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UPT rectangular and flanged shear walls of high-strength CASIEL-TLM masonry: Experimental and numerical push-over analysis ☆

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ABSTRACT

The mechanical behaviour of unbonded post-tensioned (UPT) shear walls of high-strength CAlcium SIlicate ELement masonry with Thin-Layer Mortar (CASIEL-TLM masonry) was investigated experimentally and numerically. Eight walls were tested with the following key variables: unit type, prestress level and cross-sectional shape (rectangular or T-shaped with interlocking of web and flange). An extensive measurement scheme was adopted that allowed derivation of average curvatures and strains in the bottom region of the wall in addition to wall displacements. Since UPT masonry is characterised by the absence of local compatibility between masonry and the UPT tendons, a numerical model for quasi-static, monotonic push-over analysis was developed that provides an iterative solution for the global interaction between masonry and UPT tendons. A common masonry stress–strain diagram was adopted in the numerical model. A peculiarity of CASIEL-TLM masonry is the kicker course, which reduces the stiffness of the bottom region of the shear wall. This layer was modelled with no-tension, linear-elastic behaviour and a reduced stiffness. Nevertheless, the model underestimates the experimental deformations of the rectangular shear walls, while the strength is in reasonable agreement. The walls with T-shaped cross-section failed prematurely by shear of the web-flange interface, resulting in diagonal splitting cracks in the interlocking units. This paper deals with the experimental results of UPT CASIEL-TLM masonry shear walls with rectangular and T-shaped cross-section and with the numerical modelling of the overturning behaviour of UPT shear walls with rectangular cross-section.

1. Introduction

CAlcium SIlicate ELement masonry with Thin-Layer Mortar (CASIEL-TLM masonry) is used throughout Western Europe to build terraced housing but also medium-rise buildings up to approximately 12 storeys [1–3]. CASIEL-TLM masonry is characterised by large units, called elements, that are bonded by thin-layer mortar. The high-strength units have a normalised compressive strength up to 44 MPa, resulting in a characteristic masonry compressive strength of 20 MPa.

In spite of excellent compressive strength, the moment capacity of CASIEL-TLM masonry shear walls is determined by overturning, due to a limited tensile strength, especially at the wall-floor interface. This interface contains a kicker course (KC), which is a peculiarity of CASIEL-TLM masonry that is not found in other kinds of masonry. It is used for smooth and plumb set-out of the wall and consists of a mortar joint of approximately 30 mm thick and one course of calcium silicate blocks.

The moment capacity of a shear wall can be increased by adding normal force, which can be achieved by vertical post-tensioning [4]. Unbonded post-tensioning (UPT) is preferred, since it does not require grouting and allows for additional post-tensioning at a later time to compensate prestress losses due to creep and shrinkage [5]. Before setting up experiments, finite element (FE) simulations of a typical six-storey building with CASIEL-TLM masonry shear walls subjected to monotonic (wind-)loading were conducted [6]. These simulations showed that overturning is a likely cause of failure. For seismic loading and squat shear walls shear failure may be more dominant. The test walls described in this paper have an aspect ratio of 2.5–3 in order to avoid shear failure.

A total of eight UPT CASIEL-TLM masonry shear walls with rectangular (R-) and T-shaped cross-section with interlocking of web and flange were investigated. A numerical model was developed to describe the interaction between masonry and UPT tendons, which was validated by the experiments on walls with rectangular cross-section. The walls with T-shaped cross-section failed prematurely by shear of the web-flange interface, which is currently not

☆ Calcium silicate element masonry with thin-layer mortar.

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covered by the numerical model. Additional experimental research is required to gain more insight in this type of failure.

2. Literature review

The literature review is focussed on the behaviour of UPT shear walls, i.e. in-plane loading, with special attention for UPT masonry. General overviews of prestressed masonry are given by Ganz [7], Schultz and Scolforo [8], Lissel et al. [9] and Phipps [10]. Contributions of e.g. Bean Popehn and Schultz [11] and Ismail and Ingham [12] are acknowledged, but not included in this review, because they focus mainly on out-of-plane loading.

One of the first experimental investigations on UPT masonry shear walls is that by Hinkley [13], who tested five UPT and two unreinforced brickwork shear walls. Square walls as well as rectangular walls were tested and the post-tensioning was applied either uniformly or at the wall ends. Post-tensioning was applied first and then a bond beam was constructed to which the horizontal load was applied. It is mentioned that only horizontal load was assumed to be transferred, although there was some unknown vertical restraint by friction. Monotonic loading was applied at a very slow pace until failure occurred after approximately 6 h. The behaviour was linear-elastic until cracking first occurred, while the ultimate load could be approximated most accurately by assuming a rectangular stress block and yield of all post-tensioned wires outside the compressed zone.

Over two decades later, Page and Huizer [14] investigated the racking behaviour of prestressed and reinforced hollow clay masonry walls. Only three tests were conducted: one with grouted reinforcement, one with unbonded vertical post-tensioning and one with unbonded vertical and horizontal post-tensioning. The load was applied with a spherically seated hydraulic jack via a steel bearing plate directly to the top courses of the masonry. This led to local failure of the hollow masonry in the third test. Uplift (base separation) was measured, but the walls failed by diagonal cracking of the masonry.

Within the framework of the PREcast Seismic Structural Systems (PRESSS) research program [15], Kurama et al. [16] investigated the lateral load behaviour of UPT precast concrete walls. They found that, although horizontal displacements during seismic loading were larger than in conventional reinforced concrete (RC), plastic deformations and damage were smaller.

Since concrete masonry material properties are similar to those of (precast) concrete, Laursen and Ingham [17] applied the concept of UPT to single-storey concrete masonry shear walls. Eight walls were tested, of which six were fully grouted, one was partially grouted and one was ungrouted. Cyclic loading was applied. All fully grouted walls exhibited rocking response (uplift, overturning), but one wall with a higher axial load ratio failed by diagonal cracking. In addition to tests on single storey walls, tests on enhanced single-storey concrete masonry walls [18] and three-storey concrete masonry walls with confinement plates in the toe zones [19] were conducted. Research was later extended to shake-table testing [20] and the innovative design of a post-tensioned masonry house [21].

Another research project of interest is the ESECMaSE project: Enhanced Safety and Efficient Construction of Masonry Structures in Europe [22]. Shear walls made of various types of masonry, including calcium silicate block masonry, were tested at various locations in Europe. A test set-up and cyclic loading pattern, standardised within ESECMaSE, were used. Most tests had fixed–fixed boundary conditions with zero moment at mid height of the wall and therefore failed in shear. However, Magenes et al. [23] reports two wall tests with cantilevered boundary conditions, both with a normal stress of 1.0 MPa and one with additional post-tensioning of 1.0 MPa. Both exhibited rocking behaviour and large drift, but the PT wall failed prematurely due to failure of the PT anchorage.

Rosenboom and Kowalsky [24] tested UPT clay masonry and found the same rocking mechanism to occur as in UPT concrete masonry. In Germany, research on UPT calcium silicate block masonry took place, including four UPT shear wall tests [25] as well as the construction of a building with UPT calcium silicate shear walls for global lateral stiffness in case of windloading [26]. The UPT shear wall tests had realistic boundary conditions between cantilevered and fixed–fixed, because a certain length of the top floor was included in the experiment. A dead load of approximately 0.5 MPa was imposed on the wall at the centre, while an additional prestress of approximately 0.8, 1.2 or 1.6 MPa was applied by two post-tensioning tendons. Photos of the tested specimens show extensive diagonal cracking, but complete collapse did not occur.

A separate but interesting development is that of post-tensioned dry-stacked masonry, which was investigated by Marzahn [27] and Biggs [28]. The behaviour of dry-stacked post-tensioned masonry is characterised by dry friction, zero tensile strength at the interfaces and non-linear contact in compression [27]. Tolerances for unit dimensions are even smaller than for masonry with thin-layer mortar and post-tensioning is crucial for the coherence of a dry-stacked masonry wall.

It can be concluded that research on UPT shear walls has intensified over the last 10 years, especially in the field of earthquake engineering. The type of failure of UPT shear walls depends on the type of loading (seismic or wind loading), the aspect ratio of the wall, the boundary conditions imposed by the storey floor(s) and the axial load level. Shear failure mechanisms, which include gaping, sliding and diagonal cracking, are associated with a brittle response and global damage, while the flexural failure mechanism is characterised by toe crushing, local damage and a high degree of ductility.

The shear failure mechanism of a CASIEL-TLM masonry shear wall is expected to be similar to that of a calcium silicate block masonry shear wall when the wall is sufficiently large to include a number of bed and head joints. For the flexural failure mechanism, the compressive strength and the maximum compressive strain are the key parameters, which are expected to depend on the size of and the number of joints in the compressed zone.

The flexural failure mechanism of UPT shear walls is characterised by overturning, which starts with base separation and finally results in toe crushing and possibly yield of the post-tensioning tendons. To a certain extent, the behaviour of UPT shear walls is similar to the behaviour of unreinforced shear walls with additional normal force. However, overturning is associated with uplift of the wall, which activates the post-tensioning tendons. The tendons will prevent overturning, although large in-plane deformations of the wall will occur. The magnitude of these deformations depends mainly on the strength, stiffness and ductility of the bottom region of the shear wall. For CASIEL-TLM masonry the properties of this bottom region are substantially affected by the presence of the kicker course.

Little information was found in literature about flanged masonry shear walls. The behaviour of these walls is dependent on the type of connection between web and flange, in addition to the parameters mentioned for walls with rectangular cross-section. Also, shear lag may occur. Flanged reinforced masonry walls were investigated by Shedid et al. [29]. Various types of web-flange connections were investigated experimentally by Drysdale et al. [30] and Bosiljkov et al. [31], while Capuzzo-Neto et al. [32] proposed a standard test specimen and Haach et al. [33] performed numerical analysis of flanged unreinforced masonry shear walls. Since flanges improve the flexural behaviour significantly if the web-flange connection can be assured, it is important to develop a model for the failure mechanisms of the web-flange connection.