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INTRODUCTION TO POST-TENSIONED SHEAR WALLS OF CALCIUM SILICATE ELEMENT MASONRY

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ABSTRACT

In Western Europe, load-bearing masonry structures are frequently built with calcium silicate elements (CASIELs) combined with thin layer mortar. The height of CASIEL masonry shear walls is limited by the overturning moment. The recent development of high strength CASIELs opens new perspectives. By prestressing masonry, the moment and shear capacity of shear walls can be increased, providing overall stability of higher buildings. Unfortunately, application of this construction method in building practice is limited due to lack of design rules for prestressed masonry in European standards, e. g. Eurocode 6 [1]. Additionally, experimental data on prestress losses due to creep and shrinkage of high strength CASIEL masonry are not yet available. At Eindhoven University of Technology, a project has been set up to systematically investigate the moment and shear capacity of post-tensioned shear walls of CASIEL masonry by means of experimental, numerical and analytical research. Final goals of the project are the development of design rules for post-tensioned (CASIEL) masonry and guidelines for simple and effective post-tensioning systems which ensure overall stability of buildings during construction and working life.

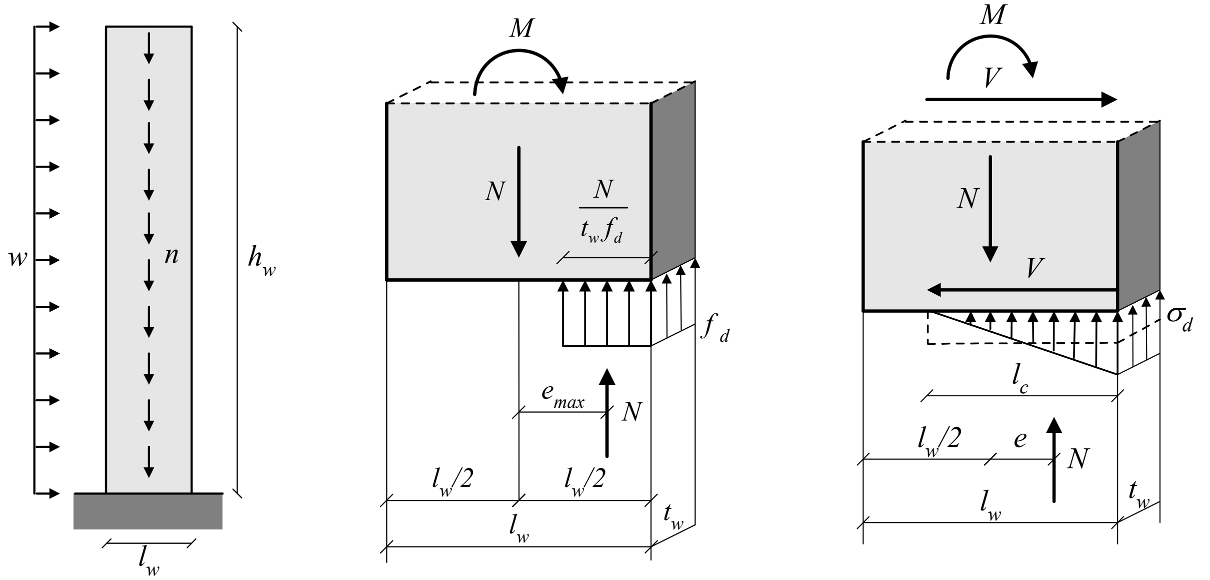
KEYWORDS: CASIEL masonry, shear walls, post-tensioning, prestressing, prestress loss

INTRODUCTION

This paper is an introduction to a research project, which has recently started at Eindhoven University of Technology, focused on vertically post-tensioned shear walls made of calcium silicate elements (CASIELs) with thin layer mortar. First, an explanation of the theoretical moment and shear capacity of a masonry shear wall is given, followed by an example which compares unreinforced masonry and post-tensioned masonry. Subsequently, CASIEL masonry and some material properties are described. Then, the problem statement and the international state-of-the-art are summarized and the resulting research program is presented. Finally, the first part of the research program, namely creep and relaxation tests on CASIEL masonry, is described in more detail.

MOMENT AND SHEAR CAPACITY OF MASONRY SHEAR WALLS

Shear walls in unreinforced masonry (URM) are limited in height by the overturning moment, which is caused by wind or other horizontal loading on the building. Tensile strength of masonry is generally neglected, so that the moment capacity is only dependent on the design compressive strength of the masonry f_d, the dimensions of the shear wall and the axial force due to the weight that is carried by the shear wall. In Figure 1a, a rectangular shear wall is depicted with horizontal and vertical loads. In Figure 1b, the equilibrium at the base of the shear wall is shown at ultimate limit state, based on a rectangular σ-ε diagram according to Eurocode 6 [1].



a) Shear wall. b) Derivation of moment capacity c) Derivation of shear capacity

Figure 1: Equilibrium of a shear wall

For wind loading, the relation between moment M and axial force N for uniformly distributed wind load w and axial load n can be derived from Figure 1a, since both are a function of the wall height h_w.

$$N = nh_w \;\rightarrow\; h_w = \frac{N}{n} \tag{1}$$

$$M = \frac{wh_w^{\,2}}{2} \;\rightarrow\; M = \frac{wN^2}{2n^2} \tag{2}$$

In moment-axial force interaction diagrams, moment and axial force are normalized according to

$$\mu = \frac{M}{f_d t_w l_w^{\,2}} \text{ and } \nu = \frac{N}{f_d t_w l_w} \tag{3}$$

in which f_d is the masonry compressive strength and l_w and t_w the length and thickness of the shear wall. Substituting in (2) leads to

$$\mu = \frac{wf_d t_w}{2n^2}\nu^2 \tag{4}$$

The number of stories n_{st} is related to μ by

$$M = \frac{wh_w^{\,2}}{2} = \frac{wh_{st}^{\,2} n_{st}^{\,2}}{2} \;\rightarrow\; n_{st} = \sqrt{\frac{2M}{wh_{st}^{\,2}}} = \sqrt{\frac{2\mu f_d t_w l_w^{\,2}}{wh_{st}^{\,2}}} \tag{5}$$

The moment capacity is derived from Figure 1b. Moment equilibrium leads to

$$M = Ne_{\max} = \frac{N}{2}\left(l_w - \frac{N}{t_w f_d}\right) \tag{6}$$

Using the definitions of (3), the μ-v relationship is given by

$$\mu = \frac{1}{2}\left(\nu - \nu^2\right) \tag{7}$$

The maximum moment capacity is determined from the intersection of (4) and (7). The maximum number of stories is determined by substituting the maximum moment capacity in (5).

The shear capacity V is dependent on the axial load N. An increase in axial load causes an increase in shear capacity according to the Mohr-Coulomb criterion for calcium silicate masonry

$$f_{vk} = f_{vk0} + 0.4\sigma_d \le 0.065 f_b \tag{8}$$

in which f_{vk0} is the initial shear strength without axial load and f_b is the compressive strength of the units. The upper limit of (8) was introduced in Eurocode 6 [1] to limit the shear capacity in case of high axial loads. The average compressive stress σ_d is calculated from

$$\sigma_d = \frac{N}{t_w l_c} \tag{9}$$

and the length of the compressed part of the section l_c should be determined by assuming a linear-elastic (triangular) σ-ε diagram according to Eurocode 6 [1], as shown in Figure 1c.

$$l_c = \frac{3}{2}\left(l_w - 2\frac{M}{N}\right) \le l_w \tag{10}$$

The shear capacity is

$$V = \frac{f_{vk} t_w l_c}{\gamma_M} \tag{11}$$

in which γ_M is a material factor, equal to 1.8 for CASIEL masonry.
The design shear load V_d at the base of the shear wall is

$$V_d = wh_w \tag{12}$$

The number of stories n_{st} is related to V_d by

$$n_{st} = \frac{V_d}{wh_{st}} \tag{13}$$

The maximum shear capacity is determined from the intersection of (11) and (12). The maximum number of stories is determined by substituting the maximum shear capacity in (13).

Both moment and shear capacity can be increased by post-tensioning. This is shown in the next section by means of an example. The prestressing force is treated as a constant axial load, independent of the deformation of the shear wall. In fact, the prestressing force increases due to large deformations after cracking. However, it is conservative to ignore this increase.

EXAMPLE

Consider the central shear wall **2** in Figure 2 with wind load *w* and axial load *n*. The total wind load is distributed over three shear walls (marked **1** - **3**). Each shear wall is assumed to receive an equal share of wind loading. The floors span parallel to the length of the shear wall. There is also an opening in the floor for vertical transport. As a result, the axial load on the shear wall is relatively low. The geometrical and physical properties of and loads on the shear wall are given in Table 1.

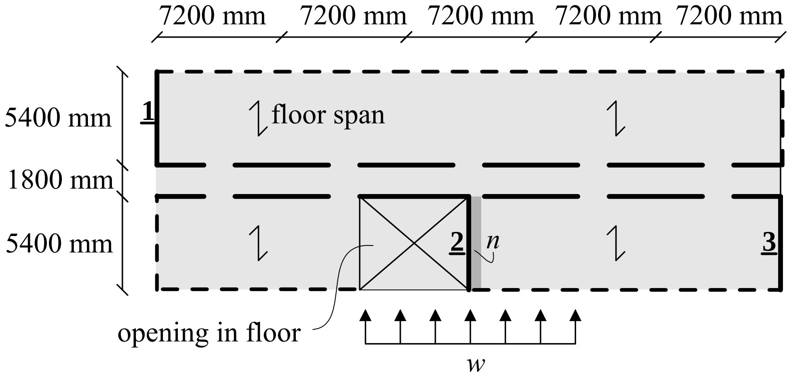


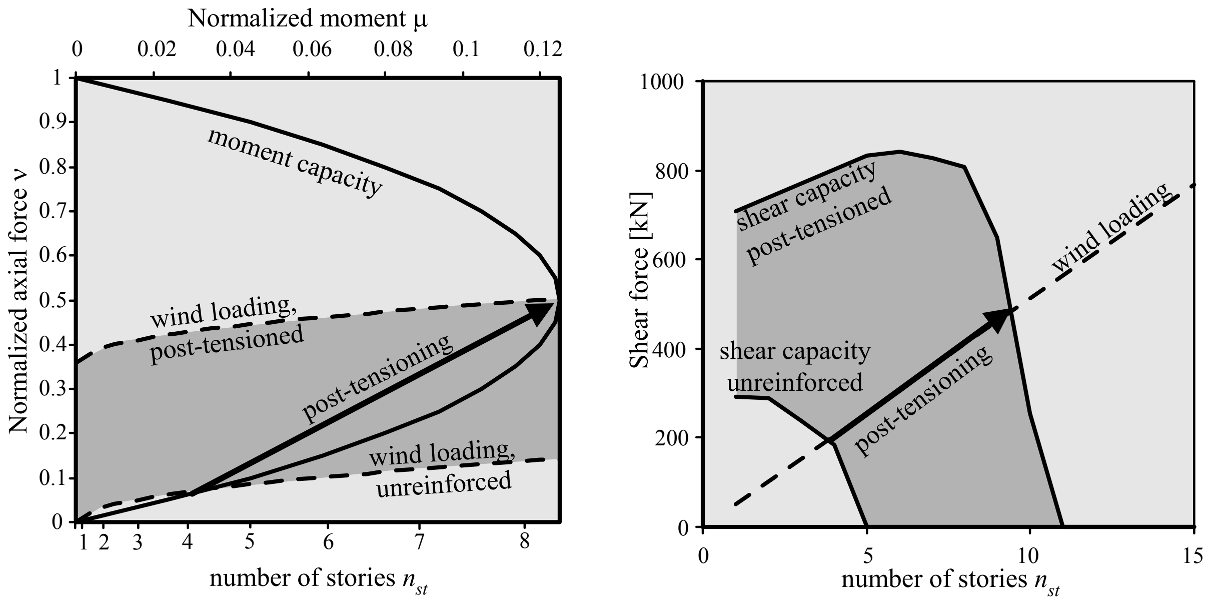
Figure 2: Example: floor plan of an office building [2]

Table 1: Properties of example shear wall

Shear wall length l_w	5500 mm	Distributed axial load n	44.0 kN/m
Shear wall thickness t_w	214 mm	Distributed wind load w	16.0 kN/m
Story height h_{st}	3200 mm	Masonry compressive strength f_d	10.0 MPa
Wall height h_w	$n_{st} \cdot h_{st}$	Buckling factor β	0.7

In Figure 3, the increase of moment and shear capacity by post-tensioning is demonstrated for the example of Figure 2 and Table 1. Figure 3a is a graphical representation of equations (4) and (7). By post-tensioning, the normalized axial force is increased. The number of stories shown on the horizontal axis is determined from μ by (5). The maximum number of stories for the example is 4 for unreinforced masonry and 8 for post-tensioned masonry. In Figure 3b, the shear capacity as given in equation (11) and the shear load as given in equation (12) are shown. The number of stories shown on the horizontal axis is determined from V_d by (13). Due to post-tensioning, the maximum number of stories is increased from 4 to 9.

The example illustrates that post-tensioning is especially useful when the normalized axial force is low ($\nu < 0.2$). It is favourable to increase ν by post-tensioning up to a maximum of 0.5. For higher values of ν, the moment capacity μ decreases again. The maximum number of stories of a post-tensioned masonry shear wall, in general, is determined by the dimensions of the shear wall, the wind load and the masonry compressive strength. For Dutch design wind loads, the maximum number of stories of a post-tensioned shear wall is approximately twice the length of the shear wall in meters. This is just an indication, based on moment capacity.



a) Moment - axial force interaction

b) Shear force - axial force interaction

Figure 3: Example : Moment and shear capacity increase by post-tensioning

CASIEL MASONRY

In Western Europe, shear walls of low- to medium-rise buildings are often built in calcium silicate element masonry with thin-layer mortar. Calcium silicate elements (CASIELs) are larger than blocks, the largest element measuring 1000 x 300 x 600 mm^3 (see Figure 4), and have to be lifted by a small crane. More information about CASIEL masonry, its material properties and applications can be found in Ngandu [3] and Vermeltfoort [4]. The recent development of high-strength CASIELs (CS44, f_b = 44 MPa) opens opportunities for prestressing masonry, resulting in higher and more slender shear walls. Properties of CASIELs are shown in Table 2, in which f_b is the normalized mean compressive strength of a masonry unit, f_k is the characteristic compressive strength of masonry, f_d is the design compressive strength of masonry and E is the short term secant modulus of elasticity of masonry (definitions according to Eurocode 6 [1]).

Table 2: Properties of CASIELs and CASIEL masonry in MPa

Code	f_b	$f_k = 0.8 f_b^{0.85}$	$f_d = f_k / \gamma_M$	E
CS12	12	6.6	3.7	6,000
CS20	20	10.2	5.7	9,000
CS36	36	16.8	9.3	15,000
CS44	44	20.0	11.1	19,000

Figure 4: CASIELs on site

PROBLEM STATEMENT

Although the concept of prestressed masonry is simple, it is seldom applied in building practice in Europe. This research project aims to stimulate application of prestressed masonry in building practice by systematically investigating the behaviour of post-tensioned shear walls of CASIEL masonry. Although there are several applications of prestressed masonry worldwide, most of these do not concern shear walls. In contemporary architecture with large open spaces at ground floor, the number of shear walls is limited, resulting in larger overturning moments per shear wall. Since it is expected that unreinforced masonry is not able to cope with these higher demands, shear walls are usually built in reinforced concrete in order to realize adequate moment capacity. However, CASIEL masonry shear walls have several advantages. They require no formwork, no reinforcement apart from prestressing reinforcement, less labour and less setting time. For these reasons, load-bearing walls are often constructed in CASIEL masonry. It would be advantageous if shear walls could be built likewise. Yet before application in building practice becomes likely, several issues need attention:

- The amount of prestress losses of post-tensioned CASIEL masonry;
- The in-plane behaviour of post-tensioned CASIEL masonry;
- The introduction of the prestressing forces into the masonry;
- Suitable construction methods for post-tensioned CASIEL masonry;
- Design guidelines and standards for post-tensioned CASIEL masonry;
- Knowledge of and familiarity with prestressed masonry in building practice.

PRESTRESSED MASONRY - STATE-OF-THE-ART

Previous reviews of prestressed masonry, such as those by Ganz [5], Schultz [6], Lissel [7] and Phipps [8], focused mainly on out-of-plane loading, although some early publications on prestressed masonry shear walls are mentioned. For example, Page [9] investigated the racking behaviour of prestressed and reinforced hollow masonry walls. A reinforced, a vertically prestressed and a horizontally and vertically prestressed single story wall were compared. The vertically prestressed wall had an ultimate racking load of 152 % of the ultimate racking load of the reinforced wall. The horizontally and vertically prestressed wall failed prematurely due to local web splitting, but the ultimate racking load was estimated to be 286 % of that of the reinforced wall. More recent research efforts regarding prestressed masonry shear walls focus on seismic response analysis. Kurama [10] examined unbonded post-tensioned precast concrete walls. Laursen [11] investigated single- and multi-story post-tensioned concrete masonry walls. These investigations focus on displacement based design under cyclic loading. Static loading is only included as a preliminary approach. Moreover, it is not known if the behaviour of precast concrete and concrete masonry is similar to that of CASIEL masonry. Prestressed calcium silicate masonry is not thoroughly investigated and especially not CASIEL masonry. Budelmann [12] describes a pilot project in Braunschweig, Germany, where a 3-story building was built of prefabricated calcium silicate block panels, which were post-tensioned on site. It can be concluded that the research conducted on post-tensioned masonry shear walls is limited, especially with respect to CASIEL masonry.

Prestress loss of clay brick masonry was investigated by Devalapura [13], while prestress loss of concrete block masonry was examined by Harvey [14] among others. Prestress loss of calcium silicate masonry has rarely been investigated. Budelmann [12] includes some on site measurements on both general purpose and thin-layer mortar. These measurements revealed a prestress loss of 8-9 % for calcium silicate block masonry with thin-layer mortar with no significant change after 6 months, while the prestress loss of the normal layer masonry was still increasing after 20 months. Creep and shrinkage of calcium silicate masonry with thin-layer mortar was investigated by Raijmakers [15] for blocks and Van der Pluijm [16] for bricks and elements. However, since the research by Van der Pluijm, the composition of the material has changed. As a result hereof, compressive strength and Young's modulus of the material have increased (Table 2). It may be expected that also the long-term behaviour will be different, which justifies the need for experimental research to determine prestress losses of CASIEL masonry, in addition to short-term behaviour of prestressed CASIEL masonry shear walls.

RESEARCH PROGRAM

Based on the problem statement and the international state-of-the-art, the following goals are set for the research project:

- Modelling of the mechanical behaviour of post-tensioned CASIEL shear walls under quasi-static loading;
- Determination of prestress losses due to creep, relaxation and shrinkage of CASIEL masonry;
- Development of design rules and complementary guidelines for construction methods of post-tensioned CASIEL shear walls.

The determination of prestress losses is the first part of the research program.

CREEP AND RELAXATION TESTS

Prestress losses in prestressed masonry are due to:

- Creep/relaxation of the masonry;
- Shrinkage of the masonry;
- Relaxation of the prestressing reinforcement.

Other contributions to prestress losses are from elastic deformations and slip of anchorages, but these can generally be overcome by overstressing initially. In a prestressed masonry wall, two axial loads are present in the same axial direction, namely the axial load due to weight and the prestressing force. The self-weight has a constant value and causes creep, which is the time dependent deformation under constant stress. Opposed to creep, relaxation is a decrease of stress under constant strain. The prestressing force decreases with time due to creep, relaxation and shrinkage of the masonry and relaxation of the prestressing reinforcement. Relaxation of prestressing reinforcement has been the subject of much research in the past and is excluded from this experimental investigation. In the tests, this is achieved by ensuring a low stress-strength ratio of the prestressing steel (≤ 0.36), for which the relaxation is negligible. Creep and relaxation are coupled to shrinkage, but it is generally accepted that shrinkage is measured on unloaded control specimens. To investigate the relation between creep and relaxation, both are measured simultaneously on identical specimens in different test-setups.

Literature research on creep, relaxation and shrinkage [17] revealed that moisture transport between the specimen and the surrounding air is an important factor for the amount of shrinkage. Drying specimens exhibit more shrinkage and creep. In building practice, CASIELs are exposed to weather until the facade is finished. When the building is in use, the climate is controlled and the CASIEL wall is subjected to more or less constant temperature and relative humidity. Despite of this, creep, relaxation and shrinkage tests are usually conducted in a climate controlled environment (usually T = 20 °C and RH = 60 %). This can be questioned, since the largest part of the time dependent deformation occurs in the first few weeks, which is the part that occurs during construction of the building. Therefore, important parameters are those that affect the speed of drying:

- The initial moisture content of the specimens with respect to the relative humidity of the surrounding air;
- The size of the specimens;
- The volume to exposed surface ratio.

Most tests will be conducted in a climate controlled environment, for comparison with other investigations, but also because results are best interpretable when fluctuations due to temperature and RH are excluded. However, as a reference, some relaxation tests are conducted in an outside environment, exposed to weather. For all tests, the humidity of the specimens is brought to 6.5 % (mass/mass), which is a realistic value according to Dutch calcium silicate manufacturers and was also used in the research of Van der Pluijm [16]. The size of the specimens was chosen with respect to the element sizes in building practice. The smallest available thickness for high-performance CASIELs is 175 mm. This resulted in single specimens of 175 x 175 x 550 mm^3. To include the influence of a thin mortar layer, two specimens with a thin mortar layer in between are placed in one test frame. The volume to exposed surface ratio (v/s ratio) [18] for the specimen is $t_w/4$ (with t_w the thickness of the wall element). The v/s ratio for a wall with $l_w >> t_w$ is approximately $t_w/2$. Since the goal is to predict creep, shrinkage and relaxation of a shear wall, the v/s ratio of the specimen is altered to equal $t_w/2$ by sealing two vertical sides of the specimen. Specimens from two manufacturers are included in the investigation, which are different in composition of the material. The proposed test scheme is shown in Table 3, in which f_b is the normalized mean compressive strength of a masonry unit.

Table 3: Scheme for creep, relaxation and shrinkage experiments

Specimen	Material	Creep		Relaxation	Shrinkage
		$0.10 f_b$	$0.20 f_b$	$0.20 f_b$	
1	a	climate room			climate room
2	a		climate room		climate room
3	a			climate room	climate room
4	a			outside	outside
5	b	climate room			climate room
6	b		climate room		climate room
7	b			climate room	climate room
8	b			outside	outside

Test-setups for creep tests can be categorized by the way in which the constant load on the specimen is maintained. Common methods are:

- Dead weight and lever arm.
- A stabilized hydraulic system.
- Prestress with compressive springs.

The third method was selected. The prestress used to apply the load, is kept constant by compressive springs with small spring stiffness and large deformation capacity compared to the prestress bars and the specimen.

This method was selected for the following reasons:

- No external regulation required, test frames can be moved individually;
- Frames take up little floor space;
- Creep frames can be used for prestress loss measurements when compressive springs are removed.

One disadvantage is the possible relaxation of the compressive springs.

The test-setup as described in this paper is based on Myers [19] and shown in Figure 5. In building practice, an axial masonry design stress of about 9 MPa is the maximum allowable for CASIEL masonry of quality CS44. Therefore, the test-setup was designed for a prestressing force of 280 kN. At this load, the Dywidag bars are loaded at 36 % of their ultimate tensile strength. The compressive springs have a spring constant of 1400 N/mm and a maximum compression of at least 50 mm. The test-setup was designed to have a maximum prestress loss of 2 %, which is prescribed in [20].

Measurements are done with a DeMec (demountable mechanical) strain gauge of 300 mm at the positions given in Figure 5. During application of the prestress by a hydraulic jack, the prestressing force in the Dywidag bars is measured continuously for one day. After that, strain in specimens and bars and spring deformation will be measured with the DeMec strain gauge on a logarithmic time scale. Measurements will continue for approximately one year, after which the test-setups will be reused for more measurements.

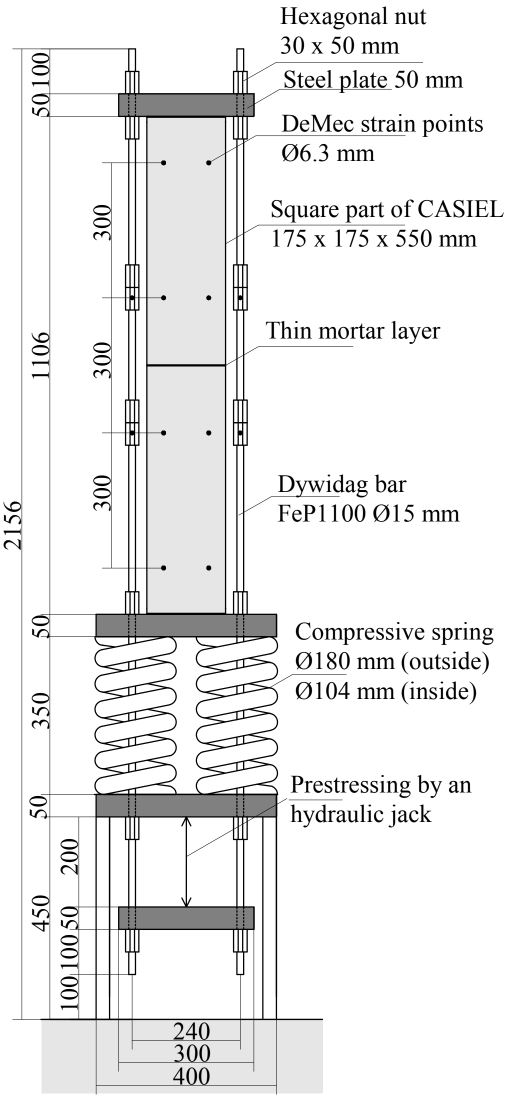


Figure 5: Creep test-setup based on [19], all units in mm

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