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FLEXURAL OUT-OF-PLANE RETROFTTING TECHNIQUE FOR MASONRY WALLS IN HISTORICAL CONSTRUCTIONS

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Abstract. *The paper presents a recent technology for the out-of-plane flexural strengthening of historic masonry walls. The method is based on the forming of an irregular net following the joint texture of the wall, which would be able to work in tension. The applied net can be hidden by repointing the joints. This way the technology does not cause visual alteration to walls without rendering, respecting their authenticity. An ongoing research in Portugal is aiming to increase the workability and efficiency of the technique by developing a new anchor element for the application of the net. The discussion includes the introduction of the method and partial results of the research from the University of Minho, Portugal.*

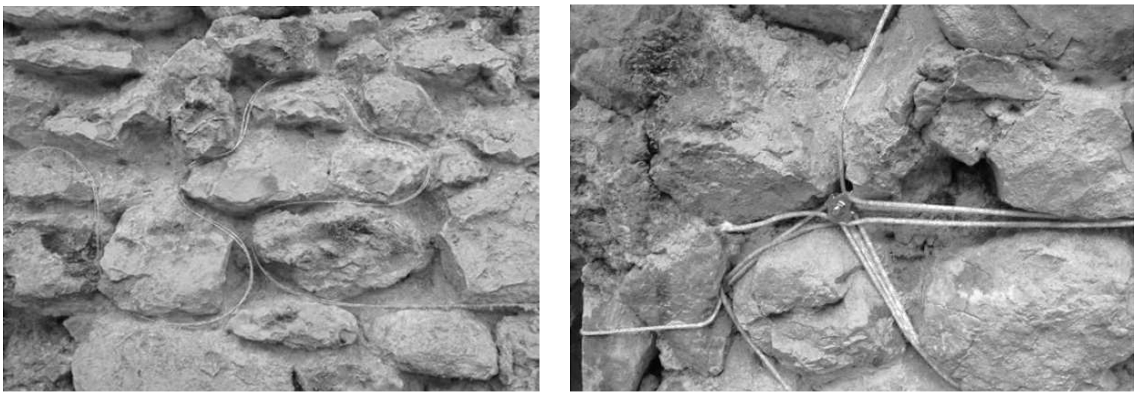
1 INTRODUCTION

Historic ruins – vacant buildings without floors and roofs; parts of ancient walls; partially destroyed castle walls or archaeological sites – representing high heritage value are unlike the current masonry buildings. These buildings are often only supported in their foundations, cantilevering with no connection to any other construction element that would function as bracing. Other types are left without horizontal support between the roof structures and their foundations, acting as thin supported wall beams. These structures are extremely vulnerable to seismic and wind effects, as they can have very low resistance against out-of-plane actions. It is difficult to find a technique, which is especially developed for the structural consolidation of these types of constructions and at the same time does not adversely affect their authenticity (see on Figure 1).

Figure 1: Additional bracing structures visibly damaging the authenticity of ruins in seismic area

In case of historic buildings it is a common mistake to misunderstand the structural behaviour. Most of the types of historic floors are not able to transport the horizontal forces to the shear walls, therefore the global structural (box) behaviour is often hard or not possible to be activated [12] without serious alterations. This possibility needs to be investigated with special care [4,8] as these building types are often under use or can be visited. If more structural integrity cannot be provided, the historical walls need to be strengthened against out-of-plane actions. In this case, increasing flexural capacity and stabilization becomes important.

Among the known ways of acceptable reinforcing [1,2,7,9,10,11,13], an innovative technique was developed by Borri in Italy [5] called the "reticulatus". The technique is unique in its way of adapting a reinforcing mesh to the joint-system of irregular stonewall types, allowing the reinforcement of unrendered irregular stone walls. The continuous mesh of steel (or polyethylene) cords is embedded in the repointed mortar joints, and at the nodes it is anchored to the wall by means of transversal metal bars, as can be seen on and Figure 2. Alternatively, Polyethylene cords were used in a previous experiment to increase resistibility of mesh. Strengthened historic wall prisms were subjected to shear tests, during which the technique proved to be more efficient than jacketing with glass fibre reinforced polymer net. An increase of capacity in compression and flexure was also expected, however yet not proved with experiments. The lack of extended testing and the relatively high labour time supports the need for further investigation and development.



a) b)

Figure 2: Reticulatus: (a) Ultra High Tensile Strength Steel cords; (b) Ultra High Molecular Weight Polyethylene cords [5].

Following the main idea of Borri a research was started at the University of Minho in Portugal, with the aim of (1) starting a test campaign that investigates the full structural capacity of stone walls reinforced with this technique, and (2) develop special constituents and equipment to increase the workability of the technique. The present article explains the results of the first series of tests and presents the developed equipment that helps the application of the reinforcing system.

2 THE TECHNIQUE

Considering the key aspects of the "reticulatus" [5], an external strengthening technique is proposed for the flexural strengthening of historic masonry. The reinforcement is chosen in a way to be able to follow the joint texture in shallow depth, and to adapt even 90° in intersections of joints (see the sketch of the technique in Figure 3). With appropriate refilling of joints, the reinforcement is hidden, and no visual damage is done on the structure.

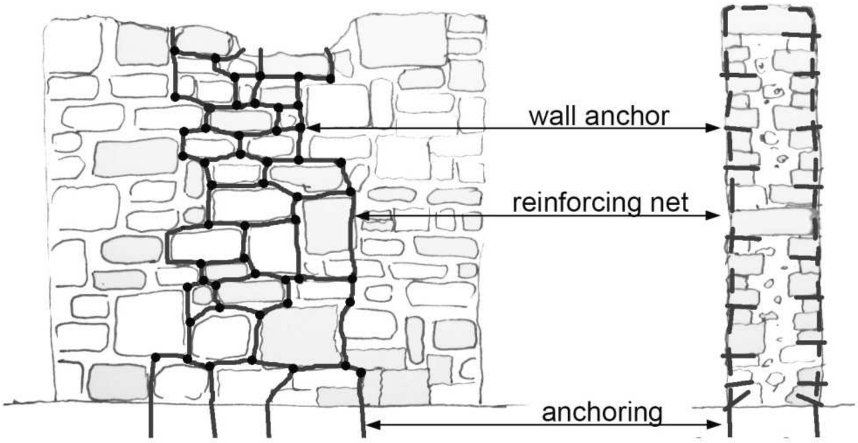
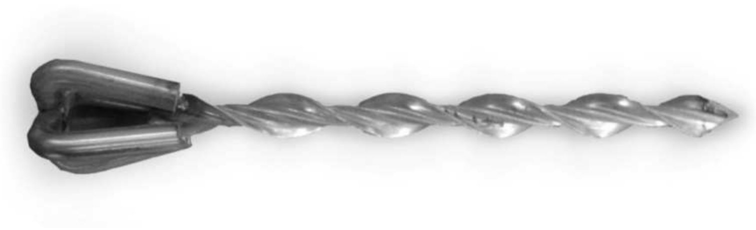


Figure 3: Implementation of "reticulatus" as flexural strengthening technique

2.1 Elements involved

The research aims to decrease labour time by implementing a helical shaped bar and developing a special head creating the Heli®-needles as anchors (as you can see on Figure 4).

(a)



(b)

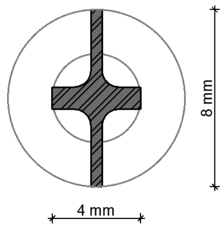


Figure 4:Prototype of heli-needles: (a) rounded head evolution; (b) cross section of a ϕ8 helibar

The head allows the passage of cords and does not allow them to fall out of the joints. The special heli®-needle allows an easy application with a simple tool that was especially developed for this purpose (see it on Figure **5** and Figure **6**). The helical bar penetrates the joint with a rotation while it is inserted. The special hammer-head is able to (a) rotate with the bar, and (b) enter the joint with the heli-needle for full insertion, allowing the connectors to be hidden in the joints.

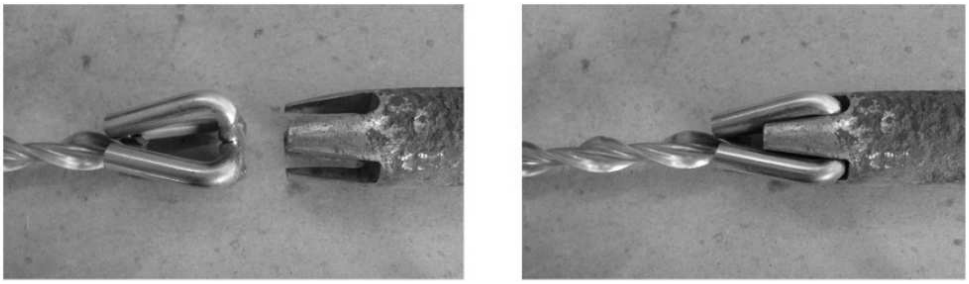


Figure 5: special hammerhead with the Heli®-needle

Figure 6: Insertion of Heli®-needle with the hammerhead prototype.

Starting and finishing connections are playing an important role in the efficiency of the method, as forces are expected to be transmitted to the wall there. The bottom connection must be placed lower than the height of the expected plastic hinge. Top connections can be made on both sides of the wall, or – with additional elements for protection on edges – the reinforcement can be passed over the wall and integrate the two sides. The chosen connection types have to be strong enough for load transition. Further investigation is planned to find the most appropriate ways of starting and finishing anchoring for different wall types. Together with these connections the way of adequate prestressing is also being investigated with the aim of developing a tool that allows easy application of prestress to the reinforcing mesh.

2.2 Application

The system includes the following steps in application

1) Removal of the mortar from the joints in a depth of 2 to 3 cm, to be able to embed the reinforcing grid
2) Introduction of helical stainless steel needles in masonry cross joints (where horizontal and vertical joints meet). Before the application of needles a pre-drill is made with a diameter smaller than the diameter of the heli-needles, in order to make the insertion easier. Subsequently the connectors are inserted by hammering with the device designed for this purpose;
3) The end of the needles close to the wall surface, is equipped with a head which allows the passage of cables or ropes (see Figure 7);

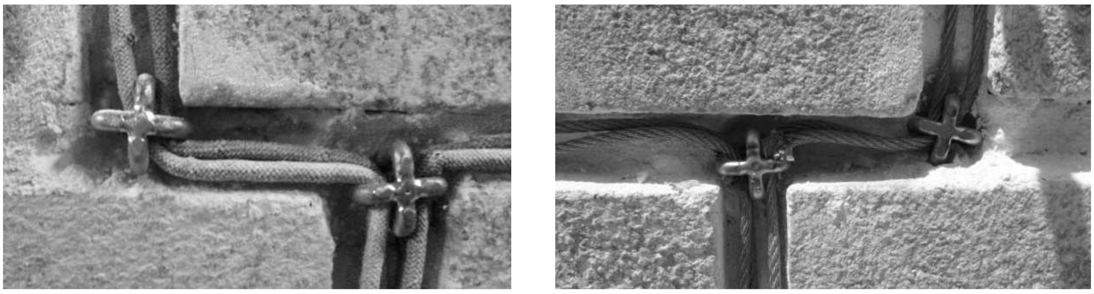


Figure 7: Synthetic and wire ropes passing in the joints

4) The cables / ropes together with the special connectors are creating irregular, distributed armour in the joints. The cables have 2 or 4 mm in diameter, in order to be flexible enough to follow the mortar joints and adapt angles of 90°. The cables should be placed to provide the desired orientation for a better resistance against bending stresses;
5) After the application of cables, all joints are repointed with the appropriate mortar, so that the reinforcement system would not be visible.

When the walls – reinforced with this system – are subjected to out-of-plane bending forces, the cables / ropes will work in tension. The adaption of helical rods for anchoring the cables is expected to improve the efficiency.

The main characteristics of this system are:

- Cables can be applied on both sides of the wall, so the strengthened structure can resist positive as well as negative bending moments;
- As the reinforcement is placed near surface, the useful height of a bending resistant cross section is quasi equivalent to the thickness of the wall;
- The required work is simple, equipment is easy to handle, and does not require skilled labour;
- The invasiveness of the technique is superficial and only affecting joints, similarly to a shallow structural repointing.
- Reinforcement is not visible after repointing;
- The authenticity of historic building is safeguarded;

3 CHARACTERISATION OF CONSTITUENS

As the first set, tensile tests of stainless steel cables and tensile tests of synthetic ropes were done to characterize mechanical properties of the system components. The results were used to start the analytical investigation and to improve the proposed technique.

Two types of cords were tested as mesh components. The influence of handmade connections was taken into account: (1) single and double sleeves in the case of wire ropes (See it on Figure 8); and (2) simple knots in the case of synthetic ropes to reduce labour time and increase workability (as you can see on Figure 9).

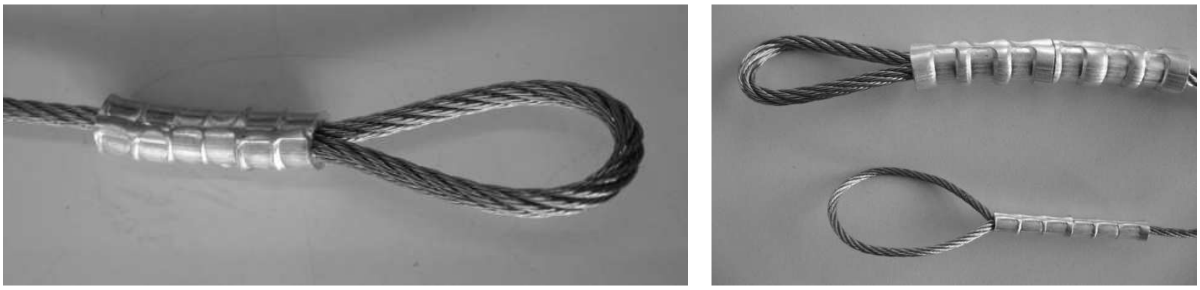


Figure 8: Single and double sleeves applied as connector elements on φ2 φ4 wire ropes

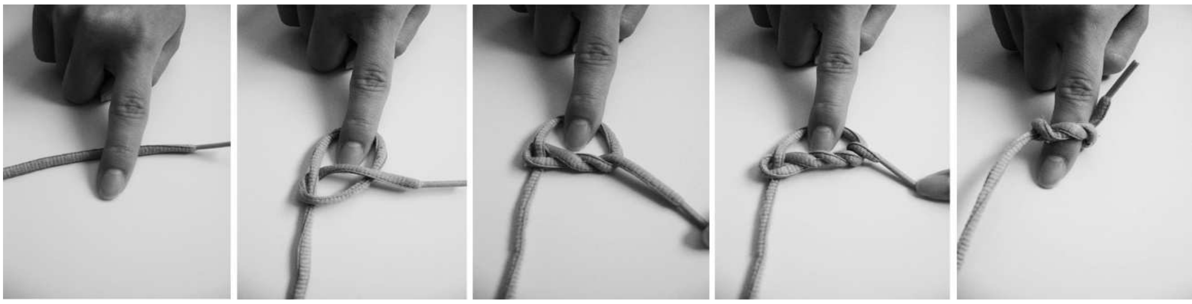


Figure 9: Procedure of knotting

Wire ropes were tested with diameters of 2 mm (CA2); 4 mm (CA4); and 6 mm (CA6). Failure happened at the connections as expected. This failure can be explained with the transversal strains that the sleeve causes in the wire ropes when it is applied. However, results reached and overcame the commercialized values (see the results in HIBA! A HIVATKOZÁSI FORRÁS NEM TALÁLHATÓ. and Table 1)

Figure 10: Wire rope test: Stress-Strain and Load-Extension diagram

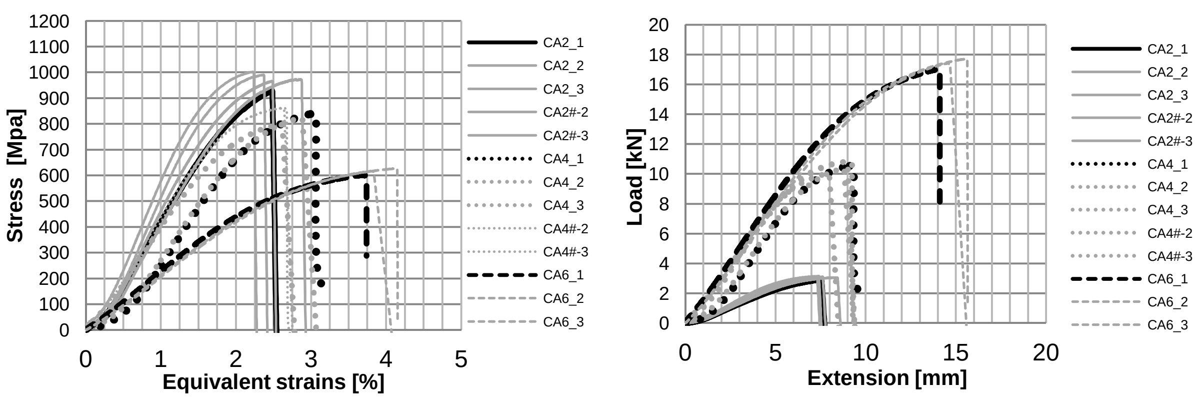


Table 1: Mechanical properties of wire ropes

Name of specimen	Elastic limit			Ultimate limit			
	E [N/mm^2]	ε_s [%]	f_y [N/mm^2]	ε_{su} [%]	f_u [N/mm^2]	P_u [kN]	Nominal P_{max} [kN]
CA2-CA2#2	53000	1,350	713	2,55	955	3,00	**2,24**
CA4-CA4#2	44000	1,600	711	3,00	820	10,3	**8,94**
CA6	22300	2,197	490	4,00	614	17,3	**14,0**

Two types of synthetic ropes were also tested: Synthetic Rope with Carbon fibre Core (SRCC) and a Polyethylene cord (MSR). In case of both composites the knot extremely reduced the strength of the ropes. Both carbon fibre and polyethylene filaments were weak against shear forces, and tore in the connections. Experimental values only reached 10-30% of the composites theoretical maximum load. Another problem was the extreme extension the specimens showed under tension (20-50% elongation in case of SRCC and up to 150% elongation in case of MSR). The results can be seen in the graphs of Figure 11.

These synthetic rope types failed to compete with wire ropes. Their stiffness (174 N/mm) was ~25% of the stainless-steel wire rope's (660 N/mm). In case of SRCC, there was also a common negative effect of initial low stiffness till ~10% of extension; which does not allow the composite to be activated in case of small movements. This phenomenon would affect adversely the behaviour of the reinforcing system on rigid walls, where the system must react to small movements.

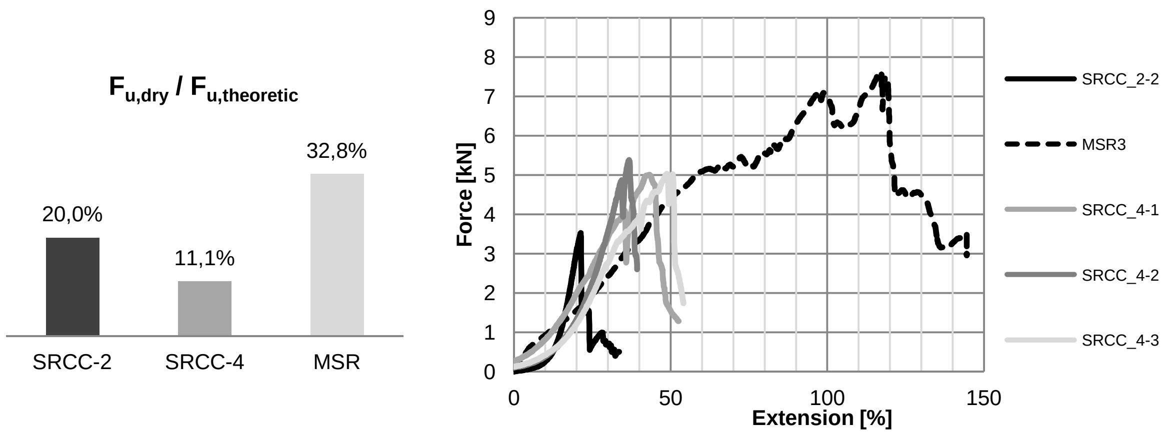


Figure 11: Test results of synthetic rope tests. On left: diagram of maximum test loads ($F_{u,dry}$) related to the theoretical strength ($F_{u,theoretic}$). On right: Force-Extension diagram

4 WALL TESTS

The aim of the first series of global experiments was to test the technology and its equipment, to show the great potential in the method, and to obtain results for the analytical investigation.

Six scaled masonry walls were tested under monotonic out-of-plane loads. Each specimen was made as double leaf, regular stone wall, 1.10 m high and 0.95 m long with a thickness of 32.5 cm, cantilevering from a reinforced concrete slab, with the dimensions of 140×118×25 cm^3. Granite stones were used as units, and Weber Tradition® lime mortar was used as binder, which provided 4 MPa strength during preliminary compression tests after 28 days of curing. In order to eliminate inherent problems of bed-joints between slabs and walls, granite stones were placed on the top of the slabs during the casting, sinking with the 2/3 of

their volume. The walls were subsequently constructed on the top of the bare stone support. The specimens were tested after 21 days of reduced curing time. This compromise was acceptable because of the main goals.
Two out of six walls were tested unstrengthened, and were named URW. Three walls were strengthened with wire ropes and were named StRW walls. One wall was strengthened with synthetic ropes, but its results were excluded due to failure. The wire ropes were connected to the deep rebars of the slab and the open cuts were filled with high strength mortar. The free ends of the cables were fixed on the top of the walls with load transmitting plates that also allowed the application of tensioning (as can be seen in Figure 12).


Figure 12: Bottom (on left) and top (on the right) connections of wire ropes.

Horizontal, monotonic load was applied between the top two rows of stone blocks (actuator load: max 50 kN), and displacement control was used to record the results. Hinges were used at both ends of the actuator to allow rotations and vertical movements during the bending test, as can be seen on the test setup on Figure 13 and Figure 14. During the experiment the following loading periods were used: Elastic range: top displacement: d_1 = 0-2 mm; v_1 = 0.005 mm/sec; Non-linear branch: d_2 = 2-6 mm; v_2 = 0.010 mm/sec; d_3 = 6-10 mm; v_3 = 0.020 mm/sec; d_4 = 10-50 mm; v_4 = 0.030 mm/sec. First cracks showed at cracking limit state (F_{cr};; d_{cr}), which was the top limit of the elastic range. Subsequently maximum resistance was reached (F_{max}; d_{Fmax}). Tests were stopped for safety reasons before reaching the ultimate limit state.

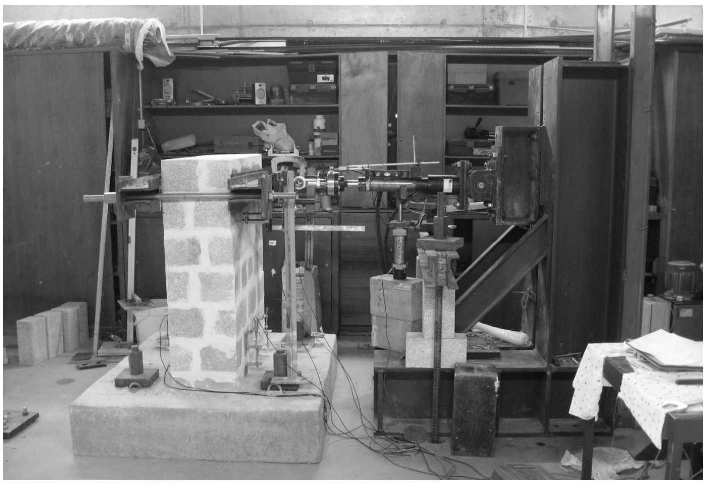


Figure 13: Test of unstrengthened wall URW.1

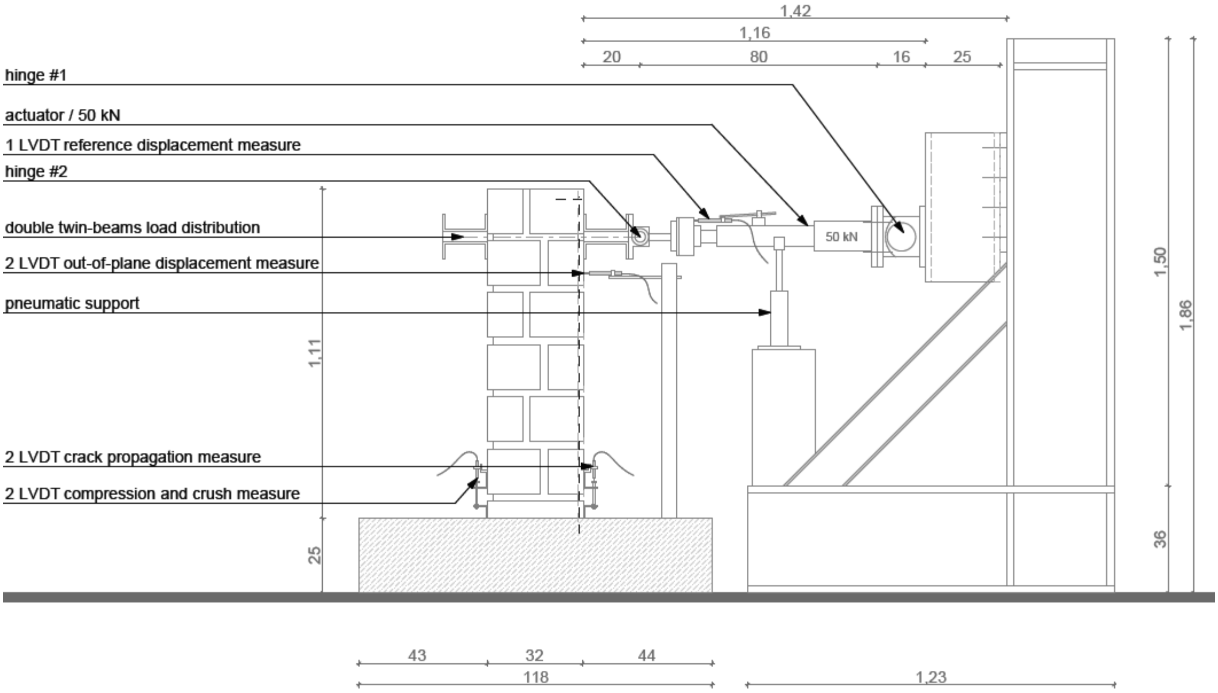


Figure 14: Test setup of wall bending tests

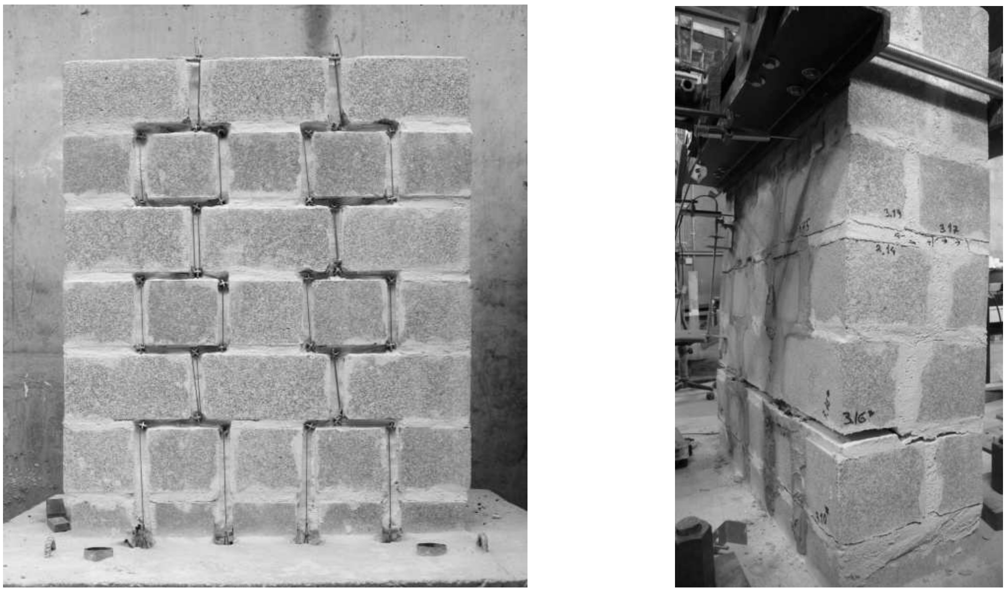


Figure15: StRW.2 wall before repointing the joints (on left) and cracked under loading (on right)

4.1 Results

The weakness of prototype helibar head-connections and the difficulty in applying efficient pretension influenced the results. As a matter of these circumstances φ4 mm wire ropes were too strong for the system, and helibar heads deformed before utilizing the strength of the wires. These φ4 mm chords are also harder to work with during application, as it is harder to bend them. However, – as you can see in Table 2 and Figure16 – by partially solving the problems and by using φ2 mm wire ropes consistently the technique significantly improved the bending resistance of the wall (StRW.2). Results were close to the calculations coming from the analytical model, in which the cables reached close values to their ultimate state.

During the test of StRW.2 a cable tore after reaching the maximum load, which was almost similar to the analytically obtained value.

Table 2: Bending test results

Name of specimen	F_{cr} [kN]	d_{cr} [mm]	F_{max} [kN]	d_{Fmax} [mm]	Stiffness_section 1 K_{s1} [kN/mm]	Stiffness_section 2 K_{s2} [kN/mm]
URW.1	0.4	0.6	1.7	6.8	0.67	0.31
URW.2	0.4	0.5	2.0	8.4	0.80	0.90
StRW.1_φ4	1.4	0.9	2.3	4.0	1.55	0.41
StRW.2_φ2	1.8	0.4	3.3	8.6	4.50	1.44
StRW.3_φ2	1.3	1.5	2.4	6.2	1.62	0.26

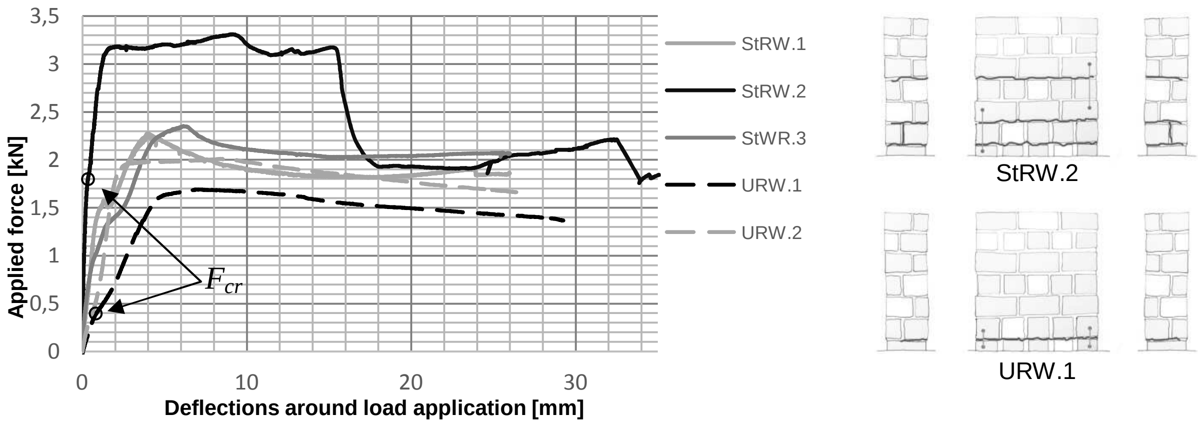


Figure16: Load –deflection graphs and crack maps.

As a clear advantage the strengthening technique helped the generation of a more distributed crackmap in all the tests, which allows greater energy dissipation during earthquakes. The initial stiffness (K_1) has significantly improved (with more than 500%; e.g.: $K_{1,URW.1}$ = 0.67 kN/mm; $K_{1,StRW.2}$ = 4.5 kN/mm). The resilient force at cracking limit state F_{cr} was four times higher in case of StRW.2 compared to URW.1. The maximum horizontal and bending force of the specimen also increased significantly ($F_{max,URW.1}$ = 1.7 kN; $F_{max,StRW.2}$ = 3.3 kN).

5 CONCLUSIONS

The research was successful in investigating the applicability and workability of the new, improved technique and to make the first steps in the definition of the mechanical performance, by applying and testing it on walls. Results proved the great potential in the technique and also highlighted the ways of further improvement. The increase in the maximum applied (bending) force, in the cracking limit point, and in the initial stiffness only could appear when appropriate pre-tension was applied. Though the application of this pre-tensioning force needs further development, plans for a new device are already set.

The key issues to be concentrated on are the pre-stressing of the reinforcing grid, the improvement of proposed anchor elements, and the extended research to find or develop the appropriate synthetic rope type, that can be used as alternative strengthening.

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