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Autor: Ballio, Giulio / Calvi, G. Michele

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Strengthening of Masonry Structures by Lateral Confinement

Renforcement de construction en maçonnerie par remplissage latéral

Verstärkung von Mauerwerksbauten durch seitliche Umfassung

Giulio BALLIO
Professor
Politecnico di Milano
Milano, Italy

G. Michele CALVI
Assoc. Professor
Univ. degli Studi di Pavia
Pavia, Italy

G. Ballio is full professor of steel structures at the Politecnico di Milano. He is author of a book on steel structures which has been translated into English and Chinese. His research and professional activity is mainly devoted to steel and concrete structures and to rehabilitation of existing structures.

G. Michele Calvi received his MS from U.C. Berkley and his PhD from the Politenico di Milano. His main research interests are related to seismic response of reinforced concrete and masonry structures, with particular emphasis on identification and assessment of existing structures.

SUMMARY

The research deals with the quantitative evaluation of the safety increment obtainable through a lateral confinement of masonry structures, made with steel plates and bars. It is expressed as a function of parameters, such as dimensions of bars and plates and mechanical properties of masonry. Specimens from ancient masonry walls have been tested, obtaining different failure modes and variations of strength, deformation and energy absorption capacity. Suggestions are made on strengthening criteria to be used in practice, in relation to applied loads, design limit states and required safety factors.

RÉSUMÉ

La recheche traite de l'évaluation quantitative de l'augmentation de sécurité obtenue par un remplissage latéral de constructions en maçonnerie, réalisé à l'aide de plaques et de tirants en acier. Elle est exprimée en fonction de paramètres tels que dimension des barres et plaques et de la propriété mécanique de la maçonnerie. Des spécimens tirés d'anciennes murailles ont été testés, permettant d'obtenir plusieurs modes de rupture, en fonction des variations de résistance, de capacité de déformation et d'absorption d'énergie. Des propositions traitent les critères de renforcement en pratique, basées sur les charges appliquées, les états limites de projet et les facteurs de sécurité exigés.

ZUSAMMENFASSUNG

Die Forschung befasst sich mit dem Quantifizieren der erhöhten Sicherheit, die bei Mauerwerksbauten mittels lateraler Verstärkung aus Stahlplatten und -spangen erreicht wird. Dies geschieht in Funktion von Parametern, wie Grösse und Dicke der Platten und Spangen sowie der mechanischen Eigenschaften des Mauerwerks. Proben von alten Mauerwerkswänden wurden getestet und je nach Festigkeit, Verformungs- und Energieabsorptionsvermögen unterschiedliche Brucharten beobachtet. Praktische Verstärkungskriterien richten sich nach den aufzunehmenden Lasten, Grenzzuständen der Bemessung und geforderten Sicherheitsfaktoren.

1. FOREWORD

1.1 Philosophic choices for strengthening monuments

In recent years numerous problems arised about basic principles and actual techniques for strengthening monumental buildings, having become apparent that the great majority of the materials used in the past have only a very short life with respect to the life of the structure. As a consequence it is now believed by most researchers that the potential reversibility of the intervention has a key role in the evaluation of the appropriateness of the strengthening technique, reversibility being defined as the possibility of restoring the situation preceeding the intervention.

1.2 Strengthening by lateral confinement

The possibility of increasing the strength (or in general the safety against collapse) of elements essentially subject to vertical loads by a lateral confinement constituted by prestressed bars and confining plates is of particular interest, the only permanent (non-reversible) result being some minor hole in the masonry texture.

From a qualitatively point of view it is evident that a confinement will increase the safety of the structure, and the basic mechanisms which will allow such an increment are qualitatively clear, as well. Nevertheless many questions remain without an answer if a precise evaluation of the safety of the strengthened structure is required, as a function of appropriate parameters of the original structure and of the strengthening intervention.

An interesting application of this technique has been applied by one of the authors to the case of a medieval masonry tower: details are presented in [1].

1.3 Objectives and methods

The main objective of the research presented in this paper consists in the determination of the increment of strength, deformability and energy absorption capacity obtained as a consequence of a lateral confinement of a masonry wall, as a function of appropriate parameters, such as ratio between bar and plate area, ratio between distance between two plates and wall thickness, and expected failure modes.

To pursue this objective twelve wallettes obtained from medieval masonry walls have been tested, varying the parameters mentioned above in order to obtain three possible failure mechanisms:

- yielding of the horizontal bars;
- punching of masonry underneath the confinement plates;
- shear-tensile failure of masonry in the less confined zones between plates.

The large scatter of material properties together with the limited number of available specimens would have not assured a dependable interpretation of the results through a correlation of different tests on different specimens. Each specimen has therefore been loaded at maximum load, strenghtened, and loaded to failure, then considering percentual increments rather than absolute values of the properties of interest.

A more detailed presentation of the research can be found in [2].

3. DESIGN OF THE EXPERIMENTAL TESTS

3.1 Properties of materials

The masonry walls to be strengthened had been taken from the debris of a medieval tower failed in 1989 [3,4]. The basic material is rather a conglomerate made with pieces of clay bricks and river stones enbedded in a lime mortar matrix, then a standard brickwork; such material is common in ancient structures, where thick walls present a regular brickwork only in the outer skin.

The ultimate strength was in the range of 2 to 4 MPa, with Young modulus varying between 700 and 4600 MPa and ultimate deformation of 0.3% to 0.5%. A significant cracking process starts at

horizontal deformations of 0.02% to 0.08%, while the ultimate horizontal deformation is between 2.5% and 5%. These values imply that the plastic deformation of confining steel bars should take place in a highly non-linear range of the masonry behaviour, with two positive consequences:
- the initial prestressing tension of the bars should not affect the results, since the corresponding strain is neglegible with respect to the potential lateral expansion of masonry;
- the properties of the steel bars are fully exploited, either in terms of strength and in terms of energy absorption capacity.

The steel used for the reinforcing bars had a yield stress of about 600 MPa and a uniform elongation capacity (i.e. at maximum force) between 3% and 4%.

3.2 Failure modes

As already mentioned three fundamental failure modes have been considered, as shown in figure 1. For the purpose of some preliminary estimation of the failure mode to be expected, a bidimensional behaviour was assumed, imposing a perfect confinement in the third direction. These conditions could correspond to those of a wall with width significantly larger than thickness, and have been reproduced in the tests applying much stiffer bars and plates covering the whole side in one of the horizontal directions (see figure 2).

The relative probability of bar yielding versus punching of masonry depends on the ratio between bar section and plate surface, as well as on material properties.

Assuming a yield strength of steel bars (f_{ys}) of 600 MPa and a punching strength of masonry of 6 MPa (f_{pm}; it has to be obviously higher than compression strength), an equal probability of failure is obtained for a ratio of 100 between area of plate (A_p) and area of bar (A_b). For this reason squared plates with side of 40 and 80 mm have been used in conjunction to 6 mm diameter bars, obtaining $A_p/A_b = 57$ and 226.

A numerical evaluation of the probability of the third failure mode (i.e. shear-tensile failure of unconfined masonry) is more difficult, since it depends on mechanical properties of masonry which are not sufficiently known; it is nevertheless clear that the ratio between plate distance and wall thickness can be assumed as a fundamental parameter. Values of 0.5 and 1 have been assumed for this parameter, since 0.5 is considered to be a lower limit, hard to prescribe in a real case.

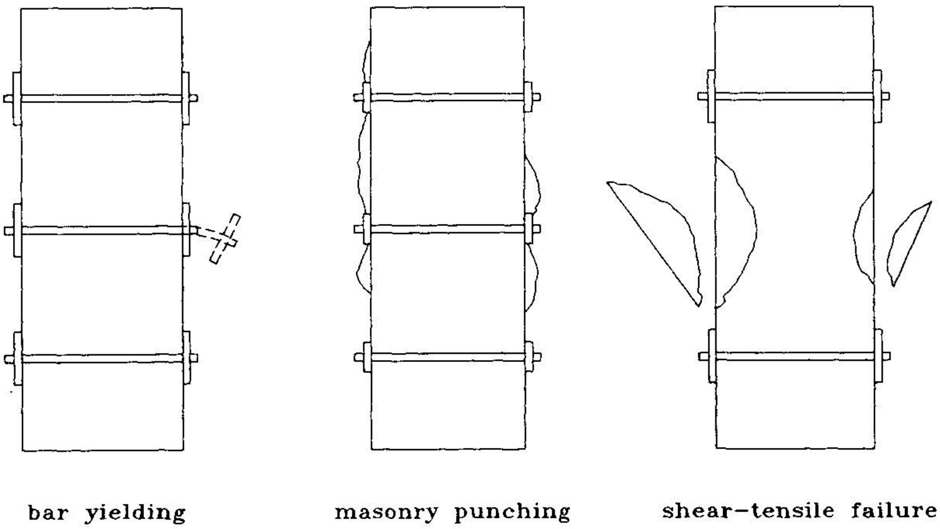

Fig. 1 Possible failure modes. From the left hand side: yielding and fracture of bars; punching of masonry beneath the confining plates; shear-tensile failure in the unconfined region

3.3 Test setup

The approximate dimensions of the wallettes were 650x700x290 mm, with a vertical load applied on the 650x290 sides, and the prevoiusly mentioned "perfect" confinement on the 700x290 sides.

On the 650x700 sides 4 or 9 plates were applied, tied with 4 or 6 mm bars located through holes very carefully drilled. A slight tensile stress (70 to 300 Mpa, depending on number and diameter of bars) was applied to the bars before testing the strengthened specimens, obtaining an average compression stress in the masonry of approximately 0.05 MPa; as already mentioned this was not considered a fundamental parameter.

All bars were instrumented with strain gauges, displacement transducers were applied to measure vertical and two horizontal deformations (see figure 2).

Each specimen had been first loaded to its maximum capacity, then unloaded to 70% of maximum load, confined by tying the plates up and stressing the horizontal bars, and finally loaded to complete collapse. Clearly all the specimens were significantly damaged before being strengthened.

It is worth mentioning that all the bars had originally a diameter of 6.5 mm, and only in the region of application of the strain gauge were milled to 6 or 4 mm; as a consequence the confining force capacities were significantly different in the two cases (of about 50%), but the corresponding total elongation of the bars was approximately the same.

3.4 Expected results

An estimation of the expected increment in strength and deformation capacity has been tempted on the base of energy considerations, assuming yielding in the steel bars and equating their strain energy to the increment of the energy absorption capacity of the masonry panels. Such an approach has been used in the past to evaluate the effects of steel confinement on reinforced concrete members [5], but it is questionable whether other dissipation mechanisms, such as friction in cracks, would not be greatly affected by the presence of confinement, therefore increasing the energy absorption capacity of the specimen. The very low reinforcement percentages contribute to raise this concern.

Assuming the materials behaviour as shown in figure 3, the total energy absorption capacity of the wall can be approximately evaluated as 1400 kN mm, the energy absorption capacity of each reinforcing bar as 140 kN mm. The energy increment should therefore be estimated as 40%, for the case with 4 bars, and 90% for the case with 9 bars, provided that the assumptions mentioned above are applicable and that the final collapse corresponds to a contemporary fracture of all bars. The energy increment could correspond to different combinations of strength and deformation capacity variations.

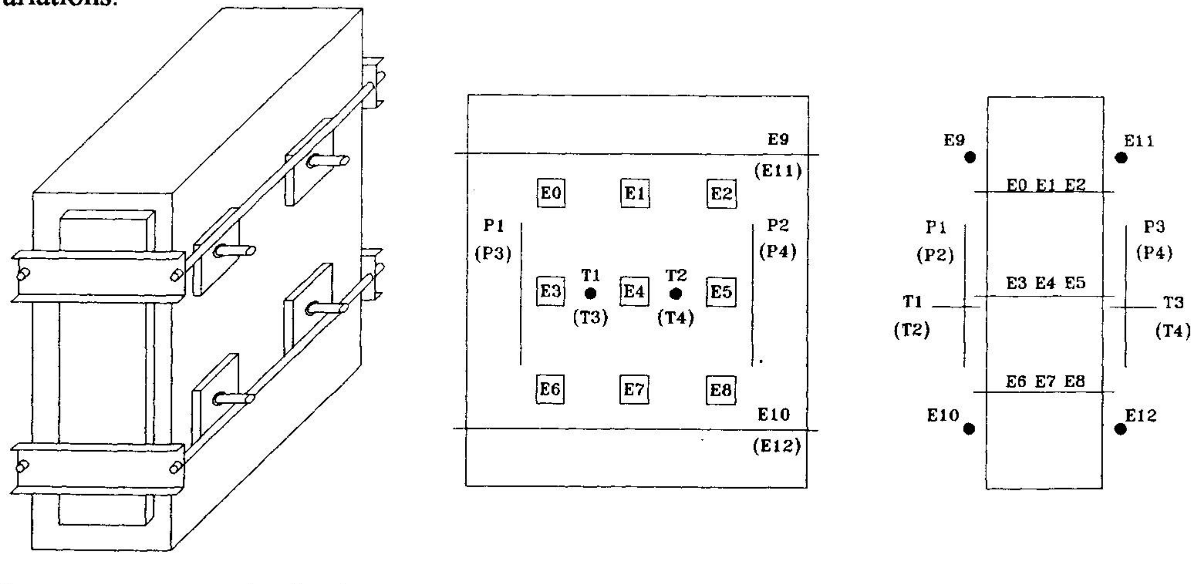

Fig. 2 Test setup (P: linear potentiometers, T: LVDT, E: Strain gauges)

4. EXPERIMENTAL RESULTS

4.1 Failure modes

The failure modes experimentally obtained corresponded substantially to the expected modes:

- in three wallettes strengthened with four bars a shear-tensile failure took place in the central (less confined) region. Only in one case one bar fractured. It has to be noted that the shear-tensile failure is strongly affected by the heterogeneity of the masonry conglomerate, it is therefore logical to expect various response in term of post-peak branch as well as in term of strength, deformation and energy absorption capacity;
- the specimens strengthened with nine 80x80 mm plates and 6 mm bars shew fracture of one or two bars followed by a rapid strength deterioration;
- punching of masonry has been detected in the cases with 40x40 mm plates. The strength deterioration progressed gradually to a final shear-tensile collapse of the no more confined masonry;
- eventually in the case of nine plates and 4 mm bars an apparently contemporary fracture of four bars took place, with an immediate total collapse of the wallette.

4.2 Strength

The unconfined specimens shew a very uniform strength (average 3.66 MPa, c.o.v. 0.13), probably because all of them had been obtained from the same block of material, therefore being characterized by a random distribution of pieces of bricks and stones, but by the same mortar matrix as well.

On the opposite the strength increments varied from 4% to 43%, with an average of 22.7%.

The greater variability was encountered, as expected, in the case of four plates (i.e. shear-tensile failure), with increments between 4% and 25%.

4.3 Deformation capacity

The recorded Young modulus (E_s, taken on the straight line to the point at 70% of the unconfined strength) was also quite uniform (2854 MPa, c.o.v. 0.22). No initial hardening due to compaction of voids and closing of microcracks has been detected.

The ultimate deformation capacity of the unconfined specimens was equal to 0.24% (average, c.o.v. 0.26), with an equivalent "ductility" (μ_u, defined according to figure 4) of 1.76 (c.o.v. 0.12).

The ductility calculated for the strengthened specimens (μ_c) was never lower than 7.18, with an average of 9.92. The ultimate deformation was therefore equal to at least five times the original ultimate deformation, no matter how the walls had been strengthened.

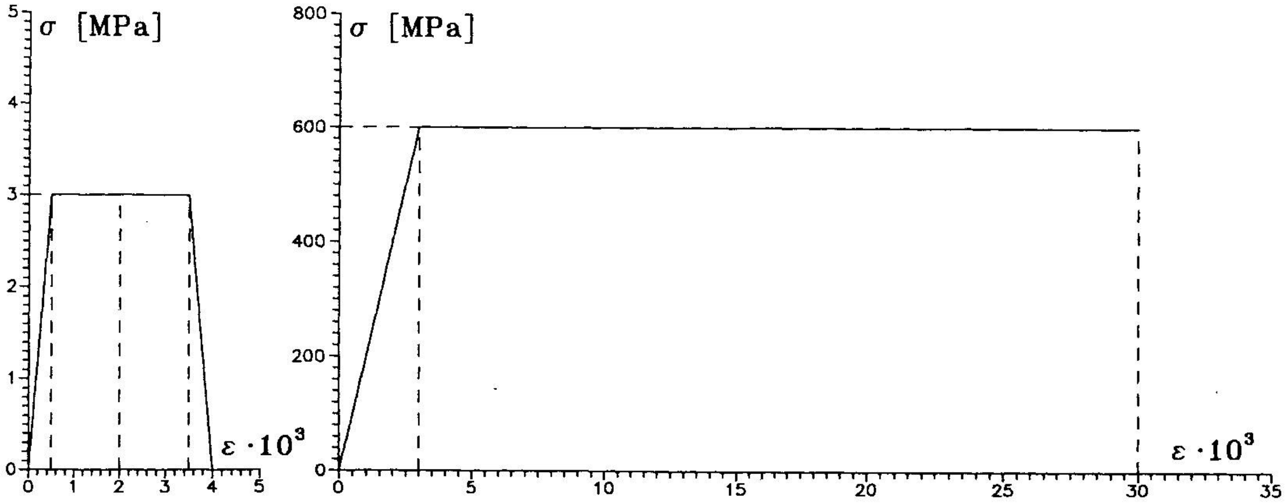

Fig. 3 Assumed material behaviour. Left: masonry; right: steel bar

4.4 Energy absorption capacity

The energy absorption capacity of the stengthened wallettes is, on the average, 5.5 larger than in the unconfined conditions (c.o.v. 0.37), as expected from the figures given on strength and deformation capacity. This results clearly indicates that the strain energy of the bars has little to do with the increment of the total energy absorption capacity. Actually if a detailed evaluation of the energy absorbed by the bars is performed values from 30 to 300 times smaller than the increment in energy absorption capacity are found.

Strengthening through confinement is therefore very convenient from an energy point of view, since a negligible amount of energy effectively added allow the exploitation of resources hidden in the original structure. For the same reason it appears that the increment in the energy absorption capacity is relatively unsensitive to modes of failure and confinemement details.

The increment of energy absorption capacity is probably related to phenomena of friction and aggregate interlock.

5. CONCLUSIONS

5.1 Strengthening criteria

The experimental investigation confirmed the expected failure modes; it is therefore reasonable to conclude that ratios between plate and bar area of about 100 separate cases for which bar yielding and punching of masonry have to be expected. For different materials the assumptions adopted in section 3.2 can be applied.

The experimental results also suggest that a shear-tensile failure is not likely to take place if the distance between plates edge is smaller than the thickness of the wall. This result may be significantly influenced by scale effects and texture of the outer skin of the wall; it has therefore to be applied with caution. For large scale structure and good masonry brickwork skin it is felt that it may result in very conservative solutions.

It has to be recommended to avoid the shear-tensile failure mode, because of the unreliable prediction of the improved behaviour after strengthening.

The punching of masonry failure mode partially compensates a less dependable behaviour up to the maximum stress with a slower strength deterioration.

It can be concluded that it is important to limit the distance between plates edge, while the ratio between plates and bars area can be maintained around the separator value.

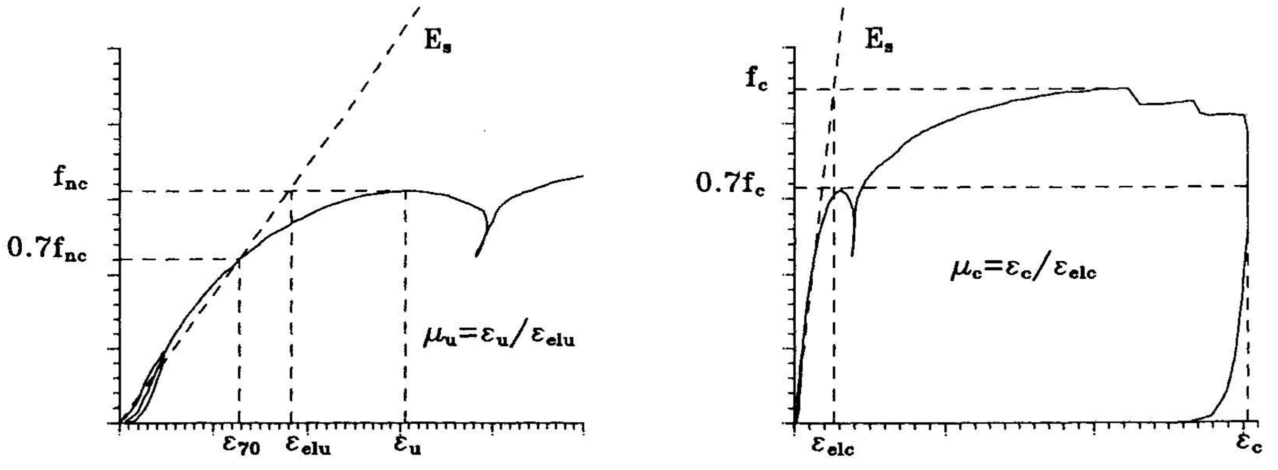

Fig. 4 Typical stress-strain curve obtained from the tests (the definition used for stiffness, equivalent elastic limit and ductility are shown)

The experimental investigation has shown that for the given materials increments of 20% in strength and of 500% in deformation capacity can be assured if proper details are used. It is then necessary to evaluate the variation of the safety of the structure which corresponds to these or other increments. For the seismic case it is common practice to translate available ductility into force reduction factors, this case will not therefore be discussed here in details. It is worth anyway to mention that a ductility of 5 could correspond to force reduction factors of the order of 3 for regular structures, the overall seismic safety for the specific case of the masonry towers from which the specimens were taken could be improved of about four times through a proper confinement.

If long duration or simply gravity loads constitutes the main concern it is still possible to obtain great benefits from ductility if the material strength varyies significantly from point to point. To make the point assume that a tower is made with three perfect materials randomly distributed, with strength equal to 2, 3 and 4 MPa. The benefit of an elastic-perfectly-plastic behaviour versus an elastic-brittle behaviour can then be estimated in an overall strength increment equal to 50 %, as shown in figure 5, which gives a total safety increment equal to 80% when combined with the a local general strength increment equal to 20%.

The most important effect of the strengthening technique here presented lies therefore in allowing stress redistributions without local collapse. An implicit confirmation of its selective effects (function of the local stress and damage level) can be learnt from the results of dynamic identification tests performed on a medieval tower before and after strengthening [6]: while the natural frequencies remain substantially unchanged, significant variations have been detected in the modes of vibration.

5.2 Future research development

The evaluation of the safety increment of a masonry tower deserves more refined studies then what presented above. For this reason extensive parametric finite element analyses are planned. The relevance of the material distribution and the possible definition of "critical volumes" for which abnormal behaviours have to be expected are of particular interest. This study involves probabilistic simulations, or at least statistical sensitivity analyses, with 3D non linear elements.

The abundance of experimental data related to the behaviour of masonry conglomerate under tridimensional states of stress and strain suggests the possible development of a constitutive model based on full strain and stress tensor. It is planned to explore Mohr-Coulomb-type constitutive relations, essentially derived from geotechnical models, as well as relations based on functions of the stress (strain) tensors invariants.

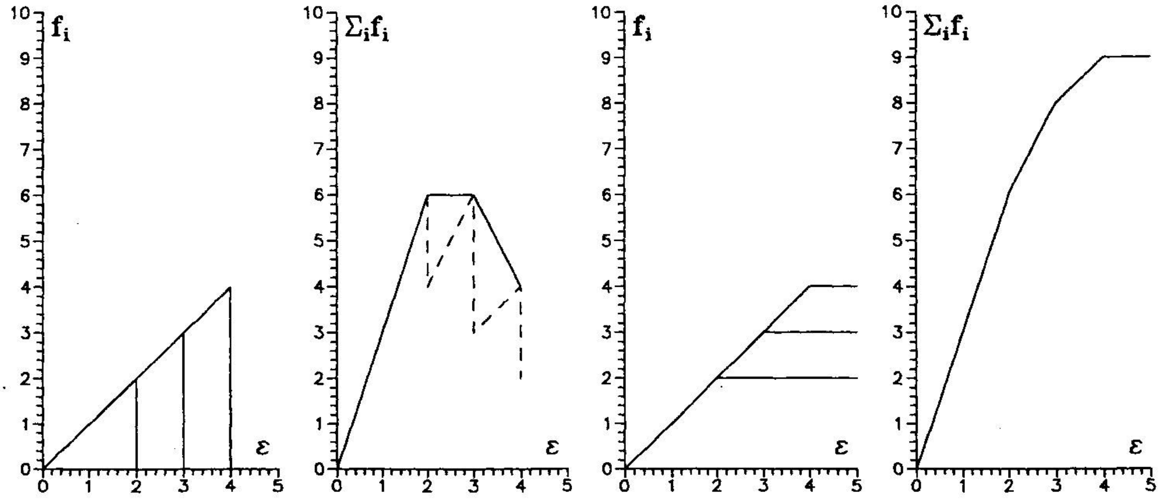

Fig. 5 Comparison of the overall behaviour shown by systems made with materials of different strength working in parallel. Left: elastic-brittle; right: elastic perfectly plastic.

n_p		4	4	4	4	6	6	6	6	6	6
l_p	[mm]	80	80	80	80	80	80	40	40	80	80
f_b	[mm]	6	6	6	6	6	6	6	6	4	4
Df/f_u	[%]	25	23	18	4	27	33	17	43	25	12
μ_u		1.83	1.48	1.71	1.46	1.76	1.87	1.89	1.67	1.71	2.25
μ_c		7.9	9.1	8.2	9.3	9.6	17.6	7.2	11.6	8.2	10.3
E_c/E_u		3.7	5.8	4.2	4.5	5.3	9.9	3.4	8.6	4.8	4.7
$\Delta E/E_s$		167	145	205	29	53	73	106	337	98	131

Table 1 Summary of the experimental results. Each column corresponds to a tested wall, with the indication of (from the top) number of plates, side of the plates, bar diameter, percentual increment of strength, equivalent ductility of the unconfined and confined specimens, ratio between absorbed energy of the confined and unconfined specimens, ratio between increment of absorbed energy and strain energy effectively absorbed by the the bars.

REFERENCES

1. Ballio, G., "Structural preservation of the Fraccaro tower in Pavia", *Structural Engineering International, Journal of IABSE*, Vol. 3, N. 1, 1993

2. Ballio, G., G. M. Calvi and L. Duico, *Rinforzo di pareti murarie per mezzo di confinamento laterale*, Report No. 46, Dipartimento di Meccanica Strutturale dell"Università di Pavia, Pavia, 1992 (in italian)

3. Binda, L., G. Gatti, G. Mangano, C. Poggi and G. Sacchi Landriani, "The collapse of the Civic Tower of Pavia: a survey of the material and structure", *Masonry International*, Vol. 6, N. 1, 1992, pp.11-20.

4. Calvi, G. M., and M. J. N. Priestley, "Investigations of the collapse of a medieval masonry tower", *The TMS Journal*, Vol. 9, 1990, pp. 51-59.

5. Mander, J. B., M. J. N. Priestley and R. Park, "Theoretical stress-strain model for confined concrete", *Journal of the Structural Division*, ASCE, Vol. 114, N. 8, 1988, pp.1804-1826.

6. Pavese, A. and M. Fanelli, "Diagnosis of masonry tower by dynamic identification using parametric techniques" *Proceedings of the IABSE Symposium "Structural preservation of the architectural heritage"*, Roma, 1993

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