Int. Journal for Housing Science, Vol.35, No.2 pp. 103-114, 2011
Published in the United States

BUILT ARCHITECTURE WITH NATURAL STONE

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ABSTRACT

In the thought of Peter Rice when the architectural design challenges the laws of nature the structure becomes architecture. A research, developed at the Department of Architecture and Urban Planning of Catania, proposes a reinforced masonry that is built with blocks of natural stone instead of artificial blocks. [8] This occurs because the local stone (basalt) has similar characteristics to artificial blocks used generally to build masonry. This research has interested different aspects related to the building procedure (construction, structural, thermal and environmental aspects). [3-4] Obtained results show good performances of reinforced masonry built with basalt. Law in seismic zone sets some limitations to the building of reinforced masonry for thickness, thinness and restraint conditions. Within this problematic a new phase of this research has been started with the objective to appraise characteristics of pre-stressed masonry built with basalt. This paper shows the contribution that pre-stressed masonry built with basalt offers in architectural design.

Key words: Natural Stone, Reinforced Masonry, Pre-stressed Masonry, Building System, Contemporary Architecture.

0146-6518/02/103-114, 2011

Introduction

From the combination of masonry and metal reinforcements, building processes in reinforced masonry have evolved and been perfected in the last centuries. [7] These have been widely used in many countries as a seismic building technique while in Italy it has been used only later on with the latest edition of technical laws for building in seismic areas. The reinforced masonry is made of half-full artificial load bearing elements to create walls enclosing special metal vertical and horizontal reinforcements and related concrete castings with a precise structural role. Considering that different kinds of Etna basalt presents the same characteristics of half-full artificial load bearing elements indicated by law since it is industrially workable in regular blocks and undergoes easily quality controls of the structural aspects, in the first step of the research has verified the validity of the building system in reinforced masonry using natural load bearing elements constituted by blocks of the above mentioned lava stone instead of the artificial elements indicated by law. [1] The constructive procedure currently being experimented, is of an integral type with modular components and it is finalized in the realization of load bearing reinforcements, inside of which, according to the requested performances it is possible to insert steel bars for the vertical and horizontal reinforcement, in the versions of diffused or concentrated reinforcements, so to absorb the traction and cutting stress induced by seismic actions and to give to the wall structure the requested ductility. The analysis of the structural behavior allowed to establish the related values of the characteristic defining the deformation and the mechanical resistance of the model taken into account for the defining of the calculus parameters. The experiments have been performed at the Laboratorio Ufficiale Prove Materiali of University of Catania. In accordance with the data reported in Table 1, deriving from the compression tests appear that the values of the characteristic resistance are greater than to the values (in accordance with the law) allowed by the permitted standard. [1-2]

Table 1 : Mechanical characteristic of reinforced masonry with Etna basalt.

Materiale	$f_{b,k}$ [kg/cm²]	$f'_{b,k}$ [kg/cm²]	M_i	E [kg/cm²]	G [kg/cm²]	dutt.	γ [kg/m³]	f_k [kg/cm²]	f_{vko} [kg/cm²]	$f_{k,tab}$ [kg/cm²]	$f_{vko,tab}$ [kg/cm²]
Basalto	1 500	1 300	1	600 000	240 000	9,9	2 700	600	12	143	.2

Legend:
fb,k – characteristic resistance of the material in the orthogonal direction respect the deposition of the mortar;
E – Young's modulus of the mortar;
dutt. – ductility of masonry;
γ – Weight density of the masonry;
fk – experimental characteristic resistance of the masonry with compressive stress;
fvko – experimental characteristic resistance of the masonry with cutting without compressive stress;

fk,tab – characteristic compressive resistance of the masonry computed by using standard tables;
fvko,tab – characteristic cutting resistance of the masonry computed by using standard tables in absence of compressive.

The behavior of the diagonal collapse, that allows us to define the resistance refereed to the horizontal solicitations, is quite different comparing the masonry reinforced panels with the not reinforced ones. In fact in the last case the collapse occurs in the plates of mortar: the collapse is fragile; while in the reinforced panels the evaluation of the crack is progressive due to the mechanisms of the mish between the basalt blocks and the steel bars. In summary we can conclude that the proposed construction system is well suitable to be used in seismic area due to the ductility requirement.

Reinforced masonry built with basalt blocks can be pre-stressed due to the high resistance of Etna basalt improving the performance of the panel. The obtained results encourage us to investigate if it is possible to use the proposed building approach also to realize non regular structural configurations. The pre-tensioning action allows us to compensate both the cutting stress that arises in the horizontal elements and the seismic stresses. Therefore the use of new approach in concerning treated materials with mechanical improved performances is very appealing. In order to evaluate the performances of the system the characteristics of masonry panels have been appraised through comparisons of not reinforced masonry, reinforced and pre-stressed masonry panels built with basalt blocks. In this paper same preliminary results concerning the analysis panels in different conditions will be reported. In particular a fixed end flat panel both in vertical and sloped position has been studied. Moreover, the behavior of a fixed end curved panel has been investigated. The previous examples allowed us to evaluate the performances of a masonry panel with a spiral shape.

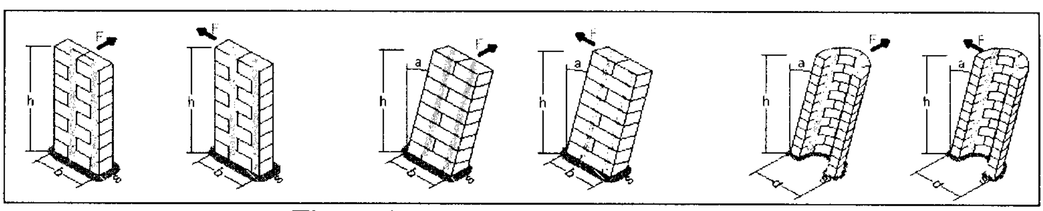


Figure 1 : Scheme of masonry panels

Results

The critical case calculus both under the condition of combined action of compression and flexure in the plain and out the plain and cutting action in the plain has been performed considering the limit state of life safeguard in accordance with the safety tests included in the NTC2008.

Taking into account equilibrium conditions it has been evaluated the horizontal force showing that the collapse occurs only due to the flexure action in the plain and out the plain and that the collapse is not related to the cutting action.

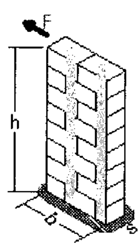
The same procedure has been repeated for different values of the panel height and its thinness for different loading and shape conditions. So, it was derived the factor of safety. It was considered in the case of tests for ***collapse in the plain*** a masonry panel with the following geometric features:
base b=100 cm; thickness s =24 cm; variable height h;
upper steel bars: 1□16 each arranged 4 cm from the compressed edge;
lower steel bars: 1□16 each arranged 96 cm from the compressed edge.

The maximum pre-compression action value for this panel is equal to 200ton.
The tests were been repeated for two different values of the pre-compression action: 100t and 200t.

In Table 4, the trend of the force that breaks the masonry panel and the factor of safety is reported. The factor of safety has been computed as ratio of the break force and the seismic action.

It was been computed for different values of height, thinness and pre-tensioning action.

Table 2 : Seismic tests of panel (s=24cm) for plain collapse



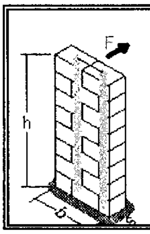
Height h [m]	λs =h/s	Seism. Force Fs [kg]	Ord. mas. P=0 t		Reinf. mas. P=0 t		Reinf. mas.. P=100 t		Reinf. mas. P=200 t	
			Collap. force Fx_R [Kg]	Saf. Fac Tx_R/Fs	Collap. force. Fx_R [Kg]	Saf. Fac. Tx_R/Fs	Collap. force. Fx_R [Kg]	Saf. Fac. Tx_R/Fs	Collap. force. Fx_R [Kg]	Saf. Fac. Tx_R/Fs
3.50	**14.58**	**425.25**	**463.30**	**1.09**	2438.17	5.73	13231.30	31.11	17285.52	40.65
9.00	**37.50**	**1093.50**	**373.50**	**0.34**	**1123.90**	**1.03**	5234.61	4.79	6732.22	6.16
20.00	**83.33**	**2430.00**	**337.63**	**0.14**	**663.90**	**0.27**	**2435.77**	**1.00**	3038.56	1.25
22.00	**91.67**	**2673.00**	**334.38**	**0.13**	**629.69**	**0.24**	**2227.59**	**0.83**	**2761.53**	**1.03**

Moreover, from Table 2, it appears as the pre-tensioning action plays a highly positive effect increasing the performances of the masonry to resist to the horizontal actions.
In the case of thickness s =24 cm, ordinary masonry panel does work until 3.5 meter of height (in accordance with the seismic test) while the reinforced masonry does work until 20 meter with a pre-tensioning action of 100 ton and respective until 22 meter with a pre-tensioning action of 200 t.

The tests for ***out plain collapse*** are the more critical for the masonry structure. These tests have been considered for different values of thickness (tab.3), pre-tensioning action (tab.4) and panel slopes (tab.5).

The mechanical parameters of the panel have been not changed while the geometric values assumed in the test are:
Base b=100 cm; thickness s =24cm, 30cm, 40cm, variable height h;
Upper steel bars 1 16 each arranged 5 cm from the compressed edge;
lower steel bars 1 16 each arranged respectably 19cm, 25cm, 35cm, from the compressed edge;

Table 3 : Seismic tests of the panel for out plain collapse for different thickness without pre-tensioning



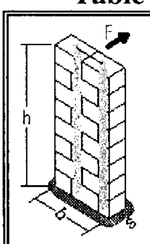
height [m]	S= 24 cm						S= 30 cm						S= 40 cm					
	λ_s =h/s	Seis. Force. Fs [kg]	Ord. mas.		Reinf. mas.		ls =h/s	Seis. Force. Fs [kg]	Ord. mas.		Reinf. mas.		ls =h/s	Seis. Force. Fs [kg]	Ord. mas.		Reinf. mas	
			Col. for Fy$_R$ [Kg]	Saf. fac. Ty$_R$/Fs	Col. for. Fy$_R$ [Kg]	Saf. fac Ty$_R$/Fs			Col. for. Fy$_R$ [Kg]	Saf. fac . Ty$_R$/Fs	Col. for. Fy$_R$ [Kg]	Saf. fac Ty$_R$/Fs			Col for. Fy$_R$ [Kg]	Saf. fac . Ty$_R$/Fs	Col. for Fy$_R$ [Kg]	Saf. fac Ty$_R$/Fs
2.0	**8**	**243**	78	0.3	898	3.7	7	304	121	0.4	1134	3.7	**5**	**405**	**215**	**0.5**	1549	3.8
3.0	13	365	77	0.2	621	1.7	10	456	121	0.3	791	1.7	8	608	214	0.4	1096	1.8
4.0	**17**	**486**	77	0.2	**483**	**1.0**	13	608	121	0.2	**620**	**1.0**	10	810	214	0.3	**869**	**1.1**
4.5	19	547	77	0.1	437	0.8	15	683	120	0.2	563	0.8	11	911	214	0.2	794	0.9

Considering the included values of Table 3 it is evident as the seismic factor safety increases with the thickness.

The ordinary masonry does not work under seismic out plain action even if structures of 40 cm thickness and 2 meter height are considered. To avoid the previous results the packing of the masonry structure is adopter. Indeed for the reinforced masonry until a height of 4 meters, the increase of thickness does not lead to signified improvements as regards the factor of safety.

The seismic test of a panel of 24 cm of thickness for out plain collapse was been repeated for two different values of the pre-compression action: 100 t and 200 t.

Table 4 : Seismic tests of a panel of 24cm of thickness for out plain collapse

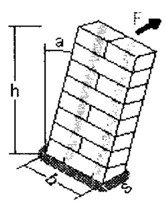


Height h [m]	λs =h/s	Seism. Force Fs [kg]	Ord. mas. P=0 t		Reinf. mas. P=0 t		Reinf. mas. P=100 t		Reinf. mas. P=200 t	
			Collap. force Fy$_R$ [Kg]	Saf. Fac. Ty$_R$/Fs	Collap. force Fy$_R$ [Kg]	Saf. Fac. Ty$_R$/Fs	Collap. force. Fy$_R$ [Kg]	Saf. Fac. Ty$_R$/Fs	Collap. force. Fy$_R$ [Kg]	Saf. Fac. Ty$_R$/Fs
2.00	**8.33**	**243.00**	**77.47**	**0.32**	897.94	3.70	5156.80	21.22	6847.52	28.18
4.00	**16.67**	**486.00**	**77.17**	**0.16**	**483.13**	**0.99**	2599.79	5.35	3423.44	7.04
9.00	**37.50**	**1093.50**	**76.44**	**0.07**	**252.67**	**0.23**	**1179.23**	**1.08**	1521.17	1.39
10.50	**43.75**	**1275.75**	**76.22**	**0.06**	**226.34**	**0.18**	**1016.88**	**0.80**	**1303.77**	**1.02**

Ordinary masonry panel does work until 2.0 meter of height (in accordance with the seismic test) while the reinforced masonry does work until 4.0 meter and the pre-stressed masonry does work until 9.0 meter with a pre-tensioning action of 100 ton and respective until 10.5 meter with a pre-tensioning action of 200 ton. The reinforcement in the masonry panel gives to the panel further performances in order to resist at the horizontal out of the plain actions. The performances of the panel are better if the pre-tensioning actions have been actuated. The included results in the previous tables remark as the contribution of pre-tensioning actions are remarkable respect the increasing of panel thickness.

The next step of the present analysis has been to evaluate the changing of the limit force with the height and with the thinness for the same type of panel but for different values of slopes for out plain collapse of panel.

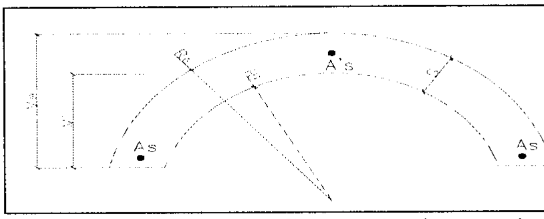
Table 5 : Seismic tests for out plain collapse of panel with different values of slopes for P=0



Height h [m]	λs =h/s	Seis. Force. Fs [kg]	Ord. mas. α=5°		Reinf. mas. α=5°		Reinf. mas. α=10°		Reinf. mas. α=20°	
			Collap. force Fy_R [Kg]	Safe. fac. Ty_R/Fs	Collap. force. Fy_R [Kg]	Safe. fac. Ty_R/Fs	Collap. force. Fy_R [Kg]	Safe. fac. Ty_R/Fs	Collap. force. Fy_R [Kg]	Safe. fac. Ty_R/Fs
2.00	**8.33**	**243.00**	**20.89**	**0.09**	838.22	3.45	774.14	3.19	644.21	2.65
2.80	**12.50**	**364.50**			579.66	1.70	497.06	1.46	**343.19**	**1.01**
3.20	**16.67**	**486.00**			494.66	1.27	**402.28**	**1.03**	234.44	0.60
3.50	**18.75**	**546.75**			**441.98**	**1.04**	342.14	0.80		

It is evident as an ordinary masonry 2 meter height and with a slope of 5°, under the force of earthquake has safety factor about zero. While for the reinforced masonries respectively of height 3.5m (α=5°), 3.2m (α=10°) and 2.8m (α=20°), the seismic tests reached satisfactory results. In conclusion we can affirm that the best benefits can be achieved with pre-stressed reinforced masonry. We remark that for usual inter plane height of the buildings (about 3m) the reinforced masonry does resist to the seismic effect deriving from the self weight for slopes until 10°. Such type of capabilities allows us to assume a stable configuration also for signified slopes.

The evaluation of **out plain collapse of a panel with curve section**, fixed end, remarks as by changing the section type an increasing of resistance can be obtained. To establish useful comparison the same condition of the previous adopter ones have been considered.

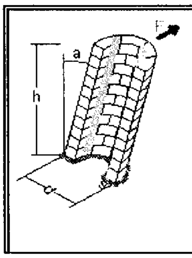


	Re	=	50	[cm]
	Me	=	40	[cm]
	s	=	24	[cm]
	Ri	=	26	[cm]
	Mi	=	16	[cm]
	G	=	29,1	[cm]
	Atot	=	2379	[cmq]

Figure 2 : Geometric characteristics of the panel cross-section

Upper steel bars 1Ø16 each arranged 5 cm from the compressed edge;
lower steel bars 1Ø16 each arranged 35 cm, from the compressed edge;
For this configuration only the out plain mechanism collapses have been evaluated changing the slopes (Table 6) and the pre-tensioning actions (Table 7).

Table 6 : Seismic test of curved and slope panel for out plain collapse and for a pre-tensioning P=0

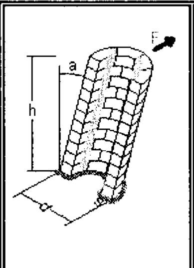


height h [m]	λs =h/s	Seis. Force. Fs [kg]	Ord. mas. α=5°		Reinf. mas. α=5°		Reinf. mas. α=10°		Reinf. mas. α=20°	
			Collap. force.	Saf. Fac.	Collap. force.	Saf. Fac.	Collap. force.	Saf. Fac.	Collap. force.	Saf. Fac.
2.00	8.33	243.00	59.79	0.25	1926.70	8.00	1848.57	7.68	1656.95	6.88
4.00	16.67	486.00	4.03	0.01	941.93	1.96	820.34	1.70	574.21	1.19
4.20	18.75	546.75			892.11	1.76	765.63	1.51	511.84	1.01
4.90	22.92	668.25			746.20	1.26	602.23	1.02	320.37	0.54
5.40	27.08	789.75			662.04	1.02	505.36	0.78	202.53	0.31

The ordinary masonry with a height of only 2 meter and with a slope of 5° with seismic action has safety factor about zero while reinforced masonry with heights of 5,4 m, 4,9 m e 4,2 m and slopes of respectively 5°, 10° e 20° widely satisfy the requirement from the seismic point of view.

We can note as the maximum height that satisfies the verification is greater of that of the plane panel of 3.5 meter height with a slope of 5°(tab.5): it reaches 5.4 meter. The conclusion is that the shape of the panel positively influences the mechanical out plain behavior of the masonry structure.

Table 7 : Seismic test: the case of out plain collapse of curved panel (α=0°).



Height h [m]	λs =h/s	Seis. Force. Fs [kg]	Ord. mas. P=0 t		Reinf. mas. P=0 t		Reinf. mas. P=100 t		Reinf. mas. P=200 t	
			Collap. force. Fy_R [Kg]	Safe. fac. Ty_R/Fs	Collap. force. Fy_R [Kg]	Safe. fac. Ty_R/Fs	Collap. force. Fy_R [Kg]	Safe. fac. Ty_R/Fs	Collap. force. Fy_R [Kg]	Safe. fac. Ty_R/Fs
2.00	8.33	240.85	125.51	0.52	1990.52	8.26	8509.37	35.33	10335.57	42.91
6.00	25.00	722.54	119.46	0.17	747.10	1.03	2865.76	3.97	3442.30	4.76
12.00	50.00	1445.07	117.95	0.08	436.25	0.30	1454.86	1.01	1718.98	1.19
13.00	54.17	1565.49	117.84	0.08	412.33	0.26	1346.33	0.86	1586.42	1.01

The ordinary masonry panel, 2 meter height, does not satisfy the seismic verification even if the safety factor is greater respect the case of plane panel.

The reinforced masonry panel does work well even if the height is 6 meter and in the case that it is pre-stressed, panel of 12 meter and 13 meter (respectively with 100 ton and 200 ton) do work in stability conditions. Due to the particular shape of curved panel it does work better respect the plane one.

The previous considerations encourage us to extend the test for buildings elements with more complex shapes. It has been studied the behavior of a wall sector that wraps itself like in a spiral shape with variable height from 0 to 4 meter with a thickness of 20 cm.

The radius of the spiral in the base is variable from 2.8 m to 7.8 m and has a variable slope with the height from 0° to 16°.

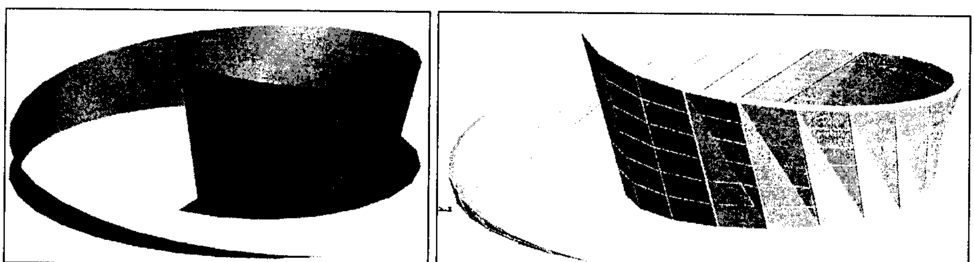
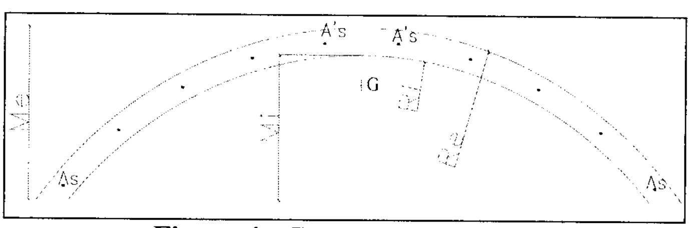


Figure 3 : Investigated spiral structure – shell model

In order perform the ***seismic verification of the spiral structure*** it is worked by using two different models: the first one is a beam, the second one is a shell. In the beam model it has been considered only the last quarter of spiral while the analysis has been performed modeling the whole structure with a set of elements each put new the others. In order to perform the test the same previous procedure has been adopted.
The following geometric parameters have been adopted.



Re	=	338	[cm]
Me	=	104	[cm]
s	=	20	[cm]
Ri	=	318	[cm]
Mi	=	84	[cm]

Figure 4 : Geometric characteristics of the panel cross-section

Upper steel bars: 2 14 each arranged 10 cm from the compressed edge;
lower steel bars: 2 14 each arranged 94cm, from the compressed edge;

The pre-tensioning is applied by a constant tension on the vertical steel bars.
The applied pre-tensioning action is about 1000ton that is the value maximizing the flexure characteristics of the section.
The seismic action has been evaluated by using an accelerator value of area equal to 0,25g and the effect of circle arch masonry load has been applied an half at the top and the other half at the base.
In order to evaluated the stress actions it has been considered a scheme of fixed end beam.
The results are reported in Table 8.

Table 8 : Seismic test of the panel with pre-tensioning P equal to 1000t.

Height h [m]	α	Calculated compression stress Nsd [kg]	Calculated flexure stress Msd [kgm]	Resistant compression stress Nrd [kg]	Resistant flexure stress Mrd [kgm]	Safety factor
4	16	1013745	16132	1013745	232374	14.40
8	16	1027491	64530	1027491	232531	3.60
14	16	1048109	197623	1048109	232767	1.18
15	16	1051545	226863	1051545	232806	1.03
16	16	1054982	258119	1054982	232846	0.90

The circle arch, with a slope of 16°, is stressed by its weight and by the seismic actions. The results are suitable with 15 meter according with the seismic tests. Due to the fact that the thickness of the masonry has been 20 cm instead of 24 cm and that the thinness of 20, the considered conditions are not in agreement with the NTC2008. Moreover to limit the maximum of thinness for such a type of structure is a very strong condition, due to the fact that the Etna basalt has a good compression proof and high Young modulus like the concrete C32-40 (400kg/cmq).

In order to analyses the shell model a further element code has been used to verify the structure in the three dimension space. The analyses shown that the suitable reinforcement in order to safety the tests must be built with steel bars of [illegible]16 arranged each 50 cm. The maximum displacement at the end of the spiral at quote 4 m is very small about 2.24 mm.

Conclusion

Today, Italian law allows the building system with ordinary masonry also in seismic area. Above seismic norms, according to the law, are very restrictive and give strong limitations to the architectural design in particular concerning the thickness, the thinness and the restraints condition of the masonry panel. The models with the packing of the masonry structure have been necessary used.

The masonry structure is composed by a closed link with small dimension; floor beams tie the load bearing walls.

Moreover, the law allows the use of the building system with reinforced masonry. The reinforced masonry regulations, according to the law, are very similar to the ordinary masonry norms. Only small differences there are about the dimensions of the building elements (minimum thickness and maximum thinness).

In this paper masonry panels built with Etna basalt blocks have been investigated. In particular reinforced panels have been analyzed in details in order to compare their performances with the ordinary masonry. The experimental results, comparing the performances of the reinforced masonry panels, allowed us to remark the improvements of the seismic response of the reinforced walls, considering in particular the case of orthogonal actions that are the more critic for the masonry structures.

The tests have been performed not considering the law indications that are: minimum thickness of 24 cm and maximum thinness of 20.

The reinforced elements have good performances in the case of orthogonal actions, also in the case of isolate, fixed end and not restraint at the top panels like the reinforced concrete walls. Moreover the reinforced masonry elements have good performances in the case of sloped structures to resist to the orthogonal actions. Easy displacement deformations in the structure have been obtained like in the case of the spiral structural shape. This allows avoiding the inclusion of string-course at the top of masonry panel in order to establish the behavior of the packed structure.

Ordinary masonry das not work in a similar manner. The behavior of the reinforced masonry is similar to the reinforced concrete and steel structures. The obtained results show that the law values are very conservative.

Moreover, the pre-tensioning action considerably increases the capability of resistance of the panel for orthogonal actions because the Etna basalt compression resistance and the Young's modulus are very large and similar to the concrete C32-40 (400kg/cmq). The included results in the tables 3 and 4 remark as the contribution of pre-tensioning actions are considerable respect the increasing of panel thickness. The pre-stressed panel, also with small thickness (table 4), does work until 10.5 meter of height while the reinforced panel does work until 4 meter of height.

Moreover the shape of the panel positively influences the mechanical out plain behavior of the masonry structure. Due to the particular shape of curved panel it does work better respect the plane one (tables 5 – 7).

The previous considerations encourage us to extend the test for structures with more complex shapes. The seismic tests remark as it is possible to build a spiral with a sloped, pre-stressed wall, with thickness of 20 centimeter, until 15 meter of height.

Small horizontal displacements have been achieved in the case of the structure with spiral shape. These displacements do not influence the verification in the deformed configuration due to the fact that the fixing moment does not increase.

Today a new step of research has been started in order to build a prototype of the analyzed spiral model. This will allow to define the building characteristics and to prove the results of the numerical analyses.

This research opens new frontiers towards the use of load bearing masonry for architectural realizations also in accordance with the severe seismic regulation.

Figure 4 : Spiral structure prototype – design of a fountain

References

1. Lombardo G., 2004, La modernità del basalto dell'Etna – Innovazione e sperimentazione, Il Lunario, Enna.
2. Lombardo G., 2007, Il ritorno della pietra nella pratica dell'architettura. In Atti del Terzo congresso internazionale Ar.Tec. "L'involucro edilizio. Una progettazione complessa", Ancona. 21-23 novembre 2007, FIRENZE: Alinea editrice (ITALY);
3. Cicero C., Lombardo G., 2007, Verso un'edilizia sostenibile: caratteristiche termofisiche e prestazioni energetiche degli involucri massivi. In Atti del Terzo congresso internazionale Ar.Tec. "L'involucro edilizio. Una progettazione complessa". Ancona. 21-23 novembre 2007. Ed. Alinea.
4. Cicero C., 2008, Muratura in pietra lavica per un'edilizia sostenibile: valutazioni energetiche ed ambientali, in Atti delle Giornata di Studio CODAT, Pavia 17 settembre 2008.

5. De Sivo M., 2004, Atlante della pietra, UTET, Torino.
6. D.M. 14 settembre 2005, "Norme Tecniche sulle Costruzioni".
7. Giuffrè A., 1993, La sicurezza e la conservazione dei centri storici: il caso Ortigia, Editore Laterza, Bari.
8. Latina C., 1994, Muratura portante in laterizio, Edizioni Laterconsult, Roma,.