Engineering Structures 143 (2017) 189–203

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Masonry walls with a multi-layer bed joint subjected to in-plane cyclic loading: An experimental investigation

Miloš Petrović, Nebojša Mojsilović *, Božidar Stojadinović

Institute of Structural Engineering, Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, 8093, Switzerland

ARTICLE INFO

Article history:
Received 6 January 2017
Revised 28 March 2017
Accepted 12 April 2017

Keywords:
Bitumen
Cork
Cork-rubber granulate
Extruded elastomer
Multi-layer bed joint
Rubber granulate
Shear behaviour
Sliding
Static-cyclic shear
Unreinforced masonry

ABSTRACT

A series of static-cyclic shear tests on full-scale unreinforced masonry (URM) walls with multi-layer bed joints have been performed within a research project on the seismic behaviour of unreinforced masonry walls with soft layer membrane placed in the bed joint to induce sliding. Walls were made using typical perforated Swiss clay blocks and standard cement mortar and the so-called multi-layer bottom bed joints, which comprise a core soft layer protected by two layers of extruded elastomer and placed in the middle of mortar joint. The preliminary testing phase was aimed at choosing the most suitable core soft layer type among the four types considered (rubber granulate, cork, cork-rubber granulate and bitumen). The main testing phase comprised five tests on storey-high URM specimens with rubber granulate core soft layers performed to investigate the influence of the size, the pre-compression level and the aspect ratio on the seismic behaviour of URM walls with a multi-layer bed joint. Sliding occurred in all tested specimens. However, the final failure mode as well as the displacement capacity of test specimens were governed by the extent of shear and tensile (vertical) cracks that developed from the bottom brick course. The response of specimens can be interpreted using a multilinear horizontal force-displacement response idealization, whose parameters can be estimated using the proposed equations.

1. Introduction

Due to their quasi-brittle behaviour, URM structures do not perform well in earthquakes. Consequently, they usually account for the majority of damage, causing the most fatalities and present the biggest obstacle to the post-earthquake recovery of communities. Such a risk posed by quasi-brittle structures exposed to seismic hazard has been recognized since ancient times. Strategies to mitigate this risk are almost as old as engineered construction itself. Sliding on a horizontal surface comprised of superimposed layers of sand and clay is a seismic response mechanism utilized by Japanese builders to protect the 1000-year old Sanjusangen-do Buddhist Temple in Kyoto (Ueda et al. [1]). Sliding was also documented as the primary mechanism that significantly reduced building damage in earthquakes in Assam, India that occurred between 1897 and 1950 (Joshi [2]). Further, sliding was proposed as an effective way to mitigate the seismic damage in unreinforced masonry (URM) structures by Arya et al. [3]. The authors introduced a sliding surface between the foundation beams and bond beams that support the masonry walls by breaking the bond by applying either a polyethylene membrane or they used motor oil. Further, other sliding materials, such as sand, grease, Teflon, graphite and geotextile/smooth marble, were investigated, see Qamaruddin et al. [4], Lou et al. [5], Nikolic-Brzev and Arya [6], Nanda et al. [7] and [8]. A review of previous research on engineered and non-engineered sliding joints enabling friction-slide behaviour and on the dynamics of masonry structures with such joints, can be found in Petrović et al. [9].

The central idea of the current research project is to modify the seismic response of individual structural masonry walls by placing engineered deformable layers (soft layers) at the bottom of such masonry walls. Such layers, mainly based on rubber, bitumen, cork or polyvinylchloride (PVC), have already been used in Swiss URM construction. However, the purpose of implementing such layers is mainly unrelated to seismic actions. Soft layers are used to provide a moisture barrier in the form of a damp-proof course (DPC) membrane, to ensure sound insulation or to accommodate short- or long-term differential movements between the walls and floor constructions. Results from the preliminary research on masonry elements with rubber granulate and elastomer soft layers, e.g. Mojsilović et al. [10] and Vögeli et al. [11], indicated that the presence of such layers in the mortar bed joint can significantly alter the mechanical characteristics of URM walls by creating a sliding plane, which, in turn, could influence the seismic response

* Corresponding author.
E-mail address: mojsilovic@ibk.baug.ethz.ch (N. Mojsilović).

http://dx.doi.org/10.1016/j.engstruct.2017.04.025
0141-0296/

of the entire structure. Rubber granulate soft layers were in some cases heavily damaged during the sliding, whereas the elastomer layers were found to be significantly more durable. Recently, as a part of the presented research project, several series of monotonic and quasi-static cyclic, displacement controlled tests were performed on masonry triplets with a multi-layer bed joint, see Mojsilović et al. [12]. The so-called multi-layer bed joint consisted of a core soft layer (rubber granulate, cork, cork-rubber granulate, bitumen and PVC based membranes were used) which, in order to reduce the damage caused by cyclic loading, was protected by two layers of elastomer, and placed in the middle of the mortar bed joint. Results indicated that multi-layer bed joints with adequate material properties could change the typical brittle shear response of masonry to a more desirable quasi-ductile one. Further, based on the observed hysteretic behaviour, considerable energy dissipation can be achieved in masonry structures with multi-layer bed joints. Such behaviour is desirable for enhanced seismic performance. Furthermore, findings indicated that the loading speed had a considerable influence on the overall behaviour of masonry with a multi-layer bed joint, and especially on the friction coefficient and thus on the shear strength of such bed joints. Similar findings were reported by Trajkovski et al. [13], where it was found that the loading speed affected the shear characteristics of masonry triplets with bitumen- and polyester-based DPCs soft layers placed in bed joints. In addition, it was shown in [12] that the friction coefficient is also a function of the normal pressure (pre-compression) acting at the interface where the sliding occurs. Having this in mind, it appears that the loading speed and pre-compression are the important parameters for the proper assessment of the horizontal force-deformation characteristics of masonry multi-layer bed joints during sliding.

This paper presents and discusses the test results obtained by performing a series of static-cyclic shear tests on full-scale URM walls with a multi-layer bed joint. A total of 9 walls were tested in two phases. The first (preliminary) testing phase allowed the most suitable core soft layer type to be chosen from the four types investigated. Results from the second (main) phase enabled an analysis of the influence of the pre-compression level, aspect ratio and size on the seismic behaviour of URM walls with a multi-layer bed joint. Besides the conventional bilinear, an extended, multilinear horizontal force-displacement response idealization is proposed, together with the equations to determine its parameters (e.g. stiffness and ultimate horizontal force). Finally, a set of conclusions as well recommendations for future work are given.

2. Test programme and masonry materials

In order to gain additional insight into the behaviour of large masonry elements with a multi-layer bed joint, nine static-cyclic tests were performed in two phases. Table 1 summarizes the test programme, where l_w, h_w and t_w are the length, height and thickness of the specimens (see Fig. 1), t_{csl} is the core soft layer thickness, f_x is the mean compressive strength of the masonry perpendicular to the bed joints, and σ_{pc} is the pre-compression stress computed with reference to the nominal wall cross section

Table 1
Testing programme and specimen designation.

Phase	Specimen	Core soft layer	t_{csl} [mm]	Dimensions $l_w x h_w x t_w$ [mm]	Aspect ratio	σ_{pc}/f_x
Preliminary	WG	Rubber granulate	3	1500 × 1600 × 150	0.94	0.10
Preliminary	WGK	Cork-rubber granulate	3.2	1500 × 1600 × 150	0.94	0.10
Preliminary	WK	Cork	3.5	1500 × 1600 × 150	0.94	0.10
Preliminary	WB	Bitumen	2	1500 × 1600 × 150	0.94	0.10
Main	Z1	Rubber granulate	3	2700 × 2600 × 150	1.04	0.10
Main	Z2	Rubber granulate	3	2700 × 2600 × 150	1.04	0.05
Main	Z3	Rubber granulate	3	2700 × 2600 × 150	1.04	0.20
Main	Z5	Rubber granulate	3	1800 × 2600 × 150	0.69	0.10
Main	Z6	Rubber granulate	3	3600 × 2600 × 150	1.38	0.10

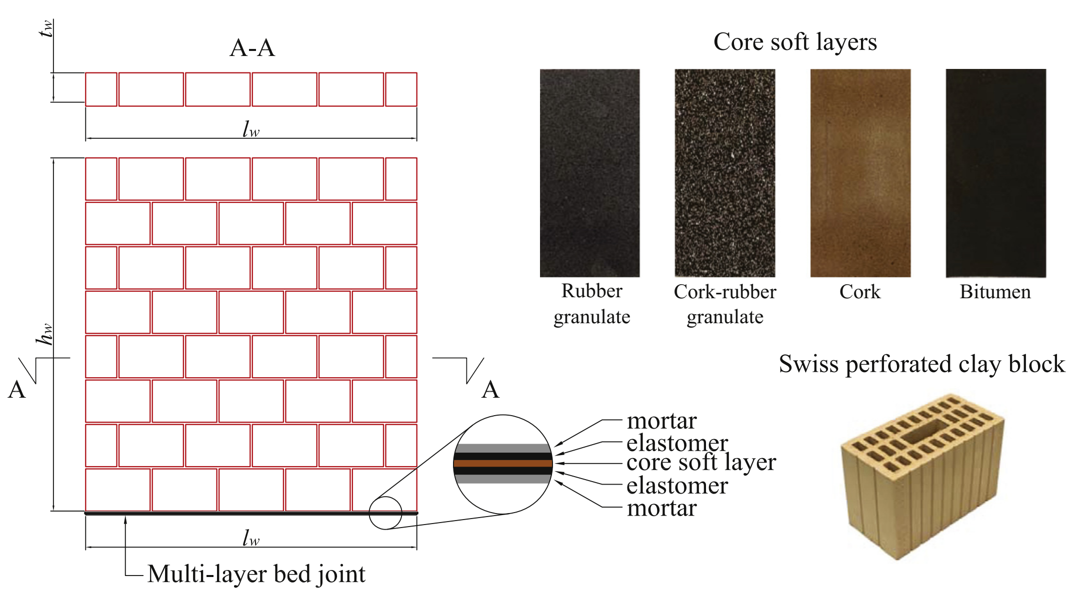

Fig. 1. Specimen layout and materials.