EXPERIMENTAL AND NUMERICAL INVESTIGATION OF PRESTRESSED MASONRY STRUCTURES UNDER EARTHQUAKE LOADING – INFLUENCES ON SIMULATION RESULTS

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SUMMARY

It is investigated how vulnerability of masonry structures can be reduced in case of earthquake action. Internal vertical prestressing is considered as a strengthening measure, which can also be industrially produced efficiently. The shear capacity and the ductility is improved. This is shown in static cyclic tests by Budelmann et al. (2004). This paper is focused on suitable simulation techniques and material models for an investigation of the dynamic in-plane behaviour, their efficiency and impacts on the simulation results, like different means to model prestressing. The importance of modelling the tendons especially for nonlinear dynamic analyses is shown.

INTRODUCTION

The resistance of masonry structures against earthquake action is limited by their low shear strength and shear capacity. In addition, changes of design codes lead to higher costs of masonry structures. A strengthening method, providing for smaller cross sections and efficient industrial production of masonry is presented. Vertical prestressing is considered in order to improve the shear strength and the ductility of masonry. The goal is to suggest possibilities, which are based on numerical methods, to investigate the dynamic behaviour of prestressed masonry structures.

STATIC CYCLIC EXPERIMENTAL TEST OF PRESTRESSED SHEAR WALLS

The experimental tests of prestressed shear walls briefly summarised below are described in detail in Budelmann et al. (2004). Four walls were tested, with dimensions and extra loads like

walls used for stiffening of buildings with three floors. In these static cyclic tests only the ground floors were considered as they are most critical under seismic action. For all walls, two tendons (strands) have been used for vertical prestressing. The complete experimental set-up is depicted in Figure 1 on the left for wall 1. Furthermore, another position of the tendons closer to the middle was investigated in wall 2. The influence of slenderness is taken into account by means of wall 3 and wall 4. With wall 4, the floor slab is supported only on one end. The wall properties are listed in Table 1. A horizontal static cyclic displacement was applied in the centre of the concrete slab. The crack patterns are shown in Figure 2. The diagonal crosses are very typical of earthquake damage. The load displacement curves are displayed in Figure 3. Wall 2 had the most useful behaviour. The shear capacity and the ductility are very high. The area enclosed by the hysteresis shows the energy dissipation, which is very good for wall 2 and wall 3. Measured values like the displacement u and the horizontal load H are summarised in Table 1 for all walls. The index u means the ultimate point of loading, whereas cr indicates the occurrence of cracks. $2xP_0$ is the sum of prestressing forces of two tendons. The dead load of the wall and upper stories is expressed by G+F. In the last column, the forces in the tendons after reaching the ultimate loading point $(2xP_0)_u$ are given. A significant decrease was observed. Moreover, the different types of failure are listed.

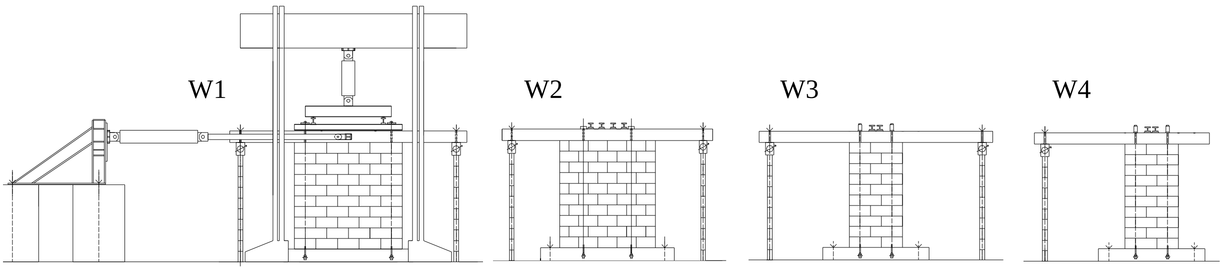

Figure 1. Complete Experimental Set-Up for Wall 1, Wall 2, Wall 3 and Wall 4

Figure 2. Crack Pattern of Wall 1, Wall 2, Wall 3 and Wall 4

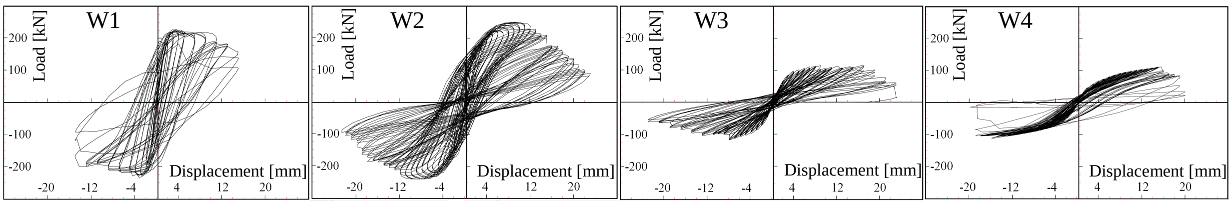

Figure 3. Horizontal Load Displacement Diagrams (Hysteresis) for Wall 1-4

Table 1. Wall Properties and Results of Experimental Tests

<table>
<tr><th rowspan="3"></th><th colspan="6">Properties of Wall</th><th colspan="9">Measurement Categories</th></tr>
<tr><th>Length</th><th>Height</th><th>Thick-ness</th><th>Distance of Ten-don to Edge</th><th>Distance of Tendons</th><th>Support</th><th>2 x P_0</th><th>G+F</th><th>H_{cr}</th><th>u_{cr}</th><th>H_u</th><th>u_u</th><th>Type of Failure</th><th>$(G+F)_u$</th><th>$(2xP_0)_u$</th></tr>
<tr><th>[m]</th><th>[m]</th><th>[m]</th><th>[m]</th><th>[m]</th><th></th><th>[kN]</th><th>[kN]</th><th>[kN]</th><th>[mm]</th><th>[kN]</th><th>[mm]</th><th></th><th>[kN]</th><th>[kN]</th></tr>
<tr><td>W1</td><td>2.5</td><td rowspan="4">2.50</td><td rowspan="4">0.175</td><td>0.25</td><td>2.00</td><td rowspan="3">on 2 sides</td><td>360</td><td>245</td><td>+217
-227</td><td>3</td><td>+109
-105</td><td>17</td><td>v_{max}</td><td>245</td><td>260</td></tr>
<tr><td>W2</td><td>2.5</td><td>0.625</td><td>1.25</td><td>356</td><td>245</td><td>+223
-220</td><td>6</td><td>+89
-94</td><td>23</td><td>Stone</td><td>245</td><td>128</td></tr>
<tr><td>W3</td><td>1.25</td><td>0.25</td><td>0.75</td><td>352</td><td>110</td><td>+110
-114</td><td>7</td><td>+60
-60</td><td>23</td><td>v_{max}</td><td>110</td><td>260</td></tr>
<tr><td>W4</td><td>1.25</td><td>0.25</td><td>0.75</td><td>on 1 side</td><td>274</td><td>110</td><td>+101
-100</td><td>11</td><td>+34
-16</td><td>20</td><td>Stone</td><td>110</td><td>140</td></tr>
</table>

Stone - partial collapse of the wall, v_{max} - max. displacement of the testing equipment

NUMERICAL SIMULATIONS

Simulation Techniques and Material Models

In the following, it is briefly discussed which simulation techniques and material models are suitable to investigate the dynamic behaviour of prestressed masonry. In case of cyclic and dynamic loading, a degradation of stiffness and strength occur. The dynamic behaviour depends on the stiffness. Thus it is important to consider this phenomenon.

Usually, micro modelling is applied to investigate masonry in detail and accurately. The material model by Oliveira (2003) includes degradation for this modelling strategy. It is based on the plasticity theory, as described in Lourenço (1996) and Rots (1997). But due to the high calculation effort, the material model is very time consuming in the case of dynamic simulations of big structures. More suitable for such simulations is the material model of Gambarotta and Lagomarsino (1997), which is based on fracture mechanics.

To validate the results of dynamic simulations of prestressed walls, the results of both material models can be used. If a comparison shows only small differences, the behaviour is predicted correctly with very high probability. The models are verified in static experimental tests. A comparison of simulation and experimental results is given. Static shear wall tests by Verfmeltfoort and Raijmakers (1993) are used to verify the results of micro and macro modelling. In Figure 4 the deformations of the results are compared.

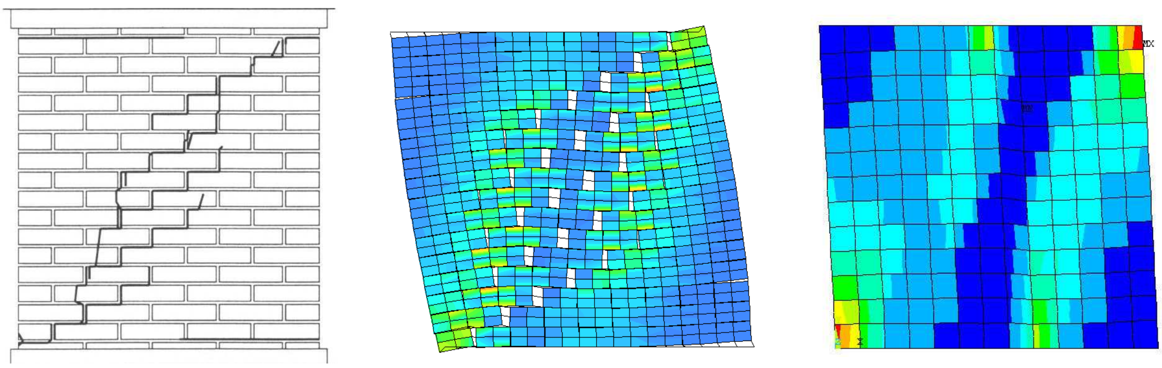

Figure 4. Deformation, Left: Experimental Tests by Verfmeltfoort and Raijmakers (1993), Middle: Micro Model, Right: Macro Model

Figure 5 depicts the horizontal load displacement diagram of the three experimental tests in comparison with the numerical results of micro and macro models. The behaviour can be well predicted with both modelling strategies used.

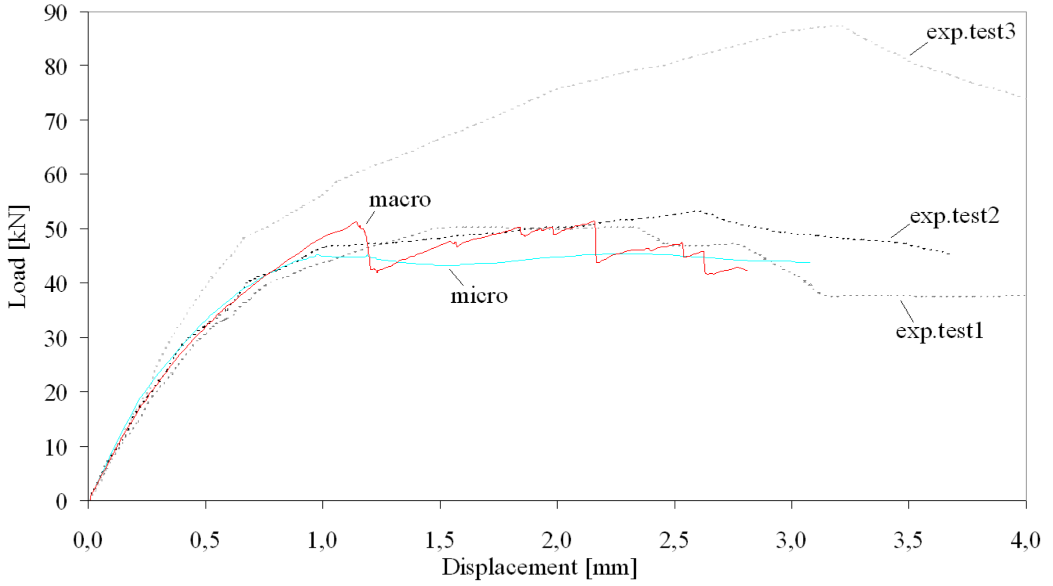

Figure 5. Horizontal Load Displacement Diagram of Experimental Tests and Simulations

Impacts on Numerical Results Investigated Through Case Studies

It is important to know which parameters have a significant influence on the numerical results. The findings of a literature review and of simulations made for this contribution, by means of the material model of Gambarotta and Lagomarsino, are discussed as follows.

The boundary conditions influence the behaviour and the failure mechanisms strongly. This is explained in more detail in Ötes and Löring (2006). Two worst cases are given. For case BC 1, the top of the wall is constrained, because of that it stays horizontal. Mainly shear loading occurs. For case BC 2, the top of the wall is free and can rotate. Thus, the wall behaves like a cantilever, and bending loading occurs. Below it is designated as BC 2. Figure 6 shows walls with these boundary conditions and shapes.

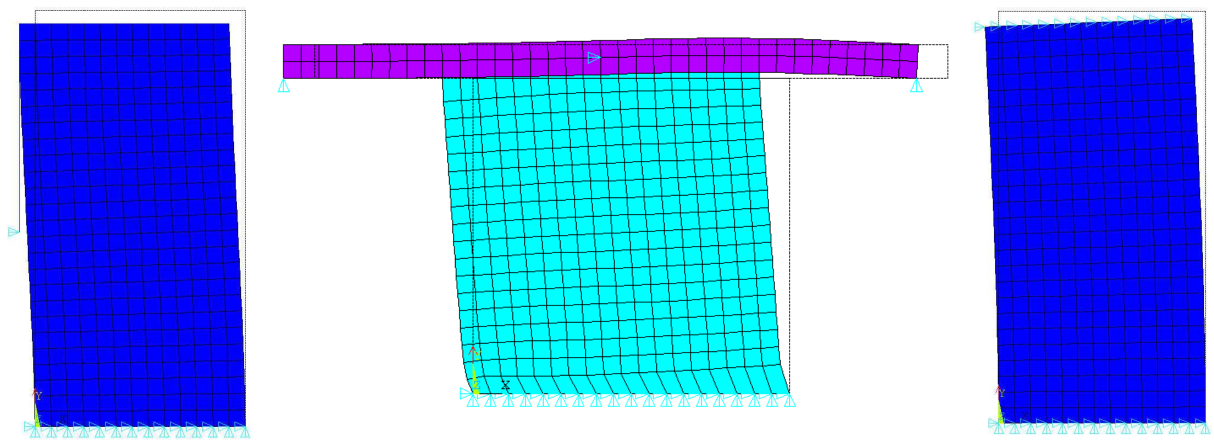

Figure 6. Left: BC 1 “Constrained”, Middle: Real Boundary Conditions, Right: BC 2 “Free”

In reality, the support of the wall is between these worst cases, depending on the behaviour of the floor slabs. Beams should thus also be modelled as depicted in Figure 6, to predict the behaviour realistically. Below, the impacts are explained in more detail.

To gain a deeper insight, a case study was performed in which the following parameters were varied to investigate their impacts. Four variations of slenderness S (0.5, 1, 2, 3) are made. For the different slenderness values, different heights of 1.25 m, 2.5 m, 5 m and 7.5 m are obtained. The boundary conditions on the top of the wall BC 1 ("constrained"), modelled by means of a ridge L-framework, and BC 2 ("free") are used. Moreover, four BC 2 walls with tendons close to the middle are investigated. Two means to model prestressing are applied (external forces and tendons). This case study is illustrated in Figure 7. Its outcome are the impacts on: the change of prestressing forces in the tendons, the restoring forces, the rotation of the top, the shear capacity, the ductility as well as the suitability of the location of tendons.

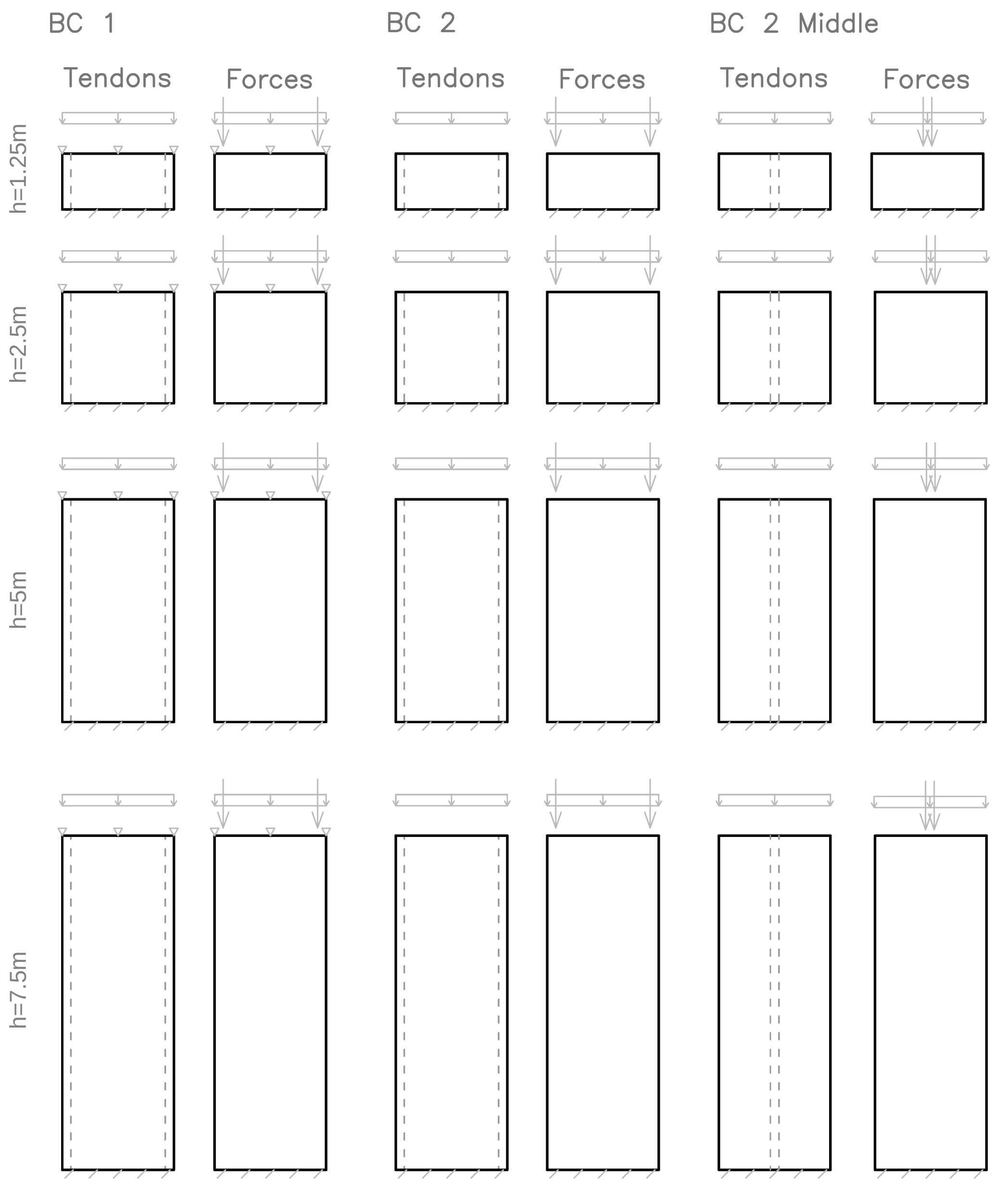

Figure 7. Investigated Walls in Dependency of the Slenderness, Boundary Conditions, Mean to Model the Prestressing and Position of Tendons

The subsequent values are fixed for all variations of the models: the width of the walls is 2.5 m, the thickness 0.175 m, the prestressing force per each tendon is 189 kN, the vertical load of upper stories is 197.3 kN. Furthermore, the material parameters are the same for all models and are listed in Table 2.

Table 2. Material Parameters Used for the Case Study

Symbol	Variable	Value	Symbol	Variable	Value
μ	Friction coefficient	0.8	η	Poissons ratio	0.1
σ_{mr}	Tensile strength	0.15 N/mm²	ρ	Density	2000 kg/m³
	of mortar joints		E	Young's modulus	2000 N/mm²
τ_{mr}	Shear strength of	0.20 N/mm²	β_m	Softening mortar	0.6
	mortar joints		β_h	Softening brick	0.4
σ_{hr}	Compressive	3.5 N/mm²	cmt	Inelastic deformation	1.0
	strength of masonry			parameter for mortar	
τ_{hr}	Shear strength	1.5 N/mm²	cbt	Inelastic deformation	1.0
	of masonry			parameter for brick	

In the following, some important results of this case study are briefly summarised. In general, the means to simulate prestressing is important for BC 2, especially when the tendons are close to the edges. For BC 1 this phenomenon can often be neglected. Restoring forces occur and can be simulated when prestressing is modelled by means of tendons. The restoring forces have to be divided into horizontal and vertical components. The latter is important only for BC 2. Here, the vertical movement of the corners during the top rotation leads to changes of length of the tendons. The result is a variation of the prestressing forces in the tendons, which decrease in the tendons on the lower corner and increase in the tendons on the upper corner. In case of low walls, the top rotation leads to significant differences in the prestressing forces. It reduces as wall height increases, as depicted in Figure 8.

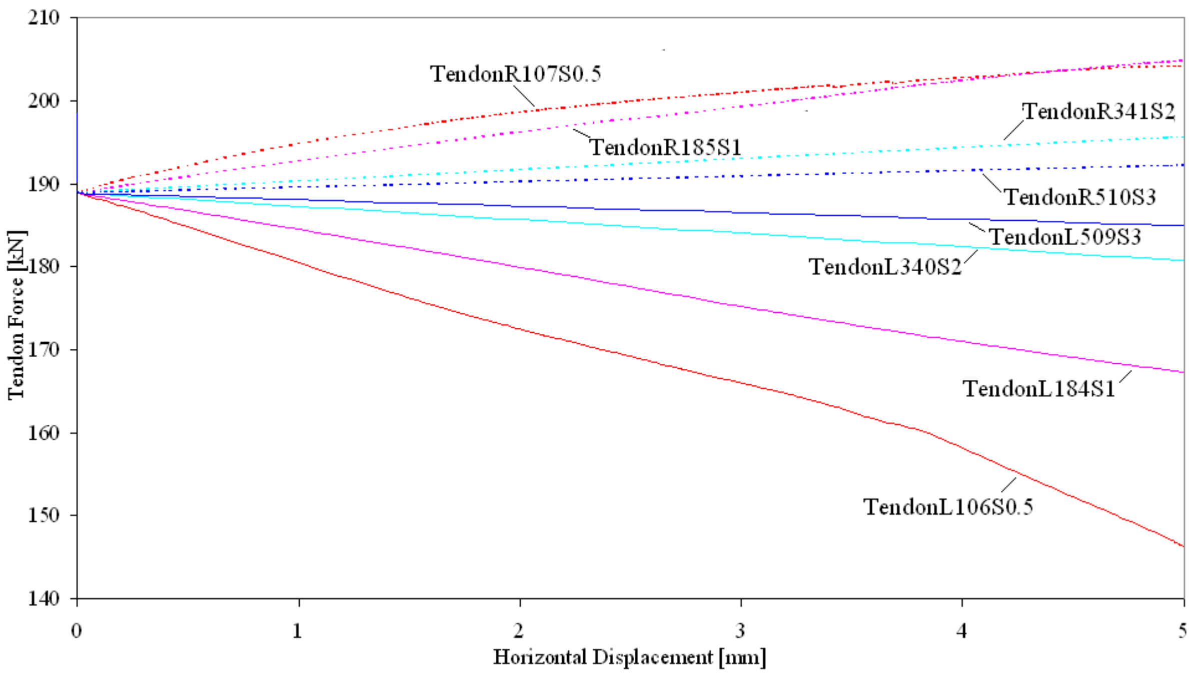

Figure 8. Forces in Tendons in Dependency on the Horizontal Top Displacement of Walls for BC 2 and Tendons Close to the Edges

For models with tendons close to the edges, the rotation of the top edge is smaller, but the tendons have to be modelled. If only external forces are used to model prestressing, no significant difference can be observed. Of course, the shear capacity and the ductility depend decisively on the slenderness and boundary conditions, as already known. To get information about the shear capacities and ductilities, it is necessary to apply a horizontal loading higher than 5 mm. Figure 9 depicts higher stiffness and higher shear capacities for walls with BC 1 than for BC 2, but smaller ductilities especially for slender walls. A new result is that in case of BC 2 the shear capacity is higher, if the tendons are also modelled (Figure 10), but the ductility is slightly smaller. This means of modelling leads to smaller horizontal displacement. Figure 10 shows also higher stiffness for walls modelled with tendons. But if the tendons are placed close to the middle, no significant difference can be observed, as shown in Figure 11. The post-peak behaviour of models with tendons near the edges is more useful. Higher forces can be applied. Obviously, the tendons carry tensile loads when tensile failure has already occurred in the wall. If the tendons are close to the middle, only a small improvement regarding the post-peak behaviour can be observed. This shows a comparison of Figure 10 and Figure 11.

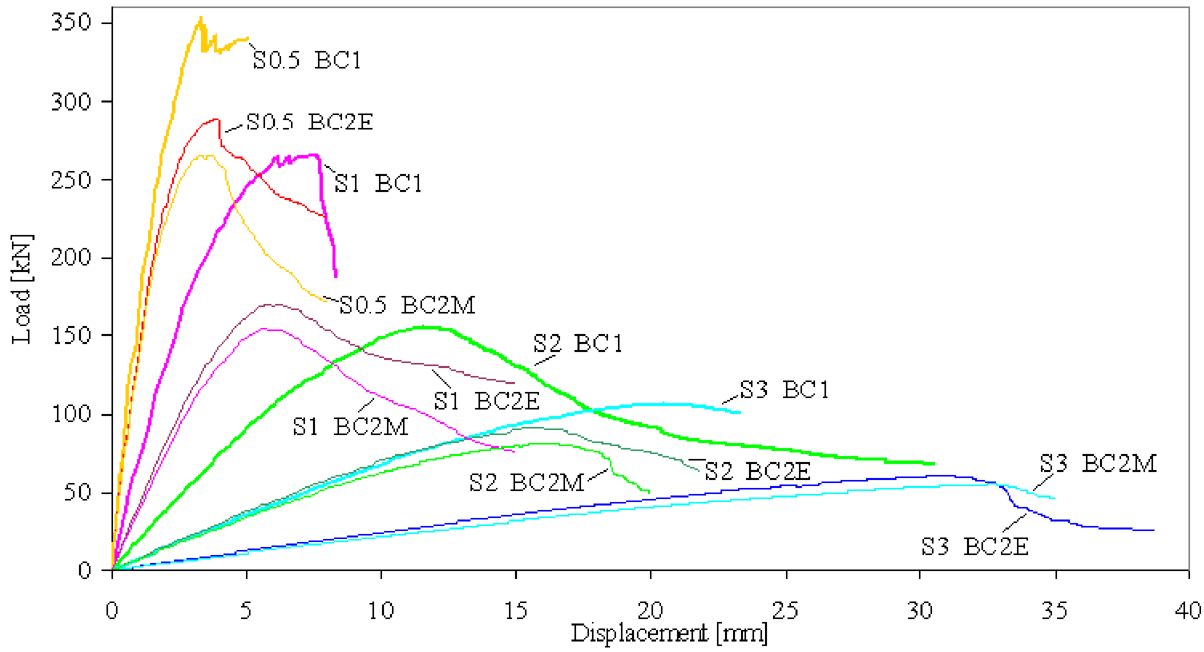

Figure 9. Horizontal Load Displacement Diagram for Models with Tendons for BC 1 and for BC 2 for Different Tendon Positions (Edges and Middle)

The findings of this case study regarding the impact of slenderness cannot be generalised, because the width of the walls is constant as well as the horizontal top displacement. For many comparisons, the angle would have to be the same rather than the horizontal displacement. Moreover, the height of the walls has an important influence, because it is equal to the basic length of the tendons. Small changes of length lead to large differences of the forces inside of short tendons. For long tendons, much higher differences in length are necessary to reach significant changes of such inner forces. It has been shown that there are many reasons for modelling the tendons, for instance the forces in the tendons already change during a static horizontal loading. This impact is significant for BC 2 and compact walls. The shear capacity depends significantly on the vertical loads. Moreover, the forces in the tendon decrease during static cyclic and seismic loading. This was observed in experimental tests by Budelmann et al. (2004), and was probably caused by the reduction in height of bed joints due to slipping in the joints.

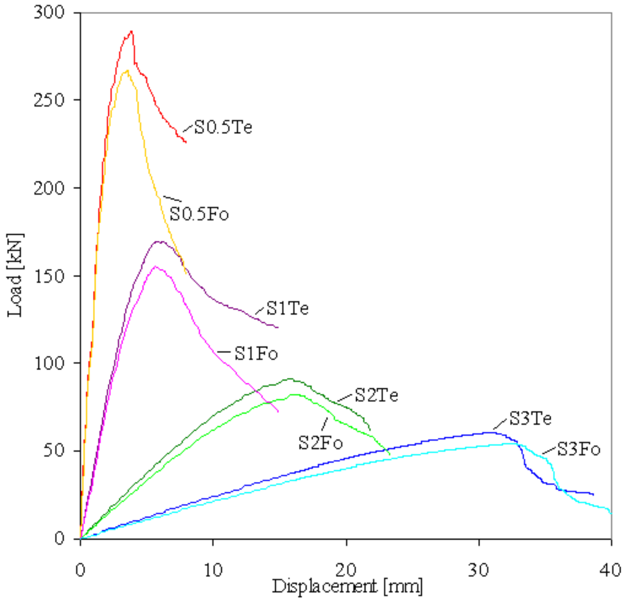

Figure 10. Load Displacement Diagram for BC 2 and Tendons Close to the Edges

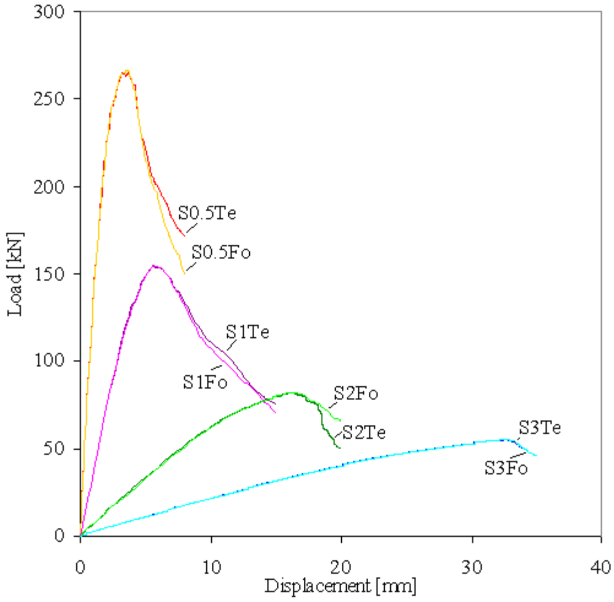

Figure 11. Load Displacement Diagram for BC 2 and Tendons Close to the Middle

Horizontal and vertical restoring forces lead to smaller horizontal displacement and smaller rotations as well as to an increased stiffness. These affect the dynamic behaviour, shown in Figure 12, which is the outcome of nonlinear dynamic simulations. The wall model is identical with the above mentioned slender model (S = 3, BC 2 and prestressing close to the edges).

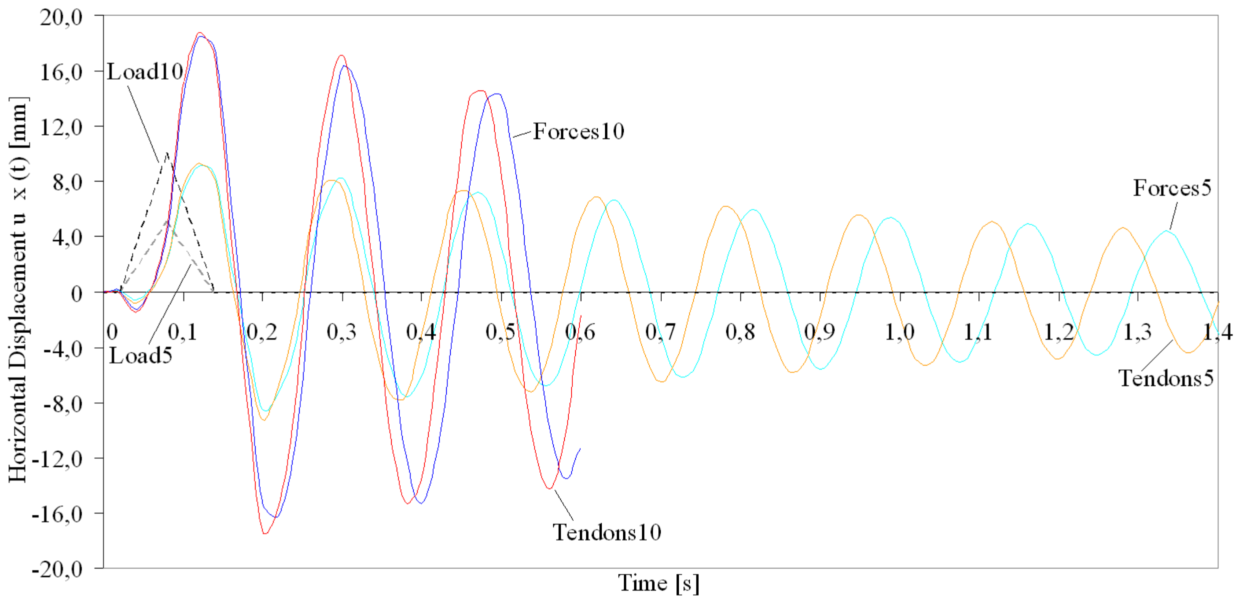

Figure 12. Time-Dependent Horizontal Drift for Modelling of Prestressing by Means of External Forces or Tendons in Case of BC 2

Tow load levels of 5 mm and 10 mm ground displacement are applied as an impulse (duration of 0.12 s) as depicted in Figure 12 with dashed lines. The vibration behaviour of prestressed walls modelled with external forces and tendons is compared (see Figure 12). There are only slight differences regarding maximal drift. But the periods vary significantly. The walls modelled with tendons vibrate faster. The reason is the higher stiffness of these walls, shown in

the above presented simulations (see Figure 10). The pre-peak behaviour and, even more so, the post-peak behaviour varies, depending on whether prestressing is modelled due to external forces or tendons. This is confirmed by experimental observations by Ötes et al. (2002. They pointed out that in the range of high loading after the occurrence of gaping joints the stiffness of the wall is mainly affected due to the spring properties of tendons.

Impacts on Numerical Results Investigated Through Sensitivity Analyses

To get information about the impact of input parameters, sensitivity analyses are useful. By means of this tool, dynamic loading and nonlinear material behaviour of conventional masonry walls are investigated in the framework of the internal research cooperation of the International Graduate College 802. The material model of Gambarotta and Lagomarsino (1997) is used. It also offers the output parameters 'brick damage' and 'mortar damage'. The walls are supported as described above for BC 2. The loading, in this case earthquake excitation, and the material input parameters varies in the range of probability density functions. A detailed description is given in Urban et al. (2006) and Urban (2007). The impact of input parameters is evaluated by means of probabilistic simulations. The results regarding brick damage are shown in Figure 13. The most important parameters in the correct order are the horizontal acceleration (xskal), density (dens) and elastic modulus (emod) of the material. Most important means that they have the largest influence on the damage parameters. The higher these parameters, the higher the damage. The compressive strength of the bricks (compm) has an opposite effect, which is shown by the negative correlation coefficient. The higher the compressive strength of the bricks, the lower the brick damage.

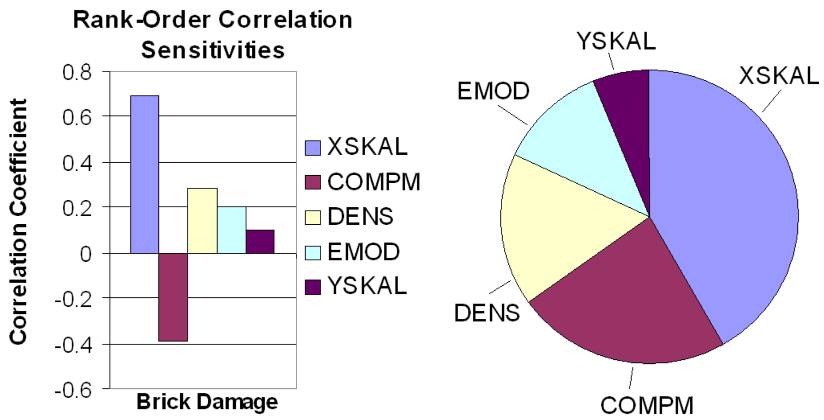

Figure 13. Sensitivities for Brick Damage

CONCLUSION

The static cyclic experimental tests on internal prestressed shear walls indicate the functionality of this method to strengthen masonry against earthquake loading. Deeper investigations especially regarding the dynamic behaviour of prestressed walls are recommended. This can be done by means of numerical simulations. Useful material models were discussed and used for first numerical investigations. Many reasons to model the tendons were pointed out, e.g. the restoring force and the impact on the dynamic behaviour. Sensitivity analyses indicate the importance of the horizontal acceleration and the compressive strength of masonry walls regarding the damage. All these factors have to be considered carefully in further simulations.

ACKNOWLEDGEMENTS

We would like to thank Prof. Lagomarsino and Dr. Calderini from the University Genoa for their permission and support in including their material model into our research. Also we have to express deepest gratitude to Prof. Bartoli from University Florence and our alumnus colleague Dr. Urban from the International Graduate College 802 for their valuable knowledge, support and cooperation.

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