition, with the inner core of enough good quality.

Generally the load carrying capacity of a three-leaf wall is evaluated summing the resistance of the two external strong leaves considered separately. This method is conservative when the inner leaf is made of poor material, and the structure is subjected only or mainly to vertical loads.

Nevertheless, when this kind of structural elements is loaded out of plane or is subjected to dynamic loads, the effective load carrying capacity depends mainly on the interaction among all the leaves. A high percentage of historical buildings in Italy, made with three-leaf stone masonry, is situated in seismic areas.

In order to better understand the capacity of transfer of shear stresses between the leaves, it is necessary to investigate experimentally the following aspects influencing the mechanical behavior of the leaf interface:

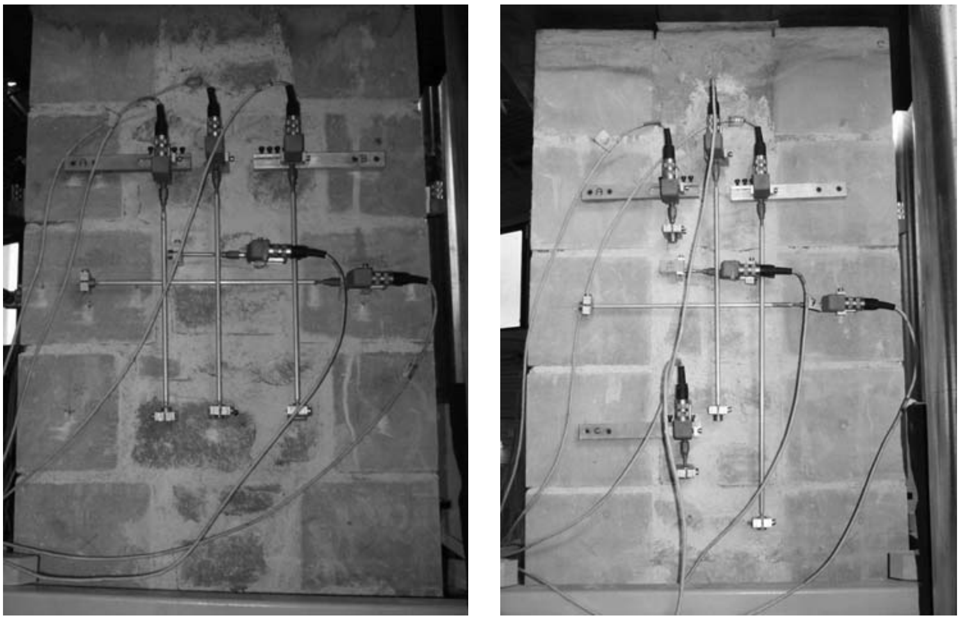
- Bond strength between the leaves influenced by the mortar quality, the roughness of the surfaces and the porosity of the units of the different leaves;
- Geometrical characteristics of the contact surfaces. The presence of indentations (offset of stones), improves the bond between the leaves and helps the stress transfer. Particularly this latter aspect in considered in the activity performed.

## 2 EXPERIMENTAL CAMPAIGN

When in a masonry building a wall subjected to out of plane horizontal transversal loads cannot transfer the action to shear walls, only its flexural behavior resists to the horizontal actions.
In fact, only the connections or the offsets between the leaves can improve the flexural behavior of the masonry.

In order to gain a better knowledge of the transfer of shear stresses between the different leaves, depending on their geometrical feature and on material properties, eight three-leaf stone specimens were prepared, using two different types of stone. Specimen dimensions were 51 cm width, 79 cm height, and 31cm thickness.

The specimens had two external leaves of regular cut stones with thin mortar joints (1 cm) and an internal layer of medium-small irregular pieces of the same stone with mortar. The eight specimens were built with the same type of commercial hydraulic mortar, used also for restoration, both for external and inner leaves. Four specimens were built with offsets in order to improve the connection between the leaves; the other four were made without offsets (Figs. 1, 2).



Figures 1, 2 : Specimens with and without offsets: displacement transducers position.

Two types of stones were used: a rather soft, porous and weak limestone (Noto stone) largely used in Sicily and in Southern Italy, and compact sandstone (Serena stone) used in Central Italy.

For each type of stone four specimens were tested: two of them with offsets and two others with straight joints between the leaves. The specimens were tested after at least 2 months of curing. The samples were tested supporting them only at the base of the external leaves and applying a monotonic compressive load on the inner leaf top, with a rate displacement of 1μm/s.

In this experimental campaign four other specimens were built, one for every type of stone and joint. They were tested in compression, applying a monotonic load, with the same rate displacement for shear tests, on the whole top section. Moreover, after the shear tests, the external and internal leaves of the specimens without offsets were tested in compression.

In this paper the interest is focused on the mechanical behavior of the Noto Stone specimens subjected to shear tests.

The main mechanical properties (specific density $\gamma$, compressive strength $\sigma_c$, Young modulus E) of Noto stone are reported in Table 1.

Table 1 : Mechanical properties of Noto stone

| $\gamma$ kg/m$^3$ | $\sigma_c$ N/mm$^2$ | E N/mm$^2$ |
|---|---|---|
| 1800 | 19.5 | 9300 |

Table 2 reports a synthesis of the main results of the shear test for the four Noto stone specimens: the peak load value P and the maximum normal stress at the top of the inner leaf, the peak displacement value s.

The shear bond between mortar and Noto stone is generally quite good, due to the stone large porosity (26%).

Table 2 : Synthesis of the main results

| Noto stone specimen | presence of off-sets | vertical joint failure | peak load kN | maximum top normal stress N/mm$^2$ | peak displacement μm |
|---|---|---|---|---|---|
| PN1 | no | 1$^{st}$ joint | 61.9 | 1.17 | 566 |
| | | 2$^{nd}$ joint | 43.4 | 0.82 | 967 |
| PN2 | no | 1$^{st}$ joint | 97.4 | 1.85 | 1230 |
| | | 2$^{nd}$ joint | 60.2 | 1.14 | 1880 |
| PN4 | yes | | 277.7 | 5.27 | 2633 |
| PN6 | yes | | 291.1 | 5.52 | 1949 |

## 3 DISTINCT ELEMENT MODELLING

The specimens have been modeled adopting a Distinct Element Software (UDEC) generally used in rock mechanics. The structural element is subdivided in blocks (rigid or deformable) connected by joints. The numerical solution procedure is the integration of the equations of motion of the blocks, with update of the block and joint position. The stones of the samples were modeled with deformable blocks (Fig. 2). The interaction among blocks takes place at the joints, and depends on the joint properties assigned. In order to model the opening of cracks in the external leaves stones, they were subdivided in small blocks, assigning joint properties simulating the stone characteristics. The blocks in the inner core and the sub-blocks of the external leaves were defined by means of a statistical tessellation.

A Coulomb friction model was assumed for the joint mechanical behavior. The friction angle was set to the plausible value of 30 degrees. To assess the values of the joint stiffness of the model, reported in table 3, the results of the compression test on the external leaves of the specimen PN2, performed after the shear test, were taken into account.

Several different numerical models were performed, changing some mechanical parameters about ±20 %, in order to get the best fit. The numerical tests were carried out assigning a displacement rate of 1.0 mm/s on the top of the inner layer. The main results are summarized in the reported graphs.

Table3 : Main joint properties

| | cohesion MPa | tensile strength MPa | normal stiffness $10^{10}$Pa/m | shear stiffness $10^{10}$Pa/m |
|---|---|---|---|---|
| | 0.9 ÷ 1.2 | 0.9 ÷1.2 | 2.5 ÷ 2.7 | 1.0 ÷ 1.2 |
| with offset | 1.2 | 1.2 | 2.5 | 1.1 |
| without offset | 1.0 ÷ 1.2 | 1.0 ÷1.2 | 2.5 ÷ 2.7 | 1.1 ÷ 1.2 |

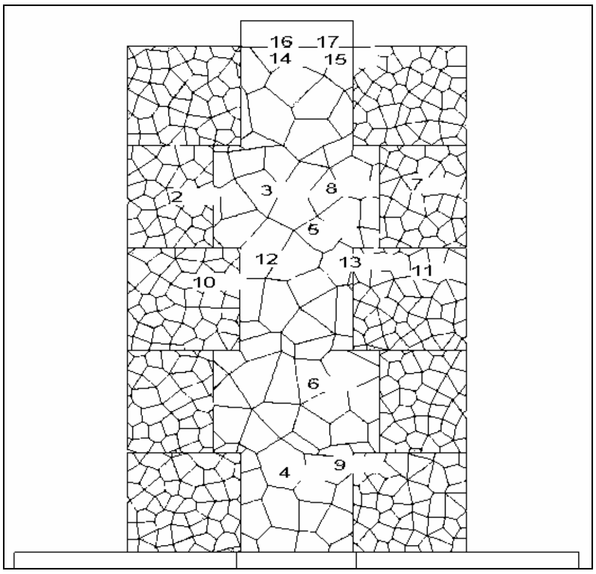



Figure 3 : block arrangement and history points position (on the right)

## 4 COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

### *4.1 Noto stone specimens with offset*

The numerical analysis performed gets quite well (Fig. 3) the global collapse of the specimens, the maximum carrying capacity is only about 10% less than the average experimental data, but the result has some difference in what regards the global stiffness.

While the geometry of the external stones corresponds to reality, the inner core is modeled by means of a statistic distribution of blocks of assigned average dimension. In the real specimens the inside blocks were sometimes quite large and regular, this is probably a cause for the difference between model and experimental stiffness. Nevertheless the result obtained shows the effectiveness of a random tessellation to describe the global behavior of the specimen.

An example of the modeling of the point displacements in the specimen is shown in Fig. 4, which reports an experimental LVDT vertical displacement and its numerical modeling. The comparison is not exact because the curve of the model is obtained by difference of the time history vertical displacements of points 2 and 3 (Fig. 2) while the experimental curve LVDT3 is between position 2 and a point in the inner core in a lower position with respect to point 3. The maximum strength stage is caught quite well, and also the initial stiffness, but the two curves have different shapes: linear for the model, and similar to ductile behavior for the specimen.

In the specimens with offset the damage was observed both in external and internal leaves. In addition to vertical cracks at the connections, diagonal cracks developed in the core of the horizontal layer without offset (the second layer from top, where there is stress concentration). They propagated upward from the corners of the offsets and split the stones of the inner leaf.

The external leaves were damaged by some diagonal cracks at the base of the specimen.

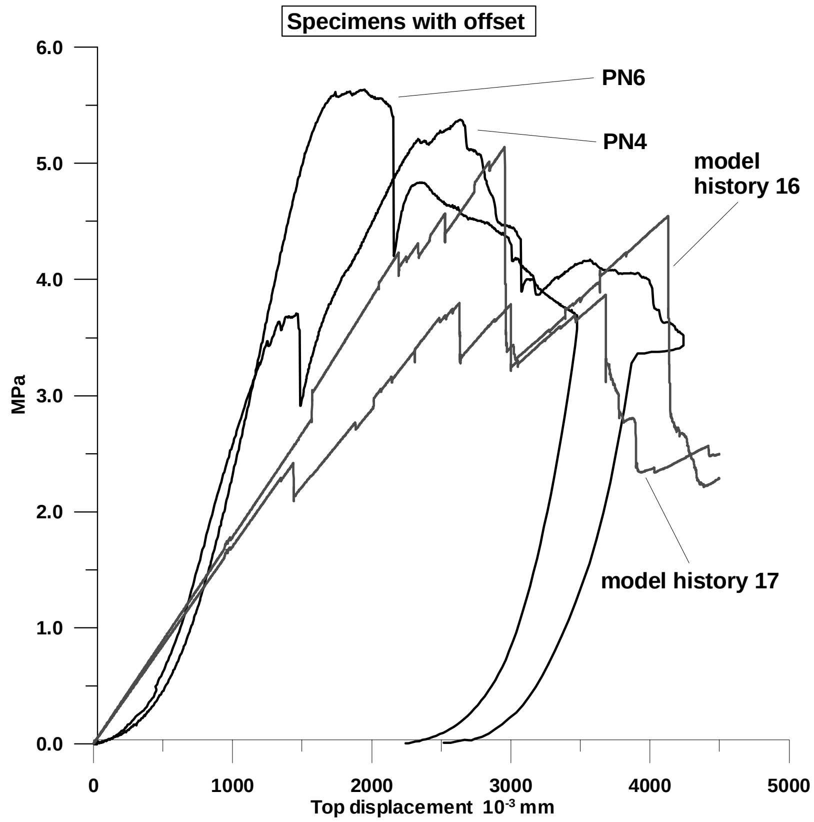



Figure 3 : Noto stone with offset – specimens PN4 and PN6
Experimental and numerical load - top displacement relations

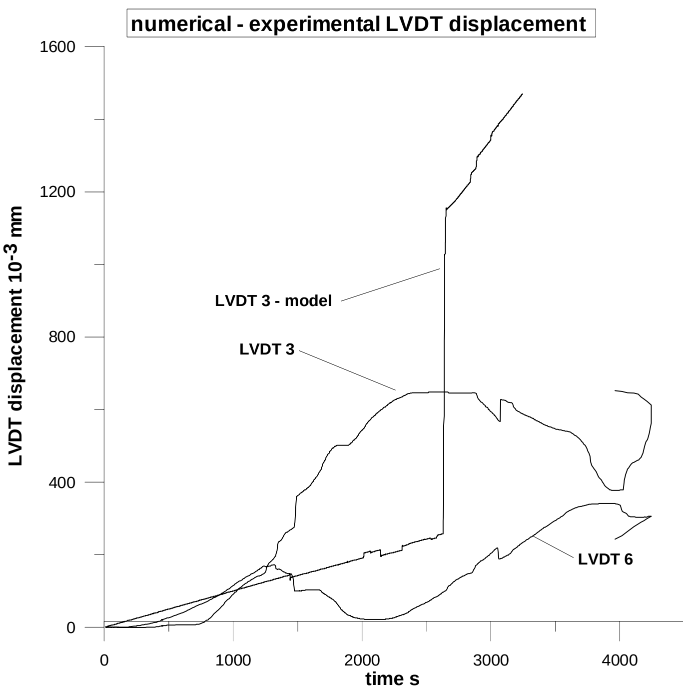
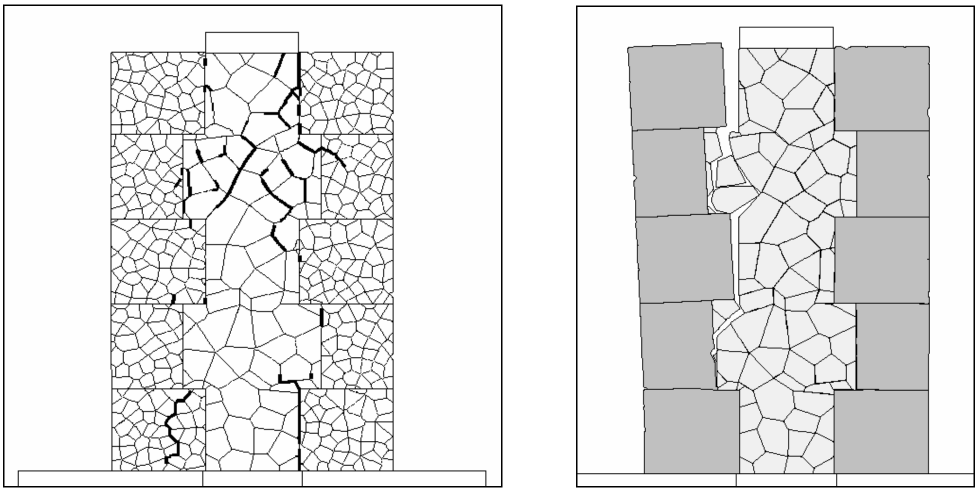



Figure 4 : Specimen PN4: experimental LVDT vertical displacement and numerical modeling

The numerical model performed simulates quite well the breaking and the damage of the stones, as it is shown in Fig. 5, where the fractures are represented with bold lines. The model corresponds to 3.5 mm top vertical displacement and normal stress about 4 MPa.

The way of the top load to the ground, from the internal core to the external leaves, is conditioned by the offsets, as expected, which capture the load especially in correspondence of the first enlargement of the core, as confirmed by the presence of several fractures.



Figures 5, 6 : Fracture modeling in blocks at 3.5 mm top displacement and collapse modeling of the specimen, at large displacements.

The loss of carrying capacity of the specimens takes place mainly for the lateral dilation of the inner material, causing the separation of the external leaves from the core, ant their opening outwards (Fig. 6). The sliding of the inner core with respect to the external leaves is efficaciously prevented by the indentation. This fact was observed in the laboratory experimental test clearly; it appears well represented also in the numerical modeling, which can be continued further on, showing the permanence of a lower, but significant carrying capacity at larger top displacements (Fig. 6). The real test was stopped at an earlier stage, at the decrease of carrying capacity, but at a displacement at least two time larger than that at the maximum strength.

### *4.2 Noto stone specimens without offset*

The modeling of specimens without offset shows a different behavior. The collapse condition of the laboratory test are not clearly identified by the displacement time histories of the numerical model, which show the straight joints between the leaves beginning both to slide at the top, and the fractures propagating downward until the whole core slides. The model global shear strength of the two vertical straight joints is almost the same, as the contact length is similar and the mechanical characteristics are the same. Therefore the numerical global collapse involves the two connections, even if the stiffness of the two joints have a certain difference, as can be argued from Fig. 8, where the point vertical displacements at the two sides of the inner layer are reported.

The laboratory experimental tests give a different behavior: there is the early failure of one vertical connection, with the joint fracture propagating downward from the top, while the second joint maintains a good residual resistance (Fig. 8). The cracks in the connections propagate quickly, and the collapse is brittle. The global behavior is similar to that of two brittle parallel elements, with different strength. This suggests a significant spreading of the values of the shear strength between the leaves and also along the joints, which can trigger the collapse. The different values are probably due to the characteristics of the bond stone-mortar (local differences in stone porosity and adhesion between the two materials).

The models carried out (Fig. 8) have a similar global stiffness, and show the same brittle behavior of the experimental tests, but do not catch the separate collapse of the connections.

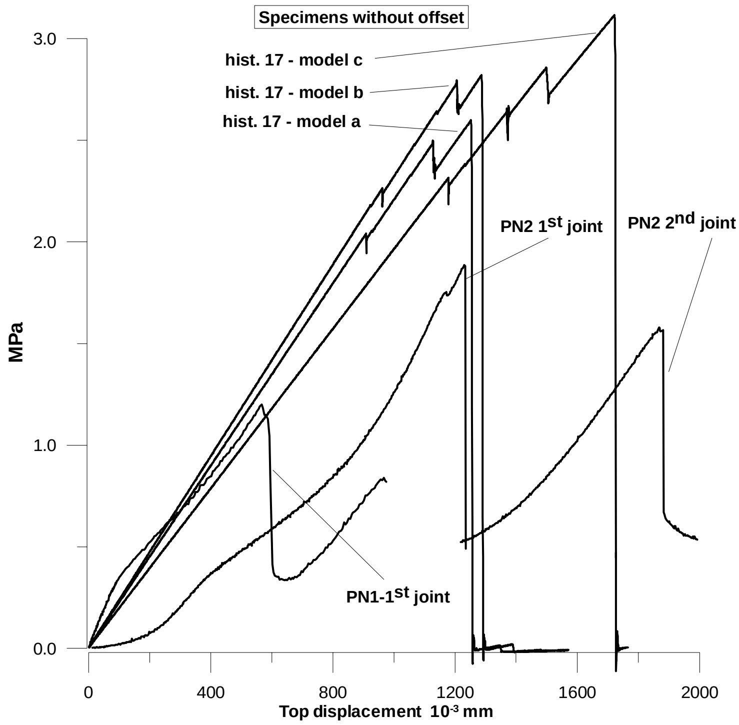



Figure 7 : Noto stone without offsets: specimens PN1 and PN2
Experimental and numerical load - top displacement relations

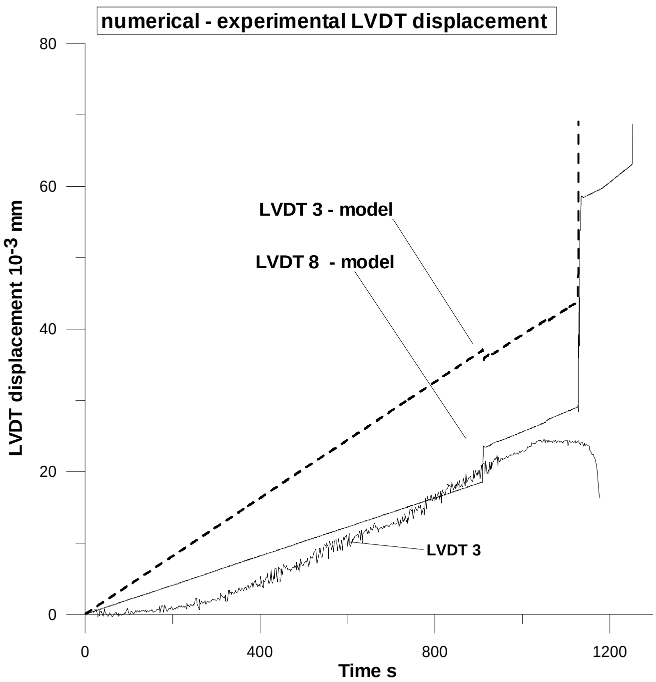



Figure 8 : Specimen PN2: experimental LVDT vertical displacement and numerical modeling at the failure of the first connection

However it is possible to perform a subsequent model with the proper joint mechanical characteristics which simulates this behavior, but the aim of the investigation is to assess how far a Distinct Element model of a three-leaves structural element (e.g. from an existing historical building) is suitable to define its ultimate bearing capacity and to evaluate a safety factor.

The modeling of the vertical point displacements is more similar to the experimental behavior (Fig. 7) than that of the specimens with offset. No fracture develops in the core and in the external leaves.

## 5 CONCLUSIONS

Some concluding remarks are possible on the contribution given by a distinct element modeling to the understanding of the mechanical behavior of three-leaf walls.

It should be pointed out that the laboratory tests and their numerical modeling, are aimed to better understand the joint behavior, therefore they do not simulate the loading and collapse of real structure, whose failure is influenced also by the type of loading.

Nevertheless, the models performed fits quite well the test physical behavior, so it is possible to obtain from numerical modeling additional indications on stress distribution, deformations, and on the collapse. Distinct element codes result suitable in modeling the behavior of three-leaf masonry, especially for the structural elements with offset. Some caution is necessary, particularly in what regards the collapse condition, for the elements without offset, or with a small indentation. In order to obtain a reliable better knowledge of the three-leaf walls, with different load conditions (e.g. horizontal loads or dynamic loads) a deeper analysis is required, modeling also a variable distribution of offset dimensions that is closer to real structures.

Finally it can be said that the results obtained are particularly interesting for the safety of historic buildings in seismic areas. Even if further research is needed to statistically control the reliability of the results, it is relevant that a reference description of the response at the interface of the leaves in three-leaf walls, depending on their nature and geometry has been stated.

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