Development of a Soft Layer for Seismic Response Modification of Structural Masonry Walls

Author(s):
Mojsilović, Nebojsa; Stojadinovic, Bozidar

Publication Date:
2014

Permanent Link:
https://doi.org/10.3929/ethz-b-000092154 →

Originally published in:
http://doi.org/10.4231/D3ZC7RV31 →

Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

DEVELOPMENT OF A SOFT LAYER FOR SEISMIC RESPONSE MODIFICATION OF STRUCTURAL MASONRY WALLS

N. Mojsilović[1] and B. Stojadinović[2]

ABSTRACT

The objective of the presented work is to utilize the engineered deformable layers at the bottom and the top of a masonry structural wall for seismic response modification. Such layers are already placed for moisture insulation and sound isolation (at the bottom of a wall) and to allow for floor slab deflection (at the top of a wall). The goal is to engineer the mechanical properties of the "soft" layers so that the structural masonry wall with such "soft" layers responds in three different regimes: 1) an initial essentially elastic regime, with relatively high stiffness; 2) a sliding regime, with relatively low stiffness, capped horizontal shear force, and stable hysteresis under repeated cycling; and 3) a conventional shear regime, engaged when the wall "soft" layer reaches its sliding limits, with relatively high stiffness and increasing horizontal shear resistance until shear failure. The wall is expected to carry its tributary gravity load until its shear failure. The preliminary work by the authors and other researchers suggests that it is possible to achieve this goal. Structural masonry wall with such engineered "soft" layers will enable the masonry structure to achieve the following performance goals: 1) experience essentially no damage in frequent earthquakes and under high wind loads when the structure is expected to remain elastic; 2) experience controlled damage while preserving the gravity load-carrying capacity in design-basis earthquakes through controlled lateral sliding deformation and an elongation of the structural response period due to low stiffness in the sliding regime; and 3) collapse prevention in beyond-design-basis earthquakes through engagement of the full shear strength of the structural masonry walls. The engineering of the "soft" layer in terms of its friction coefficient and deformation capacity to achieve these performance goals in regions of low and moderate seismicity is presented in this paper.

[1]Senior Scientist, Institute of Structural Engineering, ETH Zurich, Switzerland, CH-8093 Zurich
[2]Professor, Institute of Structural Engineering, ETH Zurich, Switzerland, CH-8093 Zurich

Mojsilović N. and Stojadinović B. Development of a Soft Layer for Seismic Response Modification of Structural Masonry Walls. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

Development of a Soft Layer for Seismic Response Modification of Structural Masonry Walls

N. Mojsilović[1] and B. Stojadinović[2]

ABSTRACT

The objective of the presented work is to utilize the engineered deformable layers at the bottom and the top of a masonry structural wall for seismic response modification. Such layers are already placed for moisture insulation and sound isolation (at the bottom of a wall) and to allow for floor slab deflection (at the top of a wall). The goal is to engineer the mechanical properties of the "soft" layers so that the structural masonry wall with such "soft" layers responds in three different regimes: 1) an initial essentially elastic regime, with relatively high stiffness; 2) a sliding regime, with relatively low stiffness, capped horizontal shear force, and stable hysteresis under repeated cycling; and 3) a conventional shear regime, engaged when the wall "soft" layer reaches its sliding limits, with relatively high stiffness and increasing horizontal shear resistance until shear failure. The wall is expected to carry its tributary gravity load until its shear failure. The preliminary work by the authors and other researchers suggests that it is possible to achieve this goal. Structural masonry wall with such engineered "soft" layers will enable the masonry structure to achieve the following performance goals: 1) experience essentially no damage in frequent earthquakes and under high wind loads when the structure is expected to remain elastic; 2) experience controlled damage while preserving the gravity load-carrying capacity in design-basis earthquakes through controlled lateral sliding deformation and an elongation of the structural response period due to low stiffness in the sliding regime; and 3) collapse prevention in beyond-design-basis earthquakes through engagement of the full shear strength of the structural masonry walls. The engineering of the "soft" layer in terms of its friction coefficient and deformation capacity to achieve these performance goals in regions of low and moderate seismicity is presented in this paper.

Introduction

Masonry represents one of the oldest building concepts. Masonry is a traditional, widely used, extremely flexible and economical construction method and possesses considerable potential for future developments. Due to lack of establishing of a more modern basis for the design and assessment of masonry structures, conventional design practice of masonry structures is quite conservative, particularly in regard to seismic design. Therefore, there is both a substantial need and a significant opportunity to develop innovative ways of enhancing the seismic response of masonry structures. The central idea of the present project is to modify the seismic response of individual structural masonry walls by changing their response mechanism to control the

[1]Senior scientist, Institute of Structural Engineering, ETH Zurich, Switzerland, CH-8093 Zurich
[2]Professor, Institute of Structural Engineering, ETH Zurich, Switzerland, CH-8093 Zurich

Mojsilović N. and Stojadinović B. Development of a Soft Layer for Seismic Response Modification of Structural Masonry Walls. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

horizontal shear force they receive. This can be achieved by placing engineered deformable "soft" layers at the bottom and the top of masonry wall. The "soft" layers are designed so, that their presence will allow the wall to slide, albeit with some friction, thus controlling shear force in the wall. The preliminary conducted research suggests that such response modification of structural masonry wall is achievable. Building on this fundamental findings, the concept of using "soft" layers in individual masonry walls is developed by: 1) investigating the mechanical properties of "soft" layers required to achieve the desired performance of the structural wall; 2) conducting the series of proof-of-concept and parameter exploration tests; and 3) developing the mechanical models to describe the seismic response of structural masonry walls with incorporated "soft" layers and optimization of mechanical properties of "soft" layer to achieve the desired seismic performance of structural masonry walls.

Previous Investigations

In the majority of the previous applications within the masonry construction a soft layer in the form of the damp-proof course (DPC) membrane has been used. A DPC membrane is often placed at the base of masonry walls as moisture barrier and/or sound insulation, as well as to act a slip joint to allow for differential movements between the walls and the floor slabs. Although it is desirable for the DPC membrane to be sandwiched in the mortar joint, in reality it is usually placed above or below the mortar. In some cases, such as when it is used as a slip joint, the DPC membrane is placed without any mortar.

It is important to understand the influence of the DPC membrane on the structural behavior of the walls, especially on the in-plane shear response of unreinforced masonry walls that are part of the lateral load resisting system for the structure. Tests conducted to date indicate that shear could be transmitted through a joint containing a DPC membrane. Griffith and Page [1] performed monotonic, static-cyclic and dynamic shear tests on small masonry elements (triplets) with bitumen coated aluminum, polythene/bitumen coated aluminum, and embossed polythene DPC membranes and reported the corresponding friction coefficients. The DPC membranes were placed in both mortar joints of the clay brick triplet; in one series the middle brick was made of concrete in order to simulate the concrete slab. A satisfactory performance of the DPC has been obtained, especially for the embossed polythene. Similar findings were reported by Suter and Ibrahim [2] and by Zhuge and Mills [3]. Within the framework of the project on the harmonization of the European construction regulations Kirtschig and Anstötz [4] reported the values of the shear strength parameter obtained from monotonic tests on clay and calcium-silicate block masonry triplets with three different DPC membranes: asphalted cardboard, polyvinyl chloride (PVC) sheet and sealing slurries. In addition, a satisfactory performance of tested DPC membranes under static shear loads has been obtained.

The main goal of the joint research project by the University of Newcastle, Australia, and ETH Zurich, Mojsilović et al. [5, 6], was to investigate the influence of the bed joint placed damp-proof course (DPC) membrane on the structural behavior of unreinforced masonry under cyclic shear loading. Load tests on the two series of masonry wallettes (dimensions of 1200x1200 mm) with built-in DPC in one of the bed joints were performed. The DPC was placed either between the first two courses or between the concrete base and first masonry course. In addition, three control specimens without DPC have been tested. The behavior of the wallettes was greatly influenced by the pre-compression level. Furthermore, the presence and position of the DPC had a considerable influence on the behavior of the wallettes, especially on the failure mode. Two types of failure were observed, namely sliding along the bed joint with DPC and compression failure, i.e. toe crushing for higher levels of pre-compression. Wallettes that failed in compression exhibited limited energy dissipation and those that slid displayed considerable energy dissipation and behaved in a quasi-ductile manner. Greater ductility was observed in the wallettes with the DPC in the bed joint rather than at the wallette-slab interface, indicating that the above detail would be more desirable for enhanced seismic performance. In the second phase of the research project a numerical study of the in-plane lateral load resistance and behavior of unreinforced masonry shear walls with DPC has been performed. The results of the numerical modelling using a simplified micro-modelling approach showed its efficiency for detailed modelling as well as for the assessment of the lateral resistance of structural elements where a good correlation with the experimental results have been obtained [7].

In order to assess the behavior and mechanical characteristics of different soft layer materials 10 series of static shear tests on masonry triplets have been performed at ETH Zurich [8]. The thickness of the DPC membranes was 1.5, 2 and 3 mm for elastomer-based, bitumen-based and polyester-based DPCs, respectively. Four different levels of pre-compression were considered (0.2 MPa, 0.6 MPa, 1.0 MPa and 1.5 MPa) and for each level three replicates were tested in each series. Additional static-cyclic tests were performed on masonry triplets with incorporated DPC membrane at the University of Newcastle in collaboration with ETH Zurich [9]. The triplets have been constructed using embossed polythene DPC membrane. Each series consisted of 9 specimens, which were firstly subjected to a given pre-compression (0.2 MPa, 0.6 MPa and 1.0 MPa) and subsequently subjected to the cyclic shear load applied using computer controlled displacement steps. Test data on the mechanical characteristics, energy dissipation and overall behavior of the masonry elements with DPC subjected to the static-cyclic loading has been obtained. As expected, the mechanical characteristics progressively degraded with an increasing number of cycles. Nevertheless, the large area of the force-slip hysteresis suggested that considerable energy dissipation could be expected in practical applications when such soft layer is incorporated in the shear wall [9].

A preliminary series of seven static-cyclic shear tests on the clay block masonry wallettes (1200 x 1200 mm) has been performed at ETH Zurich [10]. The goal of the preliminary testing was to capture the behavior of the structural masonry with incorporated neoprene-based soft layer in one bed joint, to verify the testing apparatus and to estimate the parameters for the main test series of the project described herein. Two different neoprene-based materials, extruded elastomer (E) and rubber granulate (G), were used and three different thickness of the layer were considered, namely 3, 5 and 10 mm. The soft layer has been placed between the wall brick course and mortar joint, i.e. directly on the brick course. In addition, as a control specimen, one wallette without soft layer has been tested, thus giving total of seven specimens. All specimens were subjected to the pre-compression load of 0.6 MPa, which corresponds to about 10% of masonry compressive strength. Shear strength of the specimens was influenced by the type of the soft layer: the specimens with extruded elastomer layer were stronger. Further, the shear strength of the specimens with rubber granulate was independent on the layer thickness. Considerable energy dissipation and quasi-ductile behavior (a large deformation capacity compared to that of conventional masonry and masonry with extruded elastomer soft layers), could be expected in actual masonry structures with the rubber granulate soft layer placed in the bed joints, see Fig. 1.

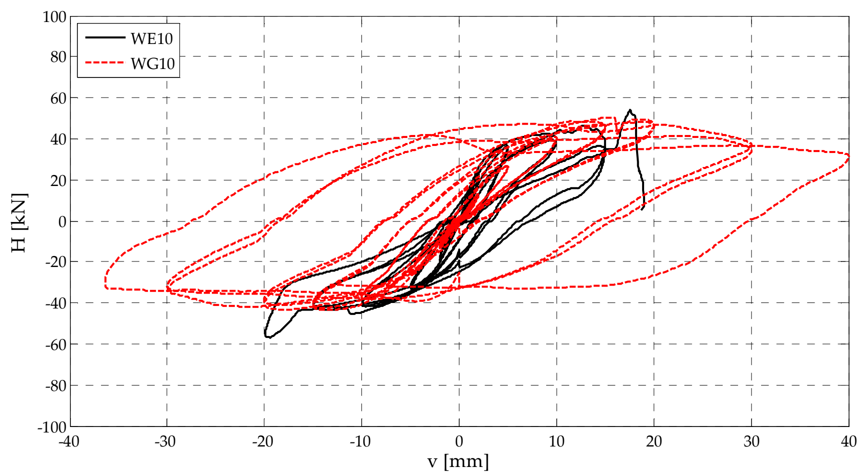

Figure 1. Shear force-deformation response comparison for two wall specimens with different 10 mm thick soft-layer materials: extruded elastomer (full black line) and rubber granulate (dashed red line).

Seismic Response Modification for Masonry Structures

Risk posed by quasi-brittle structures exposed to seismic hazard has been recognized since the ancient times. Strategies to mitigate this risk are almost as old as engineered construction itself.

Rocking of rigid column blocks is the seismic response modification mechanism utilized in Ancient Greek and Roman temples [11]. Sliding on a horizontal surface comprised of superimposed layers of sand and clay is another seismic response mechanism utilized by Japanese builders to protect the 1000-year old Sanjusangen-do Buddhist Temple in Kyoto [12]. Recently, in 1909 Calantariens patented a system to separate the structure from its foundation and let it slide on a layer of talc [13]. More recently, sliding was documented as the primary mechanism that significantly reduced building damage in earthquakes in Assam, India that occurred between 1897 and 1950 [14]. The 1960's and 1970's saw significant developments of systems and devices for seismic isolation. Sliding was proposed as an effective way to mitigate the seismic damage in unreinforced masonry structures by Arya et al. [15]. In this work they introduce a sliding surface between the foundation beams and bond beams that support the masonry walls by breaking the bond using a membrane made of polyethylene or used motor oil. Different materials, such as sand and graphite, were explored in subsequent work [16, 17]. Almost simultaneously, natural rubber, rubber reinforced with steel plates and lead-rubber bearings were developed between 1969 and 1975 [13]. High-damping rubber bearings were investigated for seismic isolation of masonry structures in 1991 [18]. A friction pendulum sliding system utilizing curved steel surfaces and Teflon sliders to restore displacements after an earthquake was patented in 1985 by Zayas [19] and used to seismically upgrade a historic masonry building [20].

Among numerous seismic isolation devices and materials developed to-date, the ones of principal interest for this project are strip-shaped rubber bearings. These bearings, intended as a low-cost seismic isolation solution for developing-world countries, were proposed by Kelly [21] after analytical [22] and experimental [23] work. The elastic and elastic-plastic models developed for these bearings will be specialized to significantly thinner elastomer strips intended for use in this project.

Research Plan

The present research project on the seismic behavior of the masonry walls with incorporated soft layer is underway and comprises the following three phases:

1. Investigation of the mechanical properties of "soft" layers required to achieve the desired performance of structural masonry walls equipped with such layers;
2. Conduction of quasi-static cyclic structural tests to prove the concept and to experimental investigate the "soft" layer parameter space;
3. Development of the mechanical models to accurately describe the seismic response of structural masonry walls with "soft" layers and optimization of the

mechanical properties of the "soft" layer to achieve the desired seismic performance of structural masonry walls.

Considering the results of the literature survey and the findings of previously conducted and on-going pilot tests, the concept of an engineered soft layer for seismic response modification of structural masonry walls will be investigated. Simplified analytical models will be developed to capture the most important parameters and to conduct a bounding analysis to define the space of parameters to be tested. A desired shape of the three-linear force-deformation response envelope, comprising an initially elastic portion, followed by a plastic portion corresponding to the sliding response regime, and ending with a hardening portion corresponding to additional shear taken by the masonry wall will also be defined.

After determining the masonry and soft layer components to be used, the standard tests to determine the component mechanical properties will be performed. In addition, tests on small masonry specimens will be carried out. These will provide the masonry strength data, provide preliminary information on the behavior of the masonry subjected to in-plane loading and serve to determine the parameters of the failure criterion for masonry. Similarly, standard tests will be used to determine the mechanical properties of the soft layer materials. Finally, masonry triplet tests will be used to establish the friction coefficient and apparent cohesion of the selected soft layers and the dependence of these parameters on the pre-compression stress levels.

The specimens and the test setup for testing full-scale structural masonry walls with soft layers will be designed. It is planned to conduct tests on at between six and eight large walls with different aspect ratios (smaller and larger than one), different pre-compression levels, and different soft layer materials. The final selection of the test parameters will depend on the conducted parameter analysis and the material characteristics determined in earlier phase of the research project. A three-actuator test setup will be used: two vertical actuators in load control will be used to apply constant pre-compression and maintain zero rotation of the specimen; a single horizontal actuator in displacement control will be used to apply a standard quasi-static cyclic loading pattern using a programmable servo-hydraulic controller. Conventional deformation and force measuring instruments will be augmented by a field deformation measurement system based on correlation of pixelated images taken by a photo camera (Digital Image Correlation - DIC). Data acquisition will be synchronized with the lateral displacement motion commands to facilitate post-processing of the measured data and correlation to specimen photographs.

The results analysis will be focused on re-assessing how the main specimen parameters, such as the aspect ratio, the pre-compression level and the mechanical characteristics of the masonry and the soft layer, influenced the observed behavior and the measured response of the tested specimens. Special attention will be paid to the influence of the soft layer and the interaction between the soft layer and the wall in terms of force transfer and allowed deformation. The effects of secondary parameters, such as the size of the specimens compared to the possible sizes of prototype walls and the rate of loading, will be established. The analysis will include not only the large-scale specimens, but also the data from the small-scale preliminary tests on masonry units and masonry triplets with a soft layer, as well as the data from previous studies conducted by the project investigators and others. Using the accurate photo-measurements of the deformations on the masonry it should be possible to determine the parameters required to describe the failure criterion and to predict the behavior of masonry walls with a soft layer. Furthermore, it should be possible to assess the durability of the soft layers and estimate the reliability and repeatability of its sliding response under different loading conditions. Finally, the parameters of the three-linear force-deformation response envelope (linear-elastic, ideal-plastic, and hardening) will be estimated using the measured cyclic response data and related to the mechanical characteristics of the masonry and the soft layer.

It is also planned to capture the load bearing behavior of masonry with a soft layer using an advanced model based on the lower bound theorem of the theory of plasticity. In previous work, see Mojsilović [24], discontinuous stress fields have been shown to be very efficient and reliable. Moreover, strut-and-tie models have been successfully applied as a simplification to describe the structural masonry response to various loadings [25]. An obvious drawback of these models, since they are based on perfectly plastic masonry behavior, i.e. zero elastic deformation prior to yielding, is that the deformation state cannot be determined. However, since the deformation state is one of the governing parameters for predicting material failure, it is planned to apply the advanced stress field models that can consider the deformation state. These models are actually under development and will be extended in order to incorporate the soft layer modelling it in two ways: as an elastic-perfectly plastic material or as Mohr-Coulomb material with small cohesion. Thus, special attention will be paid to the modelling of the soft layer itself, as well as to the contact between masonry and soft layer.

Similarly, a simplified model of cyclic force-deformation in-plane response of masonry walls with a soft layer will be developed within the OpenSees framework (http://opensees.berkeley.edu), using the advanced stress field model. This model will feature the tri-linear force-deformation response envelope and the unloading and reloading rules that closely mimic the hysteresis response of the tested specimens. This model will be able to reproduce both the in-plane lateral cyclic and the gravity force-deformation characteristics of the structural masonry walls with a soft layer. It will be validated against the test data and verified in a series of in-plane earthquake load time-history response analyses using single-wall models with associated mass mimicking that of a typical masonry building.

Finally, optimization of the mechanical characteristics of the engineered soft layer will be conducted. The parameters that will be investigated and/or optimized are the mechanical characteristics (friction coefficient, stiffness and strength/cohesion) of the soft layer material, the geometry (thickness) of the layer, and the positioning of the layer and mortar in the joint. This investigation will consider existing as well as possible new materials with respect to their compression and shear stiffness. Options for using composite materials with metallic or nonmetallic reinforcement layers will also be considered to increase the deformation capacity and durability of the soft layer and, more important, provide for the desired anisotropic behavior under horizontal (soft) and vertical (stiff) loads. Also, options for using material mixes, including recycled or organic components, will be considered to simultaneously control costs and reduce the environmental burden posed by manufacturing of the soft layers.

The objective function used in this optimization task will be derived from the desired seismic performance characteristics of the structural masonry with soft layers. Assuming a low and moderate seismic hazard environment, the following performance goals are postulated: 1) experience essentially no damage in frequent earthquakes and under high wind loads when the structure is expected to remain elastic; 2) experience controlled damage while preserving the gravity load-carrying capacity in design-basis earthquakes through controlled lateral sliding deformation and an elongation of the structural response period due to low stiffness in the sliding regime; and 3) collapse prevention in beyond-design-basis earthquakes through engagement of the full shear strength of the structural masonry walls. Evaluation of structural masonry wall performance will be conducted using the Pacific Earthquake Engineering Research (PEER) Center probabilistic performance based evaluation framework. A suite of ground motions representing typical regions of low and moderate seismicity in Switzerland and North Italy will be selected and scaled to represent different seismic hazards. Non-linear time-history analyses of the seismic response of a simple single-wall model with a mass and height appropriate for a typical masonry building to an in-plane horizontal component of the ground motions will be conducted. Performance of the wall in terms of its maximum deformation, permanent deformation, and ability to sustain gravity loads during and after the earthquake will be probabilistically evaluated to derive demand fragility curves. Damage data from the tests conducted in this project will then be used to propose preliminary damage fragility curves. These will, in turn, be used to assess if the postulated performance objectives are met, and to evaluate how mechanical and geometric parameters of the soft layer affect achieving the desired seismic performance objectives of the structural masonry walls with soft layers.

Conclusions

The scientific significance of the present research project is, first, in establishing the theoretical model framework for predicting of the behavior of structural masonry with soft layer subjected to seismic actions (the engineering knowledge base), and, second, in the development of the optimal soft layer characteristics for use in structural masonry. At a fundamental level very little research in this area has been done and reported in the literature, thus leaving numerous theoretical and practical questions unanswered. Possible advances established within the present project would improve this situation considerably. Thus, a dissemination of the research findings in the form of conference and journal papers is seen as a very important part of this research project. Experimental verification of the working hypothesis will be carried on using masonry materials produced in Switzerland, but the findings, however, will be generally applicable.

The proposed project is the first step in developing of the soft layer for the seismically loaded structural masonry walls. We plan to extend this research in two directions: one leading towards an optimal design of the "soft" layer and eventual development of a commercial product, and another towards an experimental simulation, analytical modeling, and development of design guidelines for the masonry building structures that utilize the "soft" layer structural walls. This series of project will complete the development of the "soft" layer structural masonry walls from the discovery of basic knowledge through development of enabling technologies to implementation in practice.

References

1. Griffith MC, Page AW. On the seismic capacity of typical DPC and slip joints in unreinforced masonry buildings. *Australian Journal of Structural Engineering* 1998; **1** (2): 133–140.
2. Suter GT, Ibrahim KS. Shear resistance of damp-proof-course materials in brick-mortar joints. *Proceedings of the 6th Canadian masonry symposium* 1992; Saskatoon, pp. 119–130.
3. Zhuge Y, Mills J. The behavior of masonry walls containing a damp-proof course under cyclic loads. *Proceedings of the 2nd Australasian structural engineering conference* 1998; Auckland, pp. 655–661.
4. Kirtschig K, Anstötz W. *Harmonisierung europäischer Baubestimmungen – Eurocode 6 – Mauerwerksbau – Ermittlung der Reibungsbeiwerte von Feuchtesperrschichten*. Institut für Baustoffkunde und Materialprüfung: Hannover, Germany, 1990.
5. Mojsilović N, Simundic G, Page AW. *Static-Cyclic Shear Tests on Masonry Wallettes with a Damp-Proof Course Membrane.* IBK Report Nr. 319, Institute of Structural Engineering: Zurich, 2009.
6. Mojsilović N, Simundic G, Page AW. Masonry Wallettes with Damp-Proof Course Membrane Subjected to Cyclic Shear: An Experimental Study. *Construction and Building Materials* 2010; **24**, (11): 2135-2144.
7. Mojsilović N, Bosiljkov V, Simundic G, Page AW. Assessment of unreinforced brick masonry shear walls with DPC using an experimental and numerical approach, *Proceedings of the 9th Australasian Masonry Conference* 2011; Queenstown.
8. Mojsilović N. Masonry elements with damp-proof course membrane: Assessment of shear strength parameters. *Construction and Building Materials* 2012; **35**: 1002-1012.
9. Mojsilović N, Simundic G, Page AW. Static-Cyclic Shear Tests on Masonry Triplets with a Damp-Proof Course Membrane. *Proceedings of the 12th Canadian Masonry Symposium* 2013; Vancouver.
10. Mojsilović N, Stojadinović B, Barandun A, Vögeli C. Seismic behavior of masonry walls with soft-layer wall bearings. *Proceedings of the 5th International Conference on Structural Engineering, Mechanics and Computation* 2013; Cape Town, pp. 1865-1870.
11. Konstantinidis D, Makris N. Seismic response analysis of multidrum classical columns. *Earthquake Engineering and Structural Dynamics* 2005; **34**: 1243-1270.

12. Ueda N, Onishi A, Shimizu M. Sanjusangen-do. Web recourse: http://www.kyopro.kufs.ac.jp/dp/dp01.nsf/b7eb328e75d9627a49256feb00103b33/081385aed819ec1649256f74001956b0!OpenDocument, 2012.

13. Naiem F, Kelly JM. *Design of Seismic Isolated Structures: from Theory to Practice*. Willey: New York, 1999.

14. Joshi R N. Striking behavior of structures in Assam earthquakes. *Proceedings of the 2nd World Conference on Earthquake Engineering* 1964, Tokyo, **3**: 2143-2158.

15. Arya AS, Qamaruddin M, Chandra B. A New System of Brick Buildings for Improved Behavior During Earthquakes. *Proceedings of the 7th World Conference on Earthquake Engineering* 1980, **4**: 225-232.

16. Qamarudding M, Al-Orami SK, Al-Jabri KS. Worldwide Development of Friction Seismic Isolation Scheme for Masonry Buildings. *Proceedings of the 11th World Conference on Earthquake Engineering* 1996, Acapulco, paper no. 1388.

17. Nikolic-Brzev S, Arya A S. Seismic Isolation of Masonry Buildings – An Experimental Study. *Proceedings of the 11th World Conference on Earthquake Engineering* 1996, Acapulco, paper no. 559.

18. Paulson TJ, Abrams DP, Mayes RL. Shaking-Table Study of Base Isolation for Masonry Buildings. *ASCE Journal of Structural Engineering* 1991; **117** (11): 3315-3336.

19. Zayas V, Low SS, Mahin SA. *The FPS Earthquake Resisting System: Experimental Report*. Technical Report UCB/EERC-87/01, Earthquake Engineering Research Center, University of California Berkeley: Berkeley, 1987.

20. Zayas V, Low SS. Seismic Isolation Retrofit of a Historic Building. *Proceedings of the 1993 National Earthquake Conference*; **2**: 347-356.

21. Kelley JM. Seismic Isolation Systems for Developing Countries. *EERI Earthquake Spectra* 2002; **18** (3): 385-406.

22. Chalhoub M, Kelly JM. Analysis of Infinite-Strip-Shaped Base Isolator with Elastomer Bulk Compression. *ASCE Journal of Engineering Mechanics* 1991; **117** (8): 1791-1805.

23. Moon BY, Kang GJ, Kang BS, Kim GS, Kelly JM. Mechanical Properties of Seismic Isolation System with Fiber-Reinforced Bearing of Strip Type. *International Applied Mechanics* 2003; **39** (10): 133-142.

24. Mojsilović N. *Masonry Subjected to Combined Actions* (in German). IBK Report Nr. 216, Institute of Structural Engineering: Zurich, 1995.

25. Mojsilović N, Marti, P. Strength of Masonry Subjected to Combined Loads. *The American Concrete Institute Structural Journal* 1997; **94** (6): 633-642.