Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe

WP 11: Project #7 – Transnational Access at LNEC

Seismic Response of Masonry Cross Vaults: shaking table tests and numerical validations

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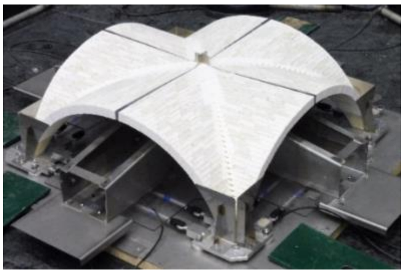
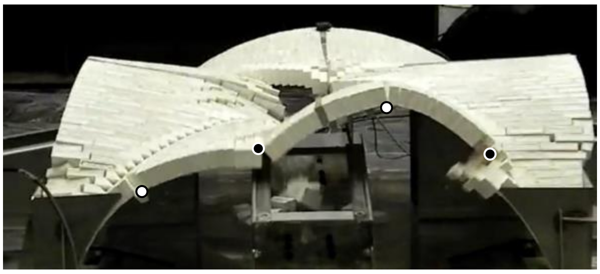
Keywords

Earthquake Engineering, shaking table, masonry structures, cross vaults, retrofitting

Figures





Figures: Masonry cross vault test specimen and collapse mechanism

Main Results

This report introduces one of the H2020 SERA project transnational access experimental activities, involving 3D shaking table tests on masonry cross vaults. Widely spread among monumental masonry buildings (mainly in churches and palaces), masonry cross vaults are some of the most vulnerable horizontal structural elements. Acting as a ceiling and a structural horizontal diaphragm with significant mass, vaults' mechanical behaviour affects the overall seismic response of buildings, in terms of strength, stiffness, and ductility. Moreover, their local damage and collapse may produce significant losses in terms of cultural assets and casualties.

The full experimental campaign consisted of three different testing phases and specimens: a 1:5 reduced scale cross vault made of 3D-printed blocks assembled with dry joints, a 1:1 scale model of a brick unreinforced masonry cross vault and a 1:1 scale model of a brick masonry cross vault reinforced with the TRM technique, covering the lack of knowledge in this field. The overall research project included the initial design of the test specimens, their construction, the preparation of the test setup, the shaking table tests and the analysis and post-processing of results.

The main focus of the research was the study of the shear failure along with the shell of the vault itself, which very often occurs during earthquakes in monumental buildings. From the experimental and numerical studies performed, it was possible to observe a systematic location of the hinges in concordance with Heyman's theory. The shear failure was obtained by designing specific boundary conditions, showing, as expected, the main concentrations of damage along the rib of the vault. The

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730900.

capacity of the structure under dynamic loading is higher than the capacity obtained from previously performed quasi-static tests.

The expected outcomes have been satisfied, namely: evaluation of the maximum acceleration applicable to cross vaults, evaluation of the diaphragm stiffness and ultimate displacement capacity of cross vaults, identification of the damage mechanisms, evaluation of the role of the seismic input on the dynamic response of these vaults, comparison between static and dynamic tests and evaluation of the influence of the test type.

In conclusion, by improving the knowledge and the modelling/analyses approaches of vaulted masonry structures, this research contributes to a better safety assessment of heritage buildings and to a better design of strengthening interventions, thus contributing to an improvement of the safety and preservation policies of heritage buildings in the EU.

List of Publications

Tsionis G., *et al.* (2018) "Technical report on SERA Transnational Access activities TA1-TA10 (M12)," *Deliverable 8.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Tsionis G., *et al.* (2019) "Technical report on SERA Transnational Access activities TA1-TA10 (M24)," *Deliverable 9.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Tsionis G., *et al.* (2020) "Technical report on SERA Transnational Access activities TA1-TA10 (M36)," *Deliverable 10.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Bianchini N., Mendes N., Lourenço, P.B., Calderini, C. & Rossi, M. (2019) "Seismic assessment of masonry cross vaults through numerical nonlinear static and dynamic analysis," *7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2019)*, Crete, Greece.

Bianchini, N., Calderini, C., Rossi, M., Mendes, N., Candeias, P.X., Lourenço, P.B., Campos Costa, A. (2020)"Seismic assessment of masonry cross vaults through shaking table testing on a scaled model under different inputs," *14th World Congress in Computational Mechanics and ECCOMAS Congress*, Paris, France.

Bianchini, N., Mendes, N., Candeias, P.X., Calderini, C., Rossi, M., Lourenço, P.B., Campos Costa, A. (2020) "Seismic performance of masonry cross vaults through shaking table testing on a scaled model," *12th International Conference on Structural Analysis of Historical Constructions (SAHC 2020)*, Barcelona, Spain.

Access to Data and Services

The test results are disseminated to the wider scientific community through the open access experimental database of the SERA project.

WP 11: Project #6 – Transnational Access at LNEC

(Towards the) Ultimate Earthquake Proof Building System: development and testing of integrated low-damage technologies for structural and non-structural elements

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Keywords

Earthquake Engineering, shaking table, performance-based design, self-centering, dissipaters

Figure

Test specimen configurations for the 3 shaking table tests performed

Main Results

This report introduces one of the H2020 SERA project transnational access experimental activities, involving 3D shaking table tests of a two-storey 1:2 scaled fully prefabricated dry-assembled building. It contains two-bay timber-concrete low-damage seismic frames, post-tensioned rocking dissipative timber seismic walls and comprising different low-damage or high-performance non-structural components (fiber-reinforced gypsum and masonry partitions/glass and GFRC facades). The project aimed to promote a research effort within the European environment for the development of an integrated low-damage building system.

The high socio-economic impact of moderate-to-strong earthquakes and the increased public awareness of seismic risk have facilitated the acceptance and implementation of damage-control technologies, whose development is nowadays demanded. Performance-based design criteria and objectives need a shift towards a low-damage design approach and technical solutions for engineers and stakeholders to control the performance/damage of the entire building system, including superstructure, foundation systems and non-structural elements. Moreover, this new design philosophy should be considered to define an ultimate “earthquake-proof” building system.

The full experimental campaign consisted of three different testing phases and specimen configurations, i.e. skeleton building, skeleton building with internal gypsum partitions, and building

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with an integrated system made of an internal masonry wall and exterior envelopes. The overall research project included the initial design of the test building and its structural and non-structural detailing, the construction of the specimen, the preparation of the test setup, the shaking table test and the analysis and post-processing of results.

Concerning the global performance, the specimen behaved as expected with demand parameters coherent with the ones calculated during the design process. Regarding the non-structural components, the in-plane behaviour confirmed the good response of these components due to the introduced non-structural detailing. The out-of-plane accelerations allowed to define the relative amplification factors which were estimated within a range of 2-3 for all non-structural systems when compared to the building levels, apart from the masonry infills where the amplification is found to be around 2.

The dynamic shaking table tests confirmed the seismic performance of the low-damage skeleton for timber-concrete structures. Furthermore, it proved the high potential for implementing an integrated low-damage or high-performance structural/non-structural building solution for the next generation of buildings. On the other hand, the observed (low) damage conditions will suggest improvements to the system detailing to be applied and studied in future research.

List of Publications

Tsionis G., *et al.* (2018) "Technical report on SERA Transnational Access activities TA1-TA10 (M12)," *Deliverable 8.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Tsionis G., *et al.* (2019) "Technical report on SERA Transnational Access activities TA1-TA10 (M24)," *Deliverable 9.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Tsionis G., *et al.* (2020) "Technical report on SERA Transnational Access activities TA1-TA10 (M36)," *Deliverable 10.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Bianchi S., Ciurlanti, J., Pampanin, S., Perrone, D. & Filiatrault, A. (2020) "Seismic demand and performance evaluation of non-structural elements in a low-damage building system," *17th World Conference on Earthquake Engineering*, Sendai, Japan.

Ciurlanti, J., Bianchi, S., Pampanin, S. (2020) "Shake-table tests of a timber-concrete low-damage building: analytical/numerical vs. experimental results," *17th World Conference on Earthquake Engineering*, Sendai, Japan.

Pampanin, S., Ciurlanti, J., Bianchi, S., Perrone, D., Palmieri, M., Grant, D., Granello, G., Palermo, A., Filiatrault, A., Campos Costa, A., Candeias, P.X., Correia, A.A. (2020) "Enhancing seismic safety and reducing seismic losses: overview and preliminary results of SERA Project – 3D shaking table tests on an integrated low-damage building system," *17th World Conference on Earthquake Engineering*, Sendai, Japan.

Access to Data and Services

The test results are disseminated to the wider scientific community through the open access experimental database of the SERA project.

WP 11: Project #19 – Transnational Access at LNEC

Seismic Testing of Adjacent Interacting Masonry Structures

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Keywords

Earthquake Engineering, shaking table, unreinforced masonry, adjacent structures, dynamic interaction

Figures

Figures: Test specimen and numerical models

Main Results

Historical city centres throughout Europe have developed and densified during long periods. The densification caused the historical centres to be characterized by masonry building aggregates. In building aggregates, facades of adjacent buildings often share a structural wall. Furthermore, the connection between the older and the newer units is often made through weakly interlocking stones or by a dry joint. Since the densification was often a process spanning throughout long periods, it is not uncommon for adjacent units to be constructed of different materials, to have different distributions of openings and different floor and roof heights. However, advances in the development of analysis methods for such aggregates have been impeded by the lack of experimental data.

This report thus introduces one of the H2020 SERA project transnational access experimental activities, involving 3D shaking table tests of a half-scale stone masonry aggregate. It consists of two building units with a common wall and different floor heights. The walls are constructed as double-leaf stone masonry without interlocking between the leaves, except at corners and openings. The overall research project included the initial design of the building aggregate, the construction of the specimen, the preparation of the test setup, the shaking table test and the analysis and post-processing of results. It contributes significantly to the collection and dissemination of experimental data on the interaction of building units in order to understand better the phenomena involved in their dynamic behaviour.

To ensure that the results can be compared with previous test campaigns, the construction material was reproduced the one used for previous shaking table tests, as much as possible. Nevertheless, the research project includes a complete set of material characterization tests, including a large number of tests on mortar samples and wallettes tested in simple and diagonal compression.

This project has received funding from the European Union's
Horizon 2020 research and innovation programme under grant
agreement No 730900.

The experimental data produced is also valuable to calibrate adequately the substantial number of complex non-linear models and modelling approaches required to capture the buildings' response. There were numerous participants from academic and professional teams in the blind prediction competition organised within the project, which confirms the interest of the research carried out.

List of Publications

Tsionis G., *et al.* (2018) "Technical report on SERA Transnational Access activities TA1-TA10 (M12)," *Deliverable 8.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Tsionis G., *et al.* (2019) "Technical report on SERA Transnational Access activities TA1-TA10 (M24)," *Deliverable 9.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Tsionis G., *et al.* (2020) "Technical report on SERA Transnational Access activities TA1-TA10 (M36)," *Deliverable 10.1 (WP8-WP17), SERA – EU H2020 Project*. Available at http://www.sera-eu.org/en/home/

Tomić, I., Penna, A., DeJong, M., Butenweg, C., Correia, A.A., Candeias, P.X., Senaldi, I., Guerrini, G., Malomo, D., Beyer, K. (2020) "Seismic testing of adjacent interacting masonry structures," *17th World Conference on Earthquake Engineering*, Sendai, Japan.

Access to Data and Services

The test results are disseminated to the wider scientific community through the open access experimental database of the SERA project.