Organized by:

ROMA TRE UNIVERSITY
Department of Engineering
Structures Research Unit

ENEA CASACCIA
Laboratory of technologies
for sustainable Innovation
SSPT-USER-SITEC

KERAKOLL S.p.A.
Structural reinforcement systems

Supported by:

Shake table tests on masonry walls retrofitted with Textile Reinforced Mortar

Following a recent shake table test series performed on two full-scale walls, one in stone masonry and one in tuff blocks, to study their out-of-plane seismic behaviour, a new investigation will be carried out on the same specimens, after repair and reinforcement was undertaken. To retrofit the masonry walls, Textile Reinforced Mortar (TRM) systems were applied. TRM composites are suitable for the safeguarding of architectural heritage as they are cost-efficient, sustainable and compatible with historic masonry substrates. The TRM systems used in this research comprise either a Ultra High Tensile Strength Steel unidirectional textile (for the tuff wall) or a basalt and stainless steel bidirectional fabric (for the stone wall). Both textiles were applied with lime-based mortar.
Natural accelerograms will be applied in both horizontal and vertical directions, with increasing scaling factor, up to collapse. The walls are provided with a top beam in reinforced brickwork, whose horizontal displacement is constrained by a steel frame connected with the shake table. Test setup is designed to investigate the out-of-plane seismic capacity of the two types of masonry, that will be tested simultaneously, to allow comparisons between their seismic behaviour. Results will be also compared to those obtained on the unreinforced specimens, to measure the gain in seismic capacity provided by TRM reinforcements

Tests will be carried out on:

Tuesday 7 March from 2.00pm to 6:00pm

Wednesday 8 March from 10.00am to 4:00pm

The experimental tests will be shared in real time by DySCO Virtual Lab at the following address:

http://connect.portici.enea.it/tavibr

For attending the tests click on “guest” and write your name, surname and your company name.
For further information, contact Prof. de Felice at the following address: **defelice@uniroma3.it**

Background

Recent earthquakes have clearly shown that existing masonry walls are highly vulnerable against out-of-plane seismic loads. Failure may occur by overturning, bending, leaf separation or disaggregation, depending on the wall section morphology and on the connections between orthogonal walls [1,2]. **Retrofitting solutions** are needed that combine structural effectiveness, economic and environmental sustainability, and possibility of being integrated with maintenance works. To this aim, Textile Reinforced Mortar (TRM) composites [3,4] appear particularly promising but their development is still at a relatively early stage and full-scale tests are needed to study their effectiveness for the protection of the built heritage against earthquakes.

In December 2016, an experimental investigation on the **shake table** was carried out on two full-scale walls, one in stone masonry and one in tuff blocks, to study their out-of-plane seismic behaviour. After the tests, repair and reinforcement was undertaken with **Textile Reinforced Mortar (TRM) systems**, that comprise either a **Ultra High Tensile Strength Steel textiles** (for the tuff wall) or a **basalt and stainless steel fabric** (for the stone wall), applied with **lime-based mortar**. A new shake table test series will be carried out on the strengthened walls to measure the gain in seismic capacity provided by TRM reinforcements.

Experimental investigation on the shake table

Two full-scale wall specimens, 3.7m high and 25cm thick, one in **stone masonry** and one in **tuff blocks**, will be tested on the shake table. The walls are provided with a **top beam in reinforced brickwork**, having high strength steel textiles in the bed joints and with steel connectors to the walls. The testing setup includes a steel frame connected to the shake table that prevented the horizontal displacement of the top beam, leaving free rotations and upward displacements.

The seismic behaviour of the two masonry walls without reinforcement was investigated in a recent experimental investigation. Both the walls failed by the development of horizontal hinges.

Test movies are available at the following links:

https://www.facebook.com/Repubblica/videos/10154916764456151/
http://video.repubblica.it/natura/dall-irpinia-ad-amatrice-cosi-i-terremoti-distruggono-gli-edifici/263244/263608?ref=HREC1-25
http://www.tg2.rai.it/dl/RaiTV/programmi/media/ContentItem-805c50f3-cfa1-4631-ba78-d2119b520739-tg2.html?

Unreinforced wall specimens on the shake table during the previous experimental investigation

Retrofitting with Textile Reinforced Mortars

After the shake table tests carried out without reinforcements, the wall specimens were repaired by replacing some stone units, and by injecting the cracks and the internal voids with a lime-based grout. Then, retrofitting works were undertaken using **Textile Reinforced Mortar (TRM) composites** [3,4] produced by **KERAKOLL S.p.A**.

The tuff wall, made of regular squared blocks, was retrofitted with **Ultra High Tensile Strength Steel (UHTSS) cords**. Cords are galvanized (coated with zinc) to prevent rusting and are spaced 6.35mm. Two 15cm wide vertical strips of steel textile were applied to each side of the wall, for its whole height, and connected to the foundation.

The other specimen, having two leaves of irregular lime stones, was retrofitted with a balanced bidirectional fabric of **basalt fibres**, with 8x8mm grid spacing, that also includes stainless steel wires, that increase the shear strength and ease handling/installation, and an alkali-resistant coating. The basalt mesh was bonded to the whole surface of the wall, on both sides. In order to prevent leaf separation, transversal connectors (made by rolling the steel cord textile) were also installed.

Prior TRM installation, the surface of the walls were cleaned and wet with water. For both the TRM systems, a **lime-based mortar matrix** was used to apply the textiles on the surface of the masonry. The **reinforcements are less than 10mm thick** and, on the whole, their installation required 3 days of two specialized workman. The specimens will be tested after about 40 days from TRM installation.

Textile Reinforced Mortar installation on the stone wall

Textile Reinforced Mortar installation on the tuff wall

Innovative monitoring with the 3DVision system

An **innovative 3D motion optical system** named **3DVision** [5] will be used in addition to accelerometers and displacement transducers, to measure displacements during the shake table tests. 3DVision system makes use of wireless passive spherical retro-reflecting markers positioned on several points of the specimen, whose spatial displacements are recorded by near-infrared digital cameras. Analyses in the time domain will allow the monitoring of the deformations of the walls and the detection of the fundamental frequencies and modal shapes.

Piezoelectric accelerometer and retro-reflecting marker for 3DVision application

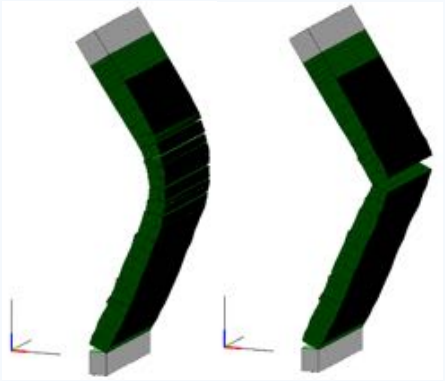
Seismic inputs

Based on previous experience on shaking table tests on masonry specimens [6,7], a set of five natural records was selected for this study amongst the most severe Italian earthquakes of the last 40 years. These input signals, which have already used for the tests on the unreinforced walls, will be applied with increasing scaling factor up to the collapse of the specimens, in both horizontal and vertical directions.

Event	Record	PGA (horizontal)	PGA (vertical)
Iripinia earthquake, 1980	Bagnoli BGI	0.187g	0.101g
Emilia earthquake, 2012	Mirandola MRN	0.262g	0.303g
Amatrice earthquake, 2016	Amatrice AMT	0.376g	0.399g
Umbria-Marche earthquake, 1997	Nocera Umbra NCR	0.423g	0.406g
L'Aquila earthquake, 2009	L'Aquila AQV	0.657g	0.496g

Numerical simulations

The project includes the development of advanced computational tools with distinct elements and macroelements for the assessment of the seismic behaviour of masonry under seismic actions [1,2]. Simulations were carried out to simulate the experimental tests on both the unreinforced and the reinforced specimens. Test outcomes will provide information for the validation of the modelling approaches.



Scientific coordination

The research project is led by Prof. Gianmarco de Felice of the **Department of Engineering of Roma Tre University**. The experimental tests are carried out at the **ENEA Casaccia Research Centre**, under the coordination of Dr. Gerardo De Canio.

Cooperation and Financial support

The experimental investigation is carried out within the following partnerships:

✓**Kerakoll SpA** Research Agreement "*Seismic retrofitting of masonry structures with composites*"

✓**Ministero degli Affari Esteri e della Cooperazione Internazionale** (Italian Ministry for Foreign Affairs), ITALY – USA Science and Technology Cooperation Project Nr. PGR00234 "*Composites with inorganic matrix for sustainable strengthening of architectural heritage*"

✓**Regione Lazio**. Progetto COBRA "*Sviluppo e diffusione di metodi, tecnologie e strumenti avanzati per la Conservazione dei Beni culturali, basati sull'applicazione di Radiazioni e di tecnologie Abilitanti*"

✓**Reluis-DPC** Executive Projects 2017 "*Assessment and Mitigation of Seismic Vulnerability of Existing Masonry Structures*"

✓**Rilem Technical Committee 250-CSM** "*Composites for the Sustainable Strengthening of Masonry*"

References

[1] Mauro A., de Felice G., DeJong M. (2015) The relative dynamic resilience of masonry collapse mechanisms, Engineering Structures, 85:182-194.

[2] de Felice G., De Santis S., Lourenço P.B., (2017) Mendes N. Methods and challenges for the seismic assessment of historic masonry structures. International Journal of Architectural Heritage, 11(1):143-160.

[3] De Santis S., de Felice G. (2015) Tensile behaviour of mortar-based composites for externally bonded reinforcement systems. Composites Part B: Engineering, 68:401-413.

[4] De Santis S., de Felice G. (2015) Steel reinforced grout systems for the strengthening of masonry structures. Composite Structures, 134:533-548.

[5] De Canio G., de Felice G., De Santis S., Giocoli A., Mongelli M., Paolacci F., Roselli I. (2016) Passive 3D motion optical data in shaking table tests of a SRG-reinforced masonry wall. Earthquakes and Structures, 10(1):53-71.

[6] AlShawa, O., de Felice, G., Mauro, A., Sorrentino, L. (2012). Out-of-plane seismic behaviour of rocking masonry walls. Earthquake Engineering & Structural Dynamics, 41(5):949-968.

[7] De Santis S., Casadei P., De Canio G., de Felice G., Malena M., Mongelli M., Roselli I. (2016) Seismic performance of masonry walls retrofitted with steel reinforced grout. Earthquake Engineering & Structural Dynamics, 45(2):229-251.