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CONNECTIONS AND DISSIPATIVE SYSTEMS WITH EARLY WARNING

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ABSTRACT

The global response of historic buildings is determined by the behaviour of the single structural elements as well as by their mutual connections. Consequently, in the last decades a number of technical solutions for the improvement of structural connections have been developed in response to the increasing demand in the field of the seismic protection of heritage assets. At the same time, the experimental assessment of structural strengthening techniques is a well established practice both in the scientific community and among commercial producers. It is therefore surprising how testing of connections is rarely performed and very few codes of practice deal with it. Additionally, the few existing experimental procedures for testing connections are neither standardised nor easily accessible to end users. Within the framework of the EU-funded NIKER project, Work Package 6 aims to address such technical gap through the development of procedures specific to the strengthening of structural connections of historic buildings.

Keywords: *Seismic strengthening, Structural connections, Heritage buildings*

1. INTRODUCTION

Strengthening of connections draws on the same principles at the basis of the construction of reinforced connections in historic construction. When connections between structural elements have sufficient capacity, vertical and horizontal loads are better distributed, out-of-plane damage mechanisms are prevented and failure of floors and roofs can be avoided [1]. Historically, builders mastered the art of careful detailing of joints from a process of trial and error [2]; today's engineers and architects posses the necessary insight into the physical and mechanical laws governing the dynamic of structures to control the process of structural upgrading. When existing connections lack adequate capacity, further elements are added to the original structure so as to achieve the performance required by codes [3, 4]. However, requirements and prescriptions regarding the strengthening of connections are mainly qualitative [4], so that end users are left with the difficult decision of how to dimension strengthening elements and where to source the values to use in the design process. Surprisingly, the technical literature offers very few examples that could be used as guidelines [5-8], despite the wide range of products available on the market and reported in various publications. Testing has instead a crucial role in scientific research and the standardisation and homogenisation of

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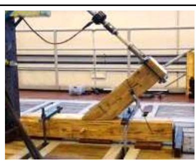
experimental procedures is fundamental to achieve a consistent method for the preservation of cultural assets and protection of human lives.
Within the framework of the FP7 Niker project (Grant No 244123), Workpackage 6 (WP6) aims to tackle the lack of both standard procedures and quantitative data by carrying out a number of tests on structural connections so as to characterise their performance before and after the strengthening by different techniques. WP6 focuses on the shift in design philosophy of seismic strengthening for heritage buildings, from the enhancement of strength or displacement capacity to the control of damage through energy dissipation.
The paper gives an overview of the development of some of the laboratory procedures carried out by the various partners as part of the Work Package and summarises the results, highlighting how these can be used to provide end users with guidance for testing and design.

2. EXPERIMENTAL PROGRAMME

Currently many strengthening techniques are tested as part of larger upgrading design involving samples of whole buildings, whereas very few set-ups focus on connections only. WP6 aims to tackle this gap and to develop a set of procedures whereby the response of the connection can be isolated from the global behaviour of the structure.

Table 1 Summary of tests performed within WP6

Type of specimen	Specimen	Materials – Description of the structure	Partner	Testing	
				Type of tests	Strengthening
Single element of the connection		English-bond brickwork masonry	UBATH/ CINTEC	Monotonic pull-out	Metallic grouted anchors
Whole connection		T-shaped double-bond brickwork masonry	UBATH/ CINTEC	Pseudo-static cyclic	Metallic grouted anchors
Single element of the connection		Earth block masonry/ rammed earth/ cob wall panels	BAM	Monotonic pull-out	GFRP/metallic grouted anchors
Whole connection		Timber halved dovetail roof joint	ITAM	Dynamic cyclic	Various (e.g. carbon plates, nails, high-friction plates, oak plates, pin)
Whole structure		Three-leaf stone masonry walls with horizontal timber structures	NTUA	Recorded signals on shaking table	Timber-lacing
Single element of the connection		Rubble stone masonry panels	UMINHO/ MONUMENTA	Monotonic pull-out	Grouted metallic anchors
Whole connection		Rubble stone masonry panels and timber beams	UMINHO/ MONUMENTA	Monotonic pull-out	Metallic L profile bolted to beam and anchored to wall

Three typologies of experimental set-ups have been adopted for the tests, namely:

- A single structural element. The action applied to the specimen represents the reaction of the remaining part of the connection, this being transmitted via a strengthening element;
- The whole connection, this being in the unreinforced or strengthened set-up;
- A whole structure. Strengthening is placed at connections only so as to analyse its effect.

Some of the procedures proposed draw on existing methodologies, yet are modified to focus on the parameters critical to the definition of the performance of strengthening systems and to take into account aspects specific to innovative techniques, i.e. those strengthening methods that are being developed and refined within the framework of the project. Tests include unreinforced specimens and specimens either reinforced by traditional techniques or strengthened by modern systems (Table 1). This will provide end users with guidelines both for assessing the performance of connections in the current lay-out (unreinforced or with reinforcement elements embedded in the original structural lay-out) and ruling in or out strengthening by a specific technology.

3. EXPERIMENTAL RESULTS

3.1 Cyclic tests on T-shaped walls

The purpose of cyclic tests is to analyse the behaviour of a connection between two vertical walls, strengthened by steel anchors or steel anchors in series with the dissipative anchoring devices jointly developed by the UBATH and CINTEC [9]. Samples are T shaped walls where the 'leg' of the T reproduces the wall parallel to the main seismic action, whereas the 'head' of the T represents a section of a wall undergoing out-of-plane damage. Cintec International Ltd's grouted anchor technology © is used: anchorage plates are not necessary as the pulling force is transferred to the masonry by a shear mechanism rather than a bearing mechanism.

Experimental results show that strength-only anchors improve the load capacity of the connection in respect to an unreinforced scenario (Fig. 1); dissipation of energy, calculated as the area of the hysteresis loops in the load-displacement graphs, is also enhanced (140%). However, such improvement largely depends on the local geometry of the anchors (Fig. 3). Indeed, due to the low capacity of the masonry substratum, failure of the bond between the grouted anchor and the parent material occurs early (Fig. 2 and Fig. 3), so that the overturning force is transmitted to the anchor mainly through mechanical locking rather than shear. However, the development of mechanical locking is less controllable than chemical bonding as it is influenced by the presence, amount and shape of voids within the masonry. Hence, the performance of strength-only anchors can be hard to predict and damage to the masonry is recurrent, this being a drawback in case of historic materials.

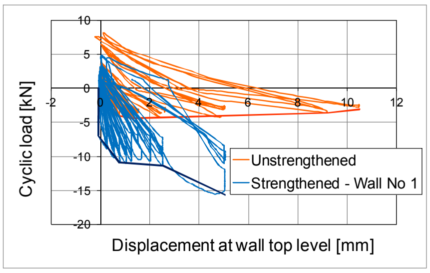


Fig. 1 Comparison between unreinforced specimen and specimen strengthened with standard ties

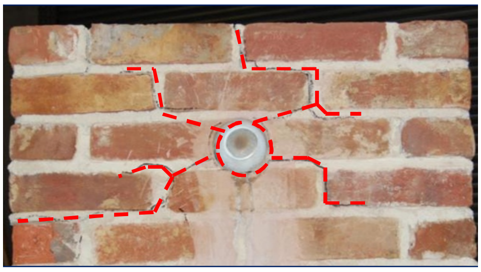


Fig. 2 Mode of failure of strength only anchors

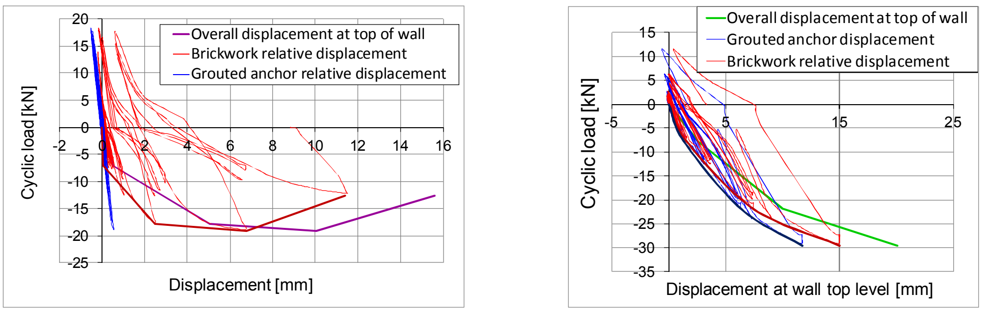


Fig. 3 Load-diplacement curves of strength-only anchors showing influence of pull-out failure of anchor on the overall performance of the connection

When a friction anchoring device is used in series with the strength-only anchor, the overall performance of the connection is considerably improved (Fig. 4): the device is able to allow relative displacements between the two structural elements; movements are activated for a chosen level of load, which overcomes the static friction within the devices, triggers sliding but it is still within an acceptable limit to prevent pull-out failure of the anchorage and extensive damage to the masonry. Most importantly dissipate energy in a stable manner as can be seen from the shape of the cycles.

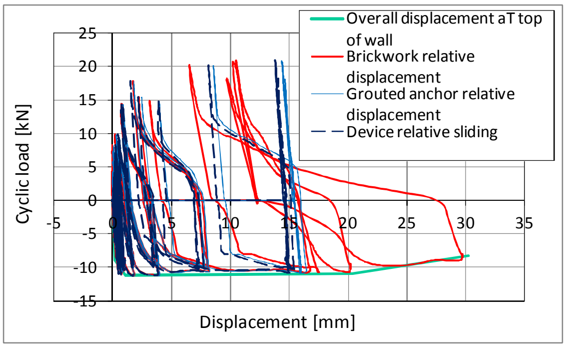
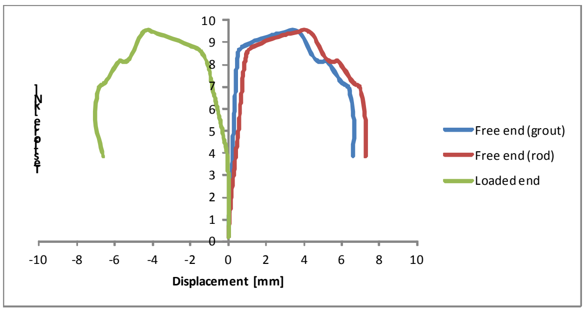


Fig. 4 Load displacement curves of anchors in series with a frictional device

3.2 Pull-out of anchor pins in earthen materials

Typical damage typologies of earthen buildings in seismic areas mainly consist of failure at the connections wall-wall and wall-floor/roof; commonly used retrofit solutions involve dowel pins, nails and anchors, although the effectiveness of these techniques is not empirically supported by appropriate testing nor is it thoroughly described or analytically justified in the literature. Therefore, a set of 31 pull-out tests is carried out to investigate the bond strength of tie rods in earthen materials. Tests focus on the influence of the relatively small water absorption capacity of hydraulic lime grouting compared to three different earthen materials: earth block masonry, rammed earth and cob.



a)


b)

Fig. 5 a) Load-displacement curves of samples with GFRP rods with nuts and b) anchor after completion of testing

Tests show that tie rods improve the quality of connections for structural earthen materials, although it should also be highlighted that a number of factors, such as the hydration conditions of the binder and the pressure adopted during the grouting, can influence the capacity of the assembly.
Two modes of failure are observed (Fig. 5): 1) failure at the interface between injected plug and earthen material and 2) failure at the interface between injected plug and rod. The bond strength capacity is mainly influenced by the injection pressure, and can be enhanced by screwing a set of nuts on the anchor bar, this being a readily available and cheap system to achieve a better performance.
Best performance is achieved in the case of metallic anchors with nuts in earthen block masonry.

3.3 Cyclic tests of dovetail halved joints of timber roof

Cyclic tests draw on previous experimental work [10] and are designed to simulate the real dynamic behaviour of a dovetail halved joint isolated from the other elements of a roof frame. Samples are placed into a special testing rig (Fig. 6a) that enables pseudo-static cyclic loading and ensures the static stability of specimens and their response only in the direction of loading. The purpose of tests is to analyse the effectiveness of strengthening interventions on joints from the point of view of dissipative properties and change in stiffness. Different typologies of strengthening, like the addition of combined damping/reinforcing elements, e.g. steel nails, or damping elements only, e.g. brake plates (Fig. 6b), are investigated in order to describe the influence of various parameters on the improvement of the seismic capacity of the joint.

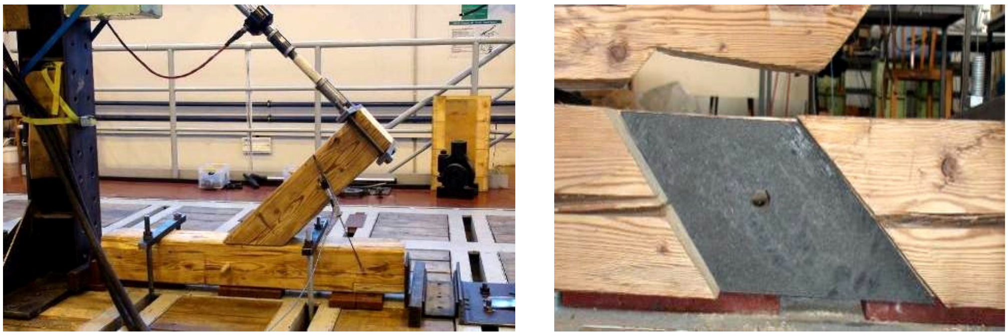


Fig. 6 a) Test set-up and b) Example of strengthening by high-friction plates

Best results in terms of dissipated energy are achieved for the joint strengthened with a combination of two plates with a high friction coefficient and a steel bolt whereby the prestress applied to the joint and hence the friction force between the plates is controlled (Fig. 7a). The greater the degree of prestress, the greater the frictional force is. However, the maximum value of the friction force is limited by the compressive deformation of wood. The brake plates fully fixed to wood with screws were the most effective. As an alternative to brake plates, oak plates can also be used, although their dissipative capacity is lower (Fig. 7b). Good results were also achieved by strengthening the joint with steel nails also in combination with the inserted plates. However this technique is not effective for successive loading events due to residual deformations that create gaps between the contact surfaces of nails and wood and impair the dissipative capacity during successive loading sequences.

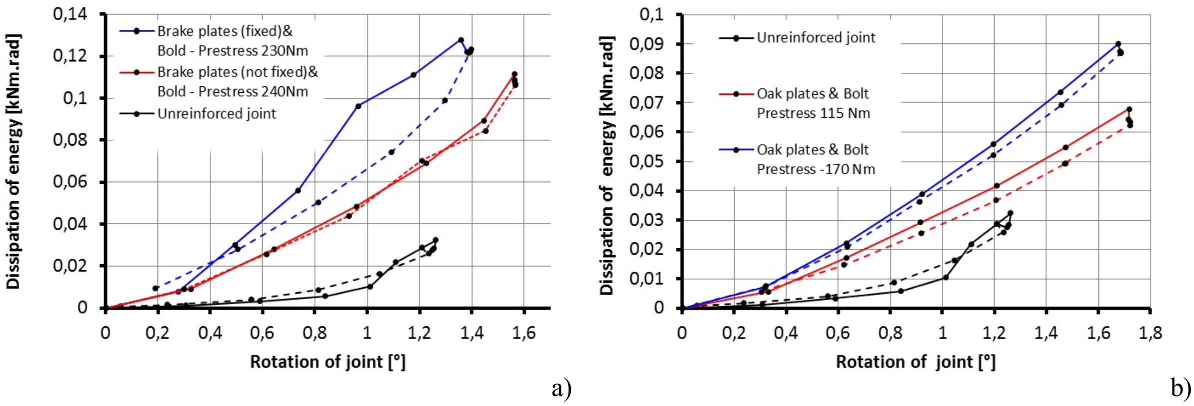


Fig. 7 Dissipation of energy as function of rotation of joint reinforced with: a) bolt and brake plates; b) bolt and oak plates. Solid line: increasing rotation amplitudes; dashed line: with decreasing rotation amplitudes

3.4 Shaking table tests of timber laced structure

Timber laced buildings constitute a common structural system in earthquake prone areas all over the world, yet they have not been investigated in a systematic way to date. Shaking table tests carried out within the NIKER project have the purpose of assessing the effect of horizontal timber ties on the connection between walls, as well as on the connection of the exterior leaves of masonry. Both an unreinforced specimen and a specimen reinforced by timber lacing are tested for increasing levels of input signal (Kalamata earthquake, Sept. 13th, 1986, Ms=6.2); sample geometry and materials, as well as input signal are the same in both cases.

Shaking table tests prove that the presence of timber structural elements within the masonry and of timber ties in the corners of the building increased the load capacity of the unreinforced model by 30%. Moreover, the formation of cracks for the reinforced model is significantly delayed: For the unreinforced model, damage starts forming at 60% of Kalamata earthquake, whereas for the timber-laced specimen cracks occur at remarkably higher values of pga (120% of signal input). Wall-to-wall connections are significantly improved thanks to the presence of timber elements (cracks are limited to the upper part of the structure and a reduction of crack width of more or less 50% are recorded at failure). Furthermore, as shown in Fig. 8, a better connection between leaves is provided thanks to the timber ties (reduced width and limitation of detachment in the upper part of the specimen). By comparing the values of the dynamic characteristics of the two specimens (Table 2), it is evident that the frequencies of the two fundamental modes in X and Y direction are closer in the case of the timber-laced specimen, thus suggesting an enhanced box-like response for this structure.

Fig. 8 Detachment of the leaves of the three-leaf masonry at the roof of the a) unreinforced (90% input signal) and b) timber-laced specimen (120% input signal)

Table 2 Dynamic characteristics of specimens

Specimen – Test	Direction	Frequency (Hz)
Unreinforced	X	6.10
	Y	4.35
Timber-laced	X	8.25
	Y	6.59

Moreover, both maximum displacements relative to the base (Fig. 9) and accelerations (Fig. 7) at the top level of the timber-laced specimen are far lower than those of the unreinforced specimen for the same level of seismic input.

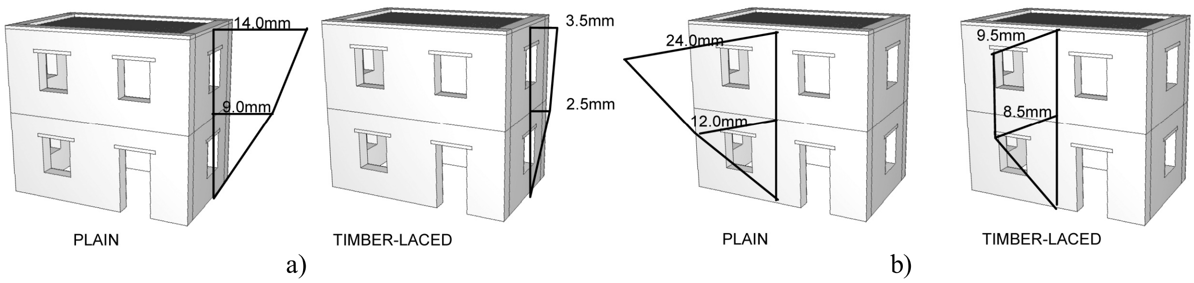


Fig. 9 Maximum displacement along a) X and b) Y direction of the unstrengthened and timber-laced buildings for 90% of Kalamata earthquake

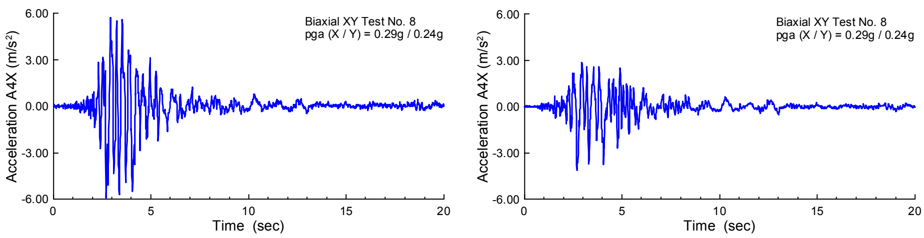


Fig. 10 Acceleration time histories at the midlength of the top floor for 90% of Kalamata earthquake. (a) unreinforced building; (b) timber-laced building

3.5 Monotonic tests of wall to horizontal timber structure connection

Monotonic tests aim to tackle the lack of experimental data regarding the influence of connections on the seismic behaviour of historic buildings, such as 'Pombalino' and 'Gaioleiro' buildings, which are typically found in Lisbon. The configuration, geometry and materials chosen for the specimens are indeed representative of this typology of structures. In order to assess and compare the seismic performance, a full characterization of the behaviour of connections as well as of the materials that are part of both original and strengthened connections is performed.

Wall-to-floor connections are studied by testing unstrengthened and strengthened specimens (Fig. 11a): rubble stone masonry panels feature a set of perpendicular timber beams nailed to a timber beam lying along the plane of the wall. Specimens are strengthened with a system involving steel ties installed with a slanted angle, anchoring the timber beams to the masonry wall, with anchor plates placed on the external surface of the wall (Fig. 11b). The pull-out load is applied on the timber pavement beam, using a metallic clamp.

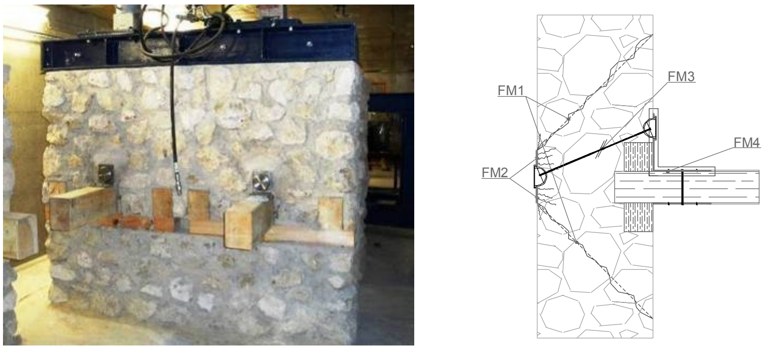


Fig. 11 Specimens set-up: a) general view and b) lay-out of strengthening element and expected failure mode

For unreinforced specimens the overall capacity is determined by the capacity of the nails connecting the beam embedded in the wall to the floor beams perpendicular to the wall (Fig. 12a) In the case of strengthened specimens, failure modes are instead related to the masonry. Indeed, failure occurs by punching of masonry, forming a conical shape (Fig. 12c). Crushing of the masonry under the anchor plate is also observed as well as bending of the bolts connecting the strengthening plate to the timber beam. Overall an increase of the capacity of the connection by 8.5 times is achieved by strengthening (Fig. 12b).

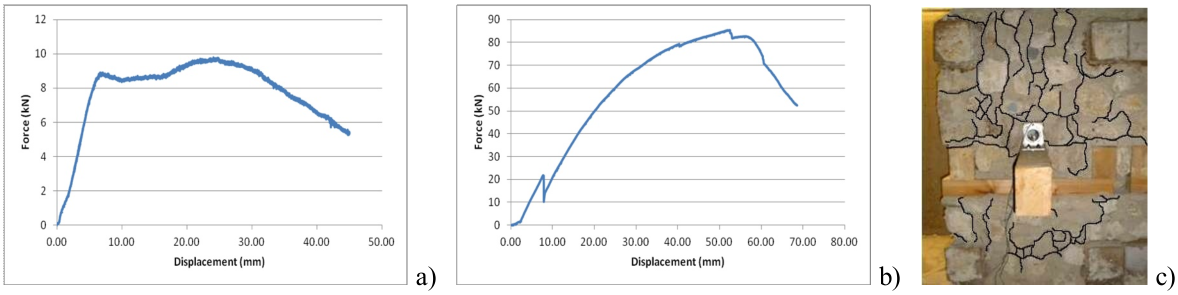


Fig. 12 Load-displacement curves of: a) unreinforced specimen and b) strengthened specimen.; c) failure mode of strengthened specimen

4. DISCUSSION AND CONCLUSIONS

The paper briefly reports the main results of a set of tests performed according to the innovative procedures developed within the framework of the NIKER-Work Package 6 to the purpose of tackling the lack of a systematic approach to the experimental assessment of unreinforced, reinforced and strengthened structural connections. While most strengthening research work focus on single structural elements or the structure as a whole, the few publications focusing on the response of connections lack the necessary homogeneity and standardisation to allow for a direct comparison between different retrofit techniques.

To achieve a consistent method for performing tests and collecting experimental results, project partners collated, classified and standardised a list of parameters that can be used to describe how each strengthening system works and what level of performance it can achieve as shown in Table 3. By quantifying, validating and grading the importance of these parameters, WP6 aims at providing end users with both experimental results and, more importantly, guidelines for performing further tests and for designing the retrofit interventions. Indeed, parameters allow for the comparison of the achieved levels of performance of different techniques against expected/required levels of performance, which are derived from design codes and guidelines or are determined depending on the application.

Table 3 Selection of performance parameters as derived from the testing procedures of WP6

Typology of strengthening	Performance parameters	Achievable range	Expected range
Grouted metallic anchors in brickwork substratum	Tensile capacity of the assembly depending on $\mathbf{f_{b\ b/p}}$: bond strength binder/parent material (N/mm^2) calculated on the cylindrical surface of the grouted socket	For tested weak brickwork masonry (f_c = 3.1 MPa, f_w = 0.5 MPa), calculated from tests as: $\mathbf{f_{b\ b/p} = f_b = F_{b/p\ bond}/A_{hole}}$ with $\mathbf{F_{b/p\ bond}}$ recorded load at failure and $\mathbf{A_{hole}}$ inner cylindrical surface of drilled hole: 0.26 MPa (CoV 34%) 0.4 MPa	Calculated as: $\mathbf{f_{b\ b/p} = f_{vk} = f_{vk,0}+0.4\sigma_d}$ [11] with $\mathbf{f_{vk,0}}$ initial shear strength and $\boldsymbol{\sigma_d}$ vertical load. For tested conditions it would be expected: 0.08 MPa 0.06 MPa
Grouted GFRP/ metallic anchors in earthen material substratum	$\mathbf{f_{b\ b/p}}$: Bond strength binder/parent material (N/mm^2) calculated on the cylindrical surface of the grouted socket	Calculated from tests as: $\mathbf{f_{b\ b/p} = f_b = F_{b/p\ bond}/A_{hole}}$ with $\mathbf{F_{b/p\ bond}}$ recorded maximum load and $\mathbf{A_{hole}}$ inner cylindrical surface of drilled hole: Cob: 0.24 MPa (GFRP anchors + nuts)	No reference value or parameter is found in technical literature or design codes
Strengthening of dovetail halved roof joint using combination of: 2 brake plates or 2 oak plates with bolt (prestressing element)	Energy dissipation calculated as area of hysteresis loops of joint (Nm·rad) and depending on: a) Coefficient of friction of plates (oak and brake plates: μ=0.4 [12, 13]) b) Bolt prestress level applied by torque (Nm) and limited by compressive strength of wood (spruce 2.0-2.5 MPa) [14]	Increase of energy dissipation in comparison with unstrengthened joint: a) Bolt with brake plates: – 180% (torque: 90 Nm) – 410% (torque 230 Nm) b) Bolt with oak plates: – 90% (torque: 90 Nm) – 240% (torque 170 Nm)	Minimum increase of energy dissipation in comparison with unstrengthened joint calculated as: $I_{min} = \mu_{plate}/\mu_{spruce}$-1 = 100% μ_{spruce} = 0.2 Coefficient of friction of wood of joint (spruce; see [13])
Timber lacing	Crack opening at wall to wall connection	Reduction of the order of 50%	Reduction [4]
Metallic ties with end plate at connection between rubble stone masonry and timber elements	Tensile capacity of the assembly depending on $\mathbf{f_{c/p}}$, strength of parent material to punching failure (N/mm^2)	Calculated from tests as: $\mathbf{f_{c/p} = F_{cp}/A_l}$ with $\mathbf{F_{cp}}$ pull-out force and $\mathbf{A_l}$ failure surface defined as trunked cone surface, with smallest base corresponding to anchor plate, apothem inclined at 45° and height equal to wall width. 0.13MPa	Calculated as: $\mathbf{f_{c/p} = f_{vk} = f_{vk,0} + 0.4\sigma_d}$ [11] with $\mathbf{f_{vk,0}}$ initial shear strength and $\boldsymbol{\sigma_d}$ vertical load. For tested conditions ($f_{vk,0}$ = 0.1 MPa, σ_d = = 0.2 MPa) it would be expected: 0.18 MPa

Furthermore, parameters are identified by subdividing the strengthening system into elements to which one type of failure controlled by a single parameter can be associated. This means they can be used to identify the capacity of each element in the anchor assembly and to correlate experimental data with a mathematical model that allows for the dimensioning of the strengthening system according to a capacity hierarchy. As such WP6, contributes to the creation of a standardised system for the assessment of structural connections that can be readily implemented in the current engineering practice. Further experimental work will be carried out in the following tasks of the NIKER project.

REFERENCES

[1] D'Ayala D., Paganoni, S. (2010). Assessment and Analysis of Damage in L'Aquila Historic City Centre after 6th April 2009. *Bulletin of Earthquake Engineering*, 9(1):81-104.

[2] D'Ayala, D. (2011). The role of connections in the seismic resilience of historic masonry structures. In *Proc. ANIDIS*, Bari, Italy.

[3] Italian Ministry of Cultural Heritage and Activities (2006). Guidelines for Evaluation and Mitigation of Seismic Risk to Cultural Heritage.

[4] EN 1998-3:2005. Eurocode 8- Design of Structure for Earthquake Resistance. Part 3: Assessment and retrofitting of buildings.

[5] Zuccarello F.A., Milani G., Olivito R.S., Tralli A., (2009). An Experimental Analysis of Unbonded Brickwork Panels Laterally Loaded. *Construction and Building Materials*, Vol. 23, pp. 2093-2106.

[6] Al Shawa O., Bellisario M., Benedetti S., de Felice G., Mauro A., Paolacci F., Nicola R., Roselli I., Sorrentino L. (2009). Prove sperimentali su tavola vibrante di pareti murarie sollecitate fuori piano. *ReLuis, progetto di ricerca n.1* (in Italian).

[7] Indirli M., Castellano M.G. (2008). Shape Memory Alloy Device for the Structural Improvement of Masonry Heritage Structures. *International Journal of Architectural Heritage*, Vol. 2, pp. 93-119.

[8] Dowling D.M., Samali B. (2006). Low-Cost, Low-Tech Means of Improving the Earthquake Resistance of Adobe-Mud Brick Houses. In Proc. *International Conference on Earthquake Engineering – ICEE 2006*, Lahore, Pakistan.

[9] D'Ayala, D., Paganoni, S. (2011). Performance Based Earthquake Damage Assessment & Development of Dissipative Retrofit Devices for Masonry Buildings. *Newsletter of the Society for Earthquake and Civil Engineering Dynamics*, Vol. 23(1): 1-15.

[10] Drdácký, M., Wald, F., Mareš, J., Sokol, Z. (2000) Component Method for Historical Timber Joints. In *The Paramount Role of Joints into the Reliable Response of Structures*, ed. C.C. Baniotopoulos and F. Wald, NATO Science Series, pp. 417-424, Kluwer Academic Publishers, Dordrecht/Boston/London, 2000.

[11] EN 1996-1-1: 2005. Eurocode 6 – Design of Masonry Structures, 2005.

[12] R.A. Serway (1995). Physics for Scientists and Engineers, 4th edition, Harcorut Brace College Publishers, Orlando, Florida, USA, p. 126.

[13] http://www.sittech.cz/brzdove/6800.htm.

[14] Leonardo da Vinci Pilot Project (CZ/06/B/F/PP/168007) (2008). Handbook 1, 2: *Design of Timber Structures according to EC5*. Educational Materials for Designing and Testing of Timber Structures. TEMTIS.