Temporary Strengthening Technique of Marble Columns with Steel Wires and Wood Spars

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***Abstract*-Granite, marble and heavy stone columns have been used in the architects from all the ages to answer to both aesthetical and structural requirements in ancient churches and historical buildings. Such materials offer great visual impact and have mechanical properties that allow their use in construction and to obtain bright and slender structures.**

Marble is a very high strength but brittle material. It often occur that marble or granite columns of historical building are cracked along their height due to external actions and the risk of buckling occurs. Because this kind of failure is sudden and very brittle in stone and rocks, an immediate strengthening of the columns is needed. Among e temporary strengthening technique consisting in steel collaring with wood spars and steel wires is of interest. This technique was widely utilised by Firemen and Civil protection during the earthquakes occurred in Italy in the last years, but very few experimental and theoretical researches are available on this topic. In this paper the interest was on this technique and an experimental program based on compressive tests on monolithic and cracked marble columns with circular cross-section reinforced externally with wood spars and steel wires was carried out. A simple model based on the determination of the critical load of an elastic beam on elastic springs is able to take into account the steel collaring. The results obtained highlight that from a theoretical point of view, the presence of steel collaring in cracked column increases the critical load, ensuring monolithic behaviour, while from the practical point of the view the technique is very cheap and easy to apply in temporary strengthening of cracked columns.

***Keywords*- Marble Column; Steel Collars; Compression; Cracked Columns; Strengthening**

I. INTRODUCTION

During the past centuries, the European architectural heritage has observed an increasing development of the column supporting. The realization of the architectural organism during the classic age should conform to detailed rules: symmetry, proportioning, commeasuring. Fig. 1 shows some examples of marble, heavy stone and granite columns employed in some religious and monumental buildings in Sicily. These materials have great values of compressive strength but they are very brittle materials [1-5]. The adopted diameters for these columns varied between 300 and 500 mm while the heights are comprised between 2 m and 4.5 m, corresponding to geometrical slenderness's of 12 and 36 respectively. In most of these cases shown in Fig. 1 the Carrara marble was adopted for construction of the columns. Table 1 summarized the values of the most important mechanical properties of this kind of stone, deduced from the main producers. The values given show than marble are a natural stone with very high strength properties.

TABLE 1 MECHANICAL PROPERTIES OF THE CARRARA MARBLE

Density	27.05 kN/m^3
Imbibition coefficient	0.6 ± 0.6
Uniaxial compressive strength	131 ± 3 MPa
Uniaxial c. strength (iced cycled)	126 ± 6 MPa
Tangent elastic modulus	75000 ± 700 MPa
Secant elastic modulus	83550 ± 250 MPa
Bending strength	16.9 ± 0.4 MPa
Poisson's ratio	0.274
Rigidity	21700 MPa

Granite or marble columns and location in Sicily (Italy)

Catena Church (Palermo)

Cathedral of Monreale (Palermo)

Interior of the Catena Church in Palermo

Interior the Monreale Cathedral

Palermo’s State Archive

St. Mary of Pieta Church (Palermo)

Fig. 1 Examples of churches and historical buildings in Sicily having granite or marble colonnades

In most of the cases of historical buildings shown in Fig. 1, columns have large cross-section if compared with acting loads, which produce low stresses very far from the compressive strength of material. Also, the slenderness ratios are very low and the risks of buckling failure are excluded. However, if columns are cracked the slenderness ratios increase significantly and the risk of buckling failure arises. Typical cases of columns damaged and cracked along the height of the member are shown in Fig. 2.

Examples of cracked granite or marble columns

Historical building Ancient Church Pantheon in Rome (Italy)

Fig. 2 Examples of cracked columns

In these cases the collaring technique can be applied in order to strengthen the column. Examples of this technique are shown in Fig. 3, referring to temporary post-emergency methods adopted by the Italian Civil Protection and firemen during the recent severe earthquakes happened in Italy (L'Aquila 2009 and Emilia Romagna 2012). More in detail the technique consists in providing wood spars in the direction of the column axis, which have to be linked together by wrapping them with metallic or polymeric strips. Even if the application of this technique resulted as an invasive technique, especially for the external visual impact, it represents a good and cheap solution to strengthen columns as a provisional solution before the final retrofitting of the columns with adequate techniques [6, 7].

Wood spars and strips

Fig. 3 Temporary Strengthening techniques

The present work focuses on this method and it refers to a compressed marble monolithic and cracked columns reinforced with the application of wood spars and metallic wires. The target is to evaluate experimentally and theoretically the efficiency of such temporary retrofitting technique on ultimate conditions of marble columns which are cracked along their height. The efficiency of the strengthening action on second order effects and buckling load was analyzed and discussed, evaluating if such a simple method could be able to restore the integrity of the member.

II. EXPERIMENTAL INVESTIGATION

Eight small-scale marble columns were made up to be tested in compression. Furthermore, two cubes and four cylinders were tested in compression in order to characterize the marble properties.

Specimens had circular transverse cross section, with diameter of 80 mm and height of 800 mm. Their slenderness ratio was 40. Such value was selected because it could be considered as representative of a lot of existing columns in the Sicilian architectural heritage. It has to be noted the scale effect could play an important role in brittle materials, but for the target of the work it was neglected at this stage. Further studies have to be addressed on this field. Some columns were cut longitudinally along their height in two halves, in order to simulate the frequent condition of cracked columns. Two couples of cut specimens were reinforced with the steel collaring technique.

Fig. 4 shows monolithic column and half column, the latter to be utilised to make up a single member constituted by two half pieces.

a) b)

Fig. 4 Marble columns a) monolithic; b) half column

Eight wood spars were disposed longitudinally along the column and in polar-symmetrical position with respect to the centre of the specimen. The spars had thickness of 5 mm, width of 20 mm and height of 750 mm. Two steel stainless wires (see Fig. 5) having diameter of 0.5 mm composed each single steel collar. In particular, two specimens were reinforced with a pitch of 180 mm (steel collar 1) while the other specimen couple the adopted pitch was 90 mm (steel collar 2). Although the steel type used is an important issue to ensure durable bond between the steel and marble, in this paper the focus was on the use of stainless steel wires for temporary retrofitting of cracked marble columns and for this reason this aspect was not taken into account.

Fig. 5 Two half marble columns reinforced with the steel collaring technique

A. *Steel Wires and Wood Spars Characterization*

The wires were made up with stainless steel and monotonic tensile tests were undertaken on both one and two coupled wires in order to characterize their mechanical properties. Table 2 summarizes the results of the tests in terms of yield f_y and ultimate f_u tensile stress, while Fig. 6 shows the obtained average stress-strain curve. The modulus of elasticity measured on steel wire was 203000 MPa.

TABLE 2 RESULTS OF TENSILE TESTS ON STAINLESS STEEL WIRES

Single wire		
Specimen	f_y (MPa)	f_u (MPa)
1	370	458
2	351	421
Two coupled wires		
Specimen	f_y (MPa)	f_u (MPa)
1	382	460
2	350	426

Tying of steel wires was made manually simply by fixing them by hand with a pincer and without adopting particular details (Fig. 6). Both the wires and the tightening nodes remained safe after all the undertaken tests. Wood spar specimens had weight density of 500 daN/m^3 and modulus of elasticity in compression of 13500 MPa.

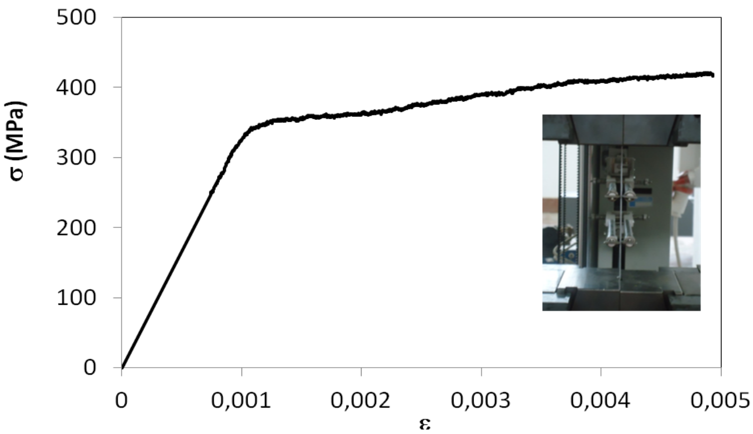

Fig. 6 Stress-strain curve of stainless steel composing the wires

B. Marble Characterization

Two marble cubes and four cylinders were tested in compression to evaluate the strength properties of the material making up the specimens. The cubes had the size of 100 mm, while the cylinders had the diameter of 60 mm and height of 120 mm. A displacement control universal testing machine having capacity of 4000 kN was adopted to perform the tests. The axial strain was recorded by means of a Linear Voltage Displacement Transducer (LVDT) having gauge length equals to the height of the specimen, and the transducer was placed between the plates of the testing machine. Table 3 summarizes the main results of compressive tests for material characterization. In particular, the values of cylinder f_c and cube R_c compressive strength were reported, together with the peak strain ε_0 and the elastic modulus E_c. The latter was calculated only for cylinders considering that for each specimen the stress ranges between the 20% and 40% of the peak stress.

TABLE 3 RESULTS OF COMPRESSIVE TESTS ON MARBLE CYLINDERS AND CUBES

Cylinders		
Specimen	fc (MPa)	εo
1	106.52	0.00437
2	100.49	0.00502
Cubes		
Specimen	Rc (MPa)	εo
1	107.76	0.0090
2	99.11	0.0088

Fig. 7 shows the stress-strain curves deduced from the compressive tests on marble cylinders and cubes. Material behaves quasi-linear up to failure, excluding the initial non-linear phase due to the settlement of the testing machine. After the peak stress, the behaviour was characterized from a strongly brittle response. The failure mode of cubes and cylinders was characterized from a few of vertical cracks, coherently with the brittle material behaviour with high strength properties. The influence of shear stresses between the steel bearing plate of testing machine and the surface of marble specimens was negligible. Therefore, compressive strengths on cylinder and cubes were almost the same.

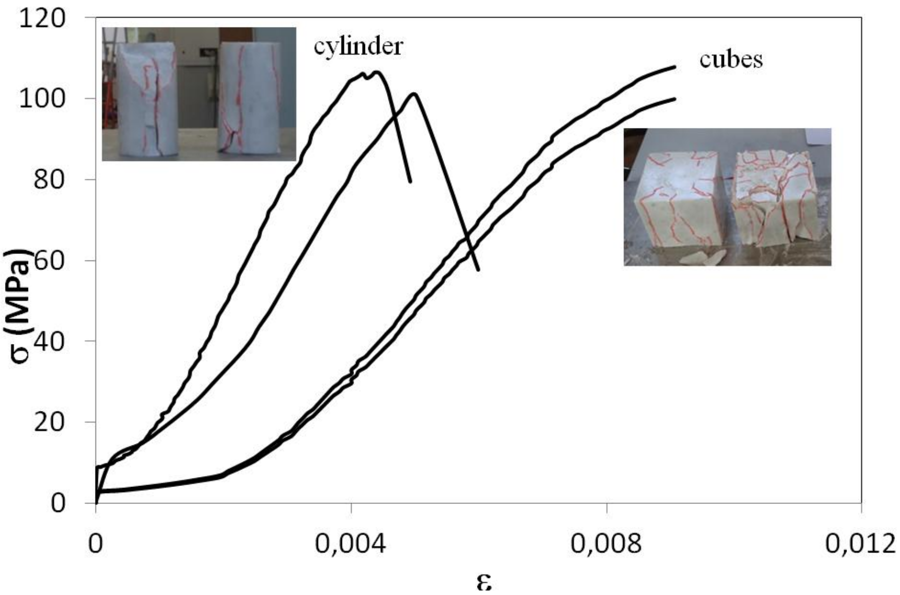

Fig. 7 Stress-strain curves of marble cylinders and cubes

C. Compressive Tests on Cracked and Un-cracked Marble Columns

Fig. 8 reports the axial load-shortening curves of solid columns cracked artificially by means of a cut along the length of the columns producing columns in two equal halves. In the same figure the results relative to columns retrofitted with the steel collaring technique with the two adopted pitches are also represented. As can be noted, the strength of solid columns was similar to that deduced from compressive tests on cylinders, while the maximum stress of the “two half columns” was evidently lower, even if the gross area of the transverse cross sections was the same.

The maximum peak load of two half columns retrofitted with the above described technique increased up to a value lightly lower that that recorded in monolithic columns. In particular the specimens reinforced with a lower pitch exhibited greater strength values, while those having the more largely spaced collars had shown lower peak loads.

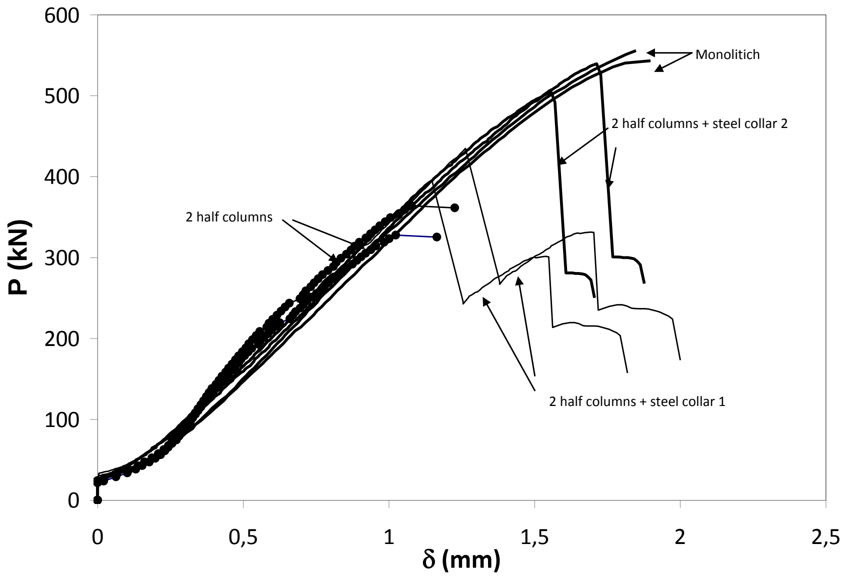

Fig. 8 Axial load-shortening curves of marble columns

Fig. 9 shows the three specimens after testing. Failure of monolithic columns occurred due to compressive crushing of marble while for the two half columns the failure was due to buckling. Both the crushing and buckling occurred in reinforced columns, while crushing is more prominent in specimens having collars spaced with smaller pitches. After testing, the reinforced columns had fewer cracks than the unreinforced cut specimens.

a) b) c)

Fig. 9 Specimens after testing: a) monolithic; b) two half column with steel collaring type 1; c) two half column with steel collaring type 2

III. THEORETICAL PREVISIONS OF THE ULTIMATE LOAD

In this section the compressive behaviour of tested specimens is analyzed, the theoretical constitutive law able to predict the behaviour of the members was studied and provided. The description for constitutive law in compression was made to highlight that the behaviour of compressed material is almost linear up to failure.

For second order analyses of compressed column, it appears appropriate to assume that the material behaves elastically up to failure and to calculate the critical load as a Eulerian value. Numerical non-linear analyses carried out with SAP (2000) [8] program were performed to validate the assumption made.

A. Compressive Behaviour of Material and Un-cracked Columns

The constitutive law of marble in compression was modelled by considering the theoretical model of Campione [9], derived for High Strength Concrete and based on the following equation:

$$\sigma = \frac{\frac{\varepsilon}{\varepsilon_o} \cdot f_c \cdot \beta}{\beta - 1 + \left(\frac{\varepsilon}{\varepsilon_o}\right)^{\beta}} \tag{1}$$

with β expressed as in Campione [9] for high strength concrete and expressed as

$$\beta = 1.4276 \cdot e^{(0.0247 f_c)} \tag{2}$$

and εo given as in Campione [9] in the form

$$\varepsilon = 0.0016 + 0.00002 \cdot f_c \tag{3}$$

adopting the compressive strength f_c determined experimentally for cylinders.

The load-shortening curves of monolithic columns were calculated on the basis of the axial compressive stress-strain relationship previously mentioned (Eq. (1)), without taking into account the size effects because of the scale of the specimens. At the moment it was observed that the size effects play an important role in brittle materials (Bazand and Kim [10]) and further studies have to be addressed on this field.

B. Critical Load for Un-cracked and Cracked Columns

With reference to the buckling phenomenon, the critical load of slender columns was calculated with reference to the classic Euler's theory, while in the case of cracked columns with steel collaring the critical load was determined by considering a model of elastic beam on elastic soil, the latter simulating the effect of the steel collars is as described below and shown schematically in Fig. 10.

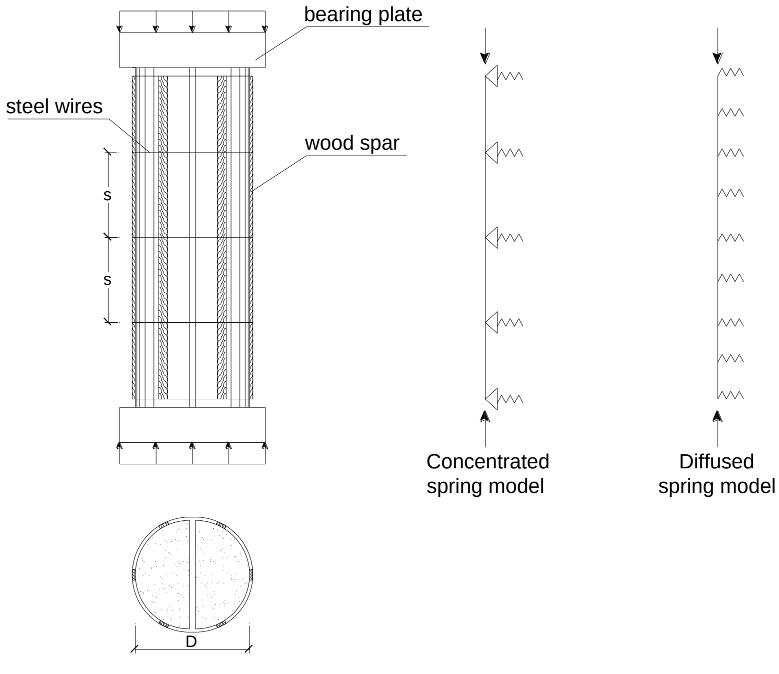

Fig. 10 Strengthened marble columns and theoretical model

The classical Euler's theory provides the expression of the critical load in the following form:

$$P_{cr} = \frac{\pi^2 \cdot E \cdot J}{L^2} \tag{4}$$

where J is the moment of inertia of the solid column and equals to:

$$J = \frac{\pi \cdot D^4}{64} \tag{5}$$

In the case of cracked column, the moment of inertia J_R could be determined as the sum of the moment of inertia of half circles:

$$J_R = \frac{D^4}{16} \cdot \left(\frac{\pi}{8} - \frac{8}{9\pi} \right) \tag{6}$$

Therefore the critical load of columns constituted by two half columns results as:

$$P_{cr} = \frac{2 \cdot \pi^2 \cdot E \cdot J_R}{L^2} \tag{7}$$

In the case of steel collaring the critical load of the marble columns increases and it can be calculated in a simplified manner by distributing the stiffness of each single collar along the column's height. The case can be studied considering the model of an axially loaded half column on an elastic springs with stiffness parameter k.

In this case, the equivalence between the external and the internal work could be written as follows:

$$\frac{P}{2} \cdot \int y'^2 dx = \frac{1}{2} \cdot \int k \cdot y^2 dx + \frac{1}{2} \int E \cdot J_R \cdot y''^2 dx \tag{8}$$

A sinusoidal function was assumed to describe the deformed shape in the following form:

$$y = y_o \cdot \sin \frac{\pi \cdot x}{L} \tag{9}$$

Substituting Eq. (9) in Eq. (8), the following relation held

$$\frac{P}{2} \cdot \left(\frac{\pi}{L} \right)^2 \cdot y_o^2 \cdot \frac{L}{2} = k \cdot {}_o^2 \cdot \frac{L}{2} + \frac{E \cdot J_R}{2} \cdot \left(\frac{\pi}{L} \right)^4 \cdot y_o^2 \cdot \frac{L}{2} \tag{10}$$

from which the critical load could be calculated by

$$P_{crit} = k \cdot \left(\frac{L}{\pi} \right)^2 + E \cdot J_R \cdot \left(\frac{\pi}{L} \right)^2 \tag{11}$$

where k is the distributed stiffness of the lateral springs:

$$k = \frac{k_s}{s} \tag{12}$$

where k_s is the stiffness of the collars, calculated as follow

$$k_s = \frac{2 \cdot E_a \cdot A_a}{D} \tag{13}$$

In Eq. (13), D is the diameter of columns measured eternally to wood spars, A_a represents the total area of the collars and E_a the steel elastic modulus, assumed here with a reduced value corresponding to the hardening phase.

It has to be stressed that the axial stiffens of collaring should consider the coupled effect of steel wires and wood spars. But, for simplicity here, only the radial axial stiffness of annular sections constituted by steel wires was considered, as shown in Eq. (13). Fig. 11 shows the comparison between the experimental and the theoretical critical load, calculated as discussed above.

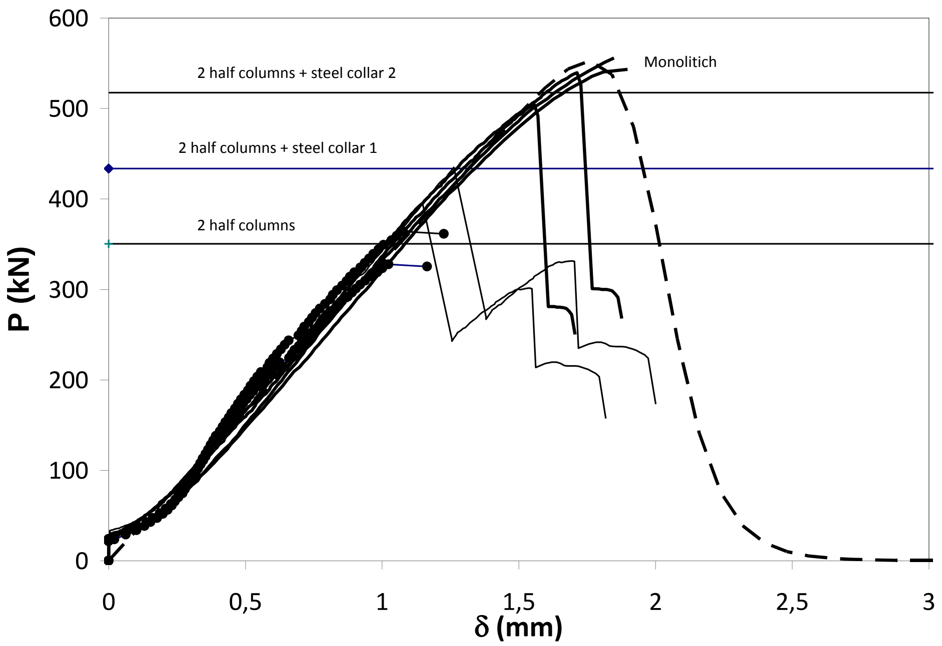

Fig. 11 Experimental and analytical prediction with the proposed model

The global compressive behaviour was also deduced by adopting the constitutive law given in Eq. (1). In all the cases, the theoretical provisions resulted in good accordance with the experimental data, highlighting the efficiency of the adopted technique in recovering the monolithic condition of the cracked column. Theoretical load values are those indicated in Fig. 11 and indicated with the horizontal continues line, while for monolithic columns complete load shortening curves was that obtained with Eq. (1). The numerical analysis was carried out by using the SAP 2000 [8] program, examining a simple beam cantilever model the model. Cross sections in both cases of circle of half-circle were modelled by using square strip elements. Non-linear compressive behaviour described by Eq. (1) was adopted. For tensile behaviour of marble stone, a linear behaviour was assumed and a maximum stress value was considered equal to 1/10 of the compressive strength. Both moduli of elasticity in compression and in tension were assumed 41750 MPa, in agreement with the expression given in Campione (2010). The variation of normalized axial load versus horizontal deflection is plotted in Fig. 12.

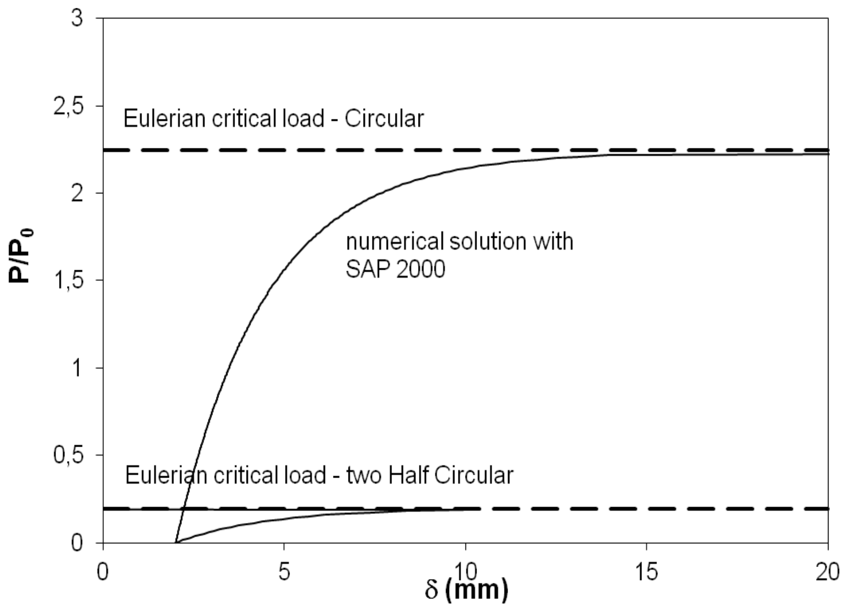

Fig. 12 Numerical solution with SAP 2000 for variation of critical load with lateral deflection

Load was normalized to compressive strength of un-cracked column. Also, theoretical values deduced by Eulerian approach are given. The numerical results are in agreement with the predicated values by Eulerian theory and the experimental values.

IV. CONCLUSIONS

In this paper it was verified the efficiency of the steel collaring technique as temporary strengthening technique of cracked marble columns under compression. Columns were reinforced with wood spars and steel wires, in order to reproduce a classical temporary technique frequently adopted by Firemen and Civil protection, also after earthquake in damaged columns. The technique is very cheap and easy to apply.

The results obtained experimentally highlight that:

- The compressive behaviour in compression of marble column is brittle and it is characterized by few vertical cracks;
- The load carrying capacity of half columns is that of slender columns related to buckling phenomenon;
- The use of steel collars increases the load carrying capacity of half columns and it ensures monolithic behaviour.

From an analytical point of view, a simple model based of the use of equivalent elastic beam on elastic springs is able to determine the load carrying capacity of half marble columns strengthened with steel collars.

Finally, further developments of the research will be addressed to investigate the size effects and to conduct a more extensive experimental research to give more general conclusions.

ACKNOWLEDGMENTS

This work has benefited from material derived the 2010-2013 Research Project ReLUIS (Rete dei Laboratori di Ingegneria Sismica), AT 1, Task 1.1.2: Strutture in Cemento Armato ordinarie e prefabricate.

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