Use of Sonic and GPR Tests to Control the Effectiveness of Grout Injections of Stone Masonry

Anna ANZANI, Luigia BINDA, Maurizio LUALDI, Cristina TEDESCHI, Luigi ZANZI
D.I.S. Politecnico di Milano, Milano, Italy

Abstract. Some specimens reproducing three leaf stone masonry walls frequently used in Italy, have been built at DIS, Milan, using two different types of stones and tested under compression and shear, up to failure. Subsequently the damaged wallettes were repaired by injection and the effectiveness of the injection was controlled by several NDT (non destructive techniques)

Introduction

Repair and strengthening of historic masonry structures by grout injection has been carried out in the last decades in many cases. Although the technique has been refined in the last years by the results of several research, the earthquakes occurred in 1997 and later in central Italy, have shown that this technique can only be applied after an appropriate investigation for the injectability assessment of the masonry. Furthermore, non destructive techniques should be applied after injection to control its effectiveness, gaining more reliable evaluations than that obtained by a local coring.
Some specimens reproducing three leaf stone masonry walls frequently used in Italy, have been built at DIS - Milano, using two different types of stones and two geometries. The wallettes were tested to failure under shear and compression and subsequently repaired by injection. High frequency radar measurements were performed before the repair intervention to assess the fracture situation. The effectiveness of the injection was controlled by different NDT (non destructive techniques) applied before and after the interventions to test the potential of these methods. Sonic velocity was measured horizontally in transmission mode between the shortest sides of the specimens. Surface measurements were also performed both horizontally and vertically on one of the longer sides of the wall to compare this testing geometry with the more conventional transmission geometry (not always applicable in real situations). High frequency radar measurements were performed before the repair intervention to assess the fracture situation.

1. Preparation of the multiple-leaf stone walls

The specimens were built choosing the materials and morphology in order to reproduce the behaviour of multiple leaf walls and piers frequently encountered in historical centres. Two external leaves, made of stone blocks with horizontal and vertical mortar joints, were connected to an internal leaf in rubble masonry made of mortar and pebbles of the same stone. Two types of connection between the leaves (with flat collar joints and with keyed collar joints) were adopted to build specimens of dimensions $310\times510\times790$ mm^3 (figure 1).

A sandstone tuff denominated Noto stone and a medium grained sandstone denominated Serena stone, having higher mechanical characteristics and lower porosity, were used [1]. To build both the external and the internal leaves of all the masonry specimens the same ready-to-mix hydraulic lime mortar was used, having a compressive strength after 180 days equal to 11 N/mm^2.

2. First series of tests

Two types of load conditions were considered: compression tests (figure 1a) and (pseudo-) shear tests (figure 1b).
Results on the whole lot of tests carried out can be found in [1]. Results of the tests carried out on the walls subsequently repaired are reported in table 1, together with the indication of the technique subsequently applied for the repair.

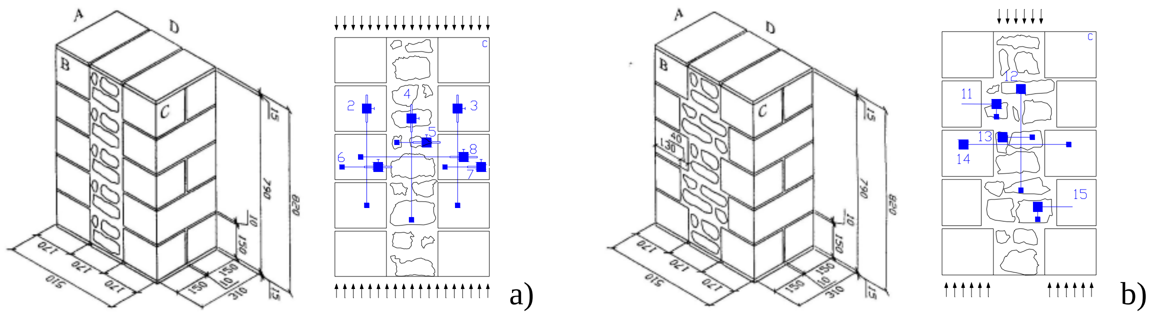


Figure 1. Geometry of the walls and types of loading conditions: (a) flat collar joints and compression test; (b) keyed collar joints and shear test.

Table 1. Results of the first series of test and technique applied for repair.

wall	test	P_{max} [KN]	d_{max} [μm]	repair technique
PN6	shear	291.36	1949	Injection
PN4	shear	277.97	2633	Injection and steel rods
PS4	shear	383.67	4057	Injection
PS3	Compression	> 2500	_	Injection

Considering the pseudo-shear tests, the Serena stone specimens presented an average peak load of about 1.5 times higher than the ones of Noto due to the higher strength of the stones. Analysing the crack patterns, many vertical and sub-vertical cracks on the inner leaf can be detected. In the case of the Noto stone specimens, such cracks often cut the stones (figures 2 and 3), whereas in the case of the Serena stone specimen cracks tended to diffuse in the mortar at the interface with the stone fragments (figure 4). This is due contemporarily to the better adhesion between the mortar and the Noto stone, characterized by a higher porosity than the Serena one, and to its lower strength. The outer leaves, in the case of the Noto stone, suffered from some cracks appeared at the base of the specimens.
The failure of the Serena specimen PS3 tested in compression was not achieved being the required load beyond the limits of the testing machine. The inner leaf underwent very low vertical strains compared to the external ones, and almost naught horizontal strain. This indicates that no collaboration between the leaves took place, that the load-bearing role was mainly played by the outer leaves, and that the outer leaves exerted a confining action towards the development of transversal deformations of the inner leaf. This was confirmed by the crack pattern, where only the separation between the leaves can be seen (figure 5).

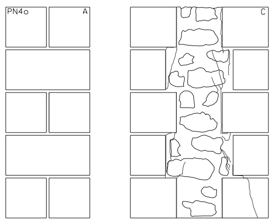


Figure 2. PN4 after shear test.

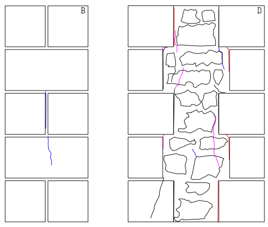


Figure 3. PN6 after shear test.

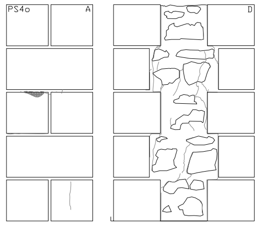


Figure 4. PS4 after shear test.

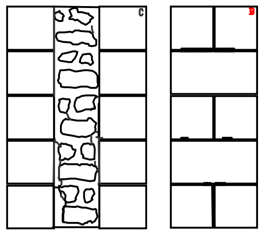


Figure 5. PS3 after compression test.

3. Repair of the specimens

Once removed from the testing machine and stored in the laboratory, the aspect of the walls was that visible in figure 6. Before repairing them by injection, a partial reconstruction of the outer leaves was necessary as appears in figure 7a. The injection was aimed to fill the main cracks appeared at the interface between inner and outer leaves. The materials chosen for the intervention were completely inorganic mixes based on microfine pozzolanic binders.

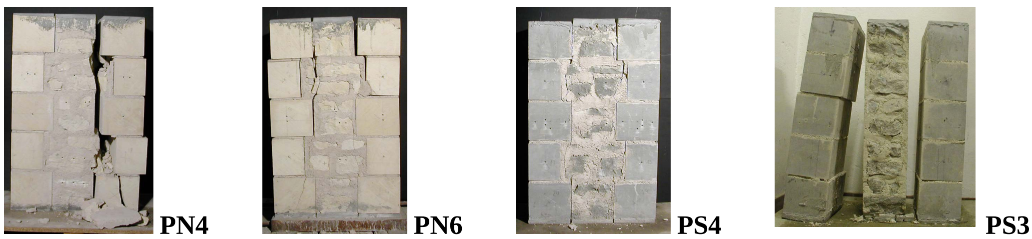


Figure 6. Aspect of the specimens once removed from the testing machine.

The walls were injected in wet conditions through small pipes drilled at regular distances along the collar joints, introducing the grout at pressure not higher than 6 atm starting from the lower pipes. Once the mix started to exit from the upper level of pipes they were then injected too. In the case of wall PS3 the injection was carried out by gravity, once the leaves constituting the wall had been re-connected as shown in figure 7e and the collar joints had been sealed for a depth of about 10 mm in order for the mix not to leek. After the wall reconstruction and after the grout injection the walls were tested by NDT as described in the following paragraph.

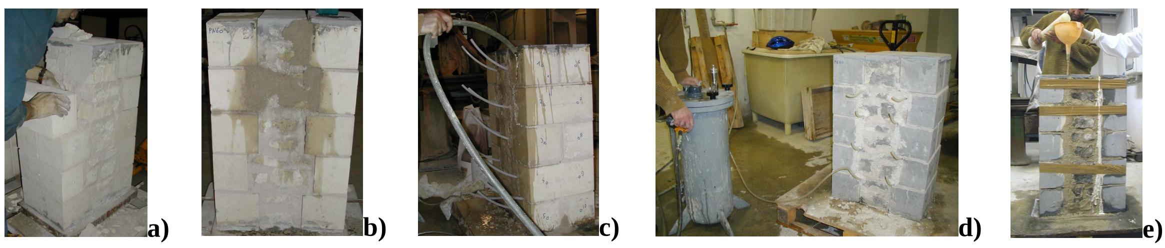
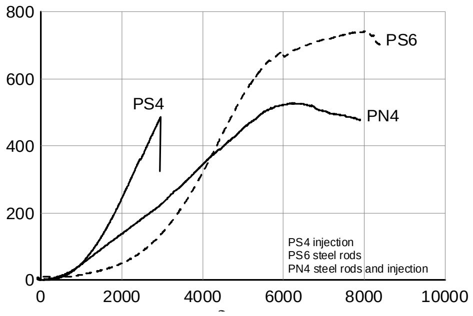


Figure 7. Phases of the repair by grout injection.

After about seven months of curing, two of the walls were tested again in pseudo-shear conditions. The results are reported in figure 10 where a comparison with wall PS6 repaired only through steel rods can be done. A higher load increase was achieved in the case of the wall PN4 repaired with both techniques; the use of grout injection only resulted into a stiffer and more brittle behaviour, whereas in the case of steel rods only a particularly ductile behaviour was performed.



Wall	$P_{max,a} / P_{max,b}$
PS40	1.24
PS60	1.68
PN40	1.83

Figure 8. Results of pseudo-shear tests on the repaired walls and ratio between the maximum load after and before the repair ($P_{max,a} / P_{max,b}$)

4. Non destructive evaluation

Sonic measures and georadar survey (figure 9) have been carried out on the masonry specimens in order to study the possibility of estimating the effectiveness of the injections, that is the penetration and diffusion of the grout soon after injection. The aim is the application of NDT to define in-situ the effectiveness of the injection technique.

Figure 9. Sonic measures and georadar survey.

Measurements were taken before and few days after the injection. The possibility of characterizing the material propagation into the masonry in situ as soon as it has been injected would concur to check and possibly complete the operation while the equipment is still on the work place.

Before the injection, a GPR 2D surveys were carried by a 1,5GHz antenna in order to produce a map of cracks and voids present inside the masonry (figure 10).

Many fractures are evident in the area enclosed in the blue rectangle, corresponding to one of the interfaces between inner and outer laves, whereas the yellow and green rectangles point out smaller cracks corresponding to the second interface.

Sonic measurements have been taken by a simple instrumentation: a hammer-trigger and an accelerometer. The sonic velocity was measured horizontally in transmission mode, hitting the specimens with the hammer according to a grid sketched symmetrically on the two short sides of the walls and measuring with the accelerometer on the correspondent points on the opposite side. Surface measurements were also performed both horizontally and vertically (figure 11) on one of the larger sides of the specimens, by hitting with the hammer and recording with the accelerometer in different points of the grid sketched on same side.

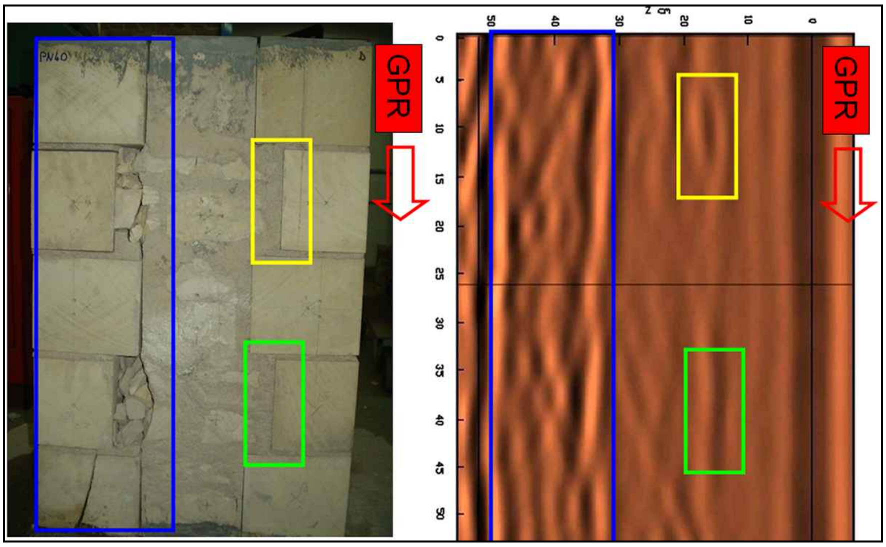


Figure 10. GPR 2D survey carried out by a 1.5GHz antenna on wall PN40.

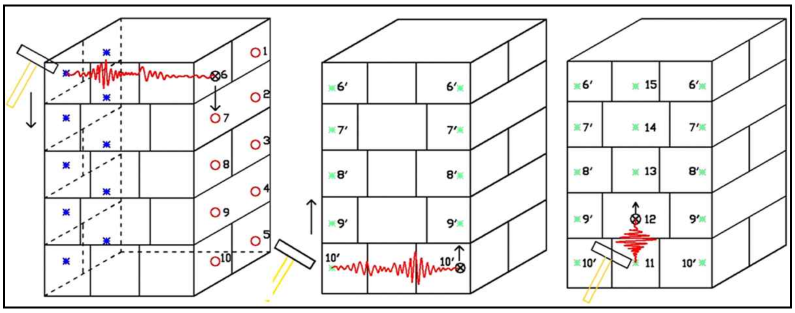


Figure 11. Scheme of the geometry of the sonic measures: on the left transmission mode, in the middle horizontal surface mode and on the right vertical surface mode.

Two campaigns of sonic measures have been carried out before and after the injections in order to determine the variation of the speed of the elastic waves due to the injection. As expected, a remarkable increase of sonic velocity was generally observed as a result of the injections (figures 12 and 13).

Conclusions

Several NDT methods were used before and after the injections to test the potential of these methods in validating the effectiveness of the repair interventions. Sonic velocity was measured horizontally in transmission mode between the shortest sides. Surface measurements were also performed both horizontally and vertically on one of the longer sides to compare this testing geometry with the more conventional transmission geometry (not always applicable on real situations).

According to the results, sonic measures turned out to be sensitive to the effects of grout injection on multiple leaf stone masonry. Applying them before and after the injection allows to estimate whether the grout is diffused inside the masonry. As expected, a remarkable velocity increase was generally observed as a result of the injections. The tests showed the importance of these measures to improve the injection technique and to control the penetration and diffusion of the grout during the works on site. In fact, they are enough simple to carry out and allow to gain data nearly immediately; therefore they can be used on site to determine how an injection is being developed and try to correct when some anomalies are evidenced.

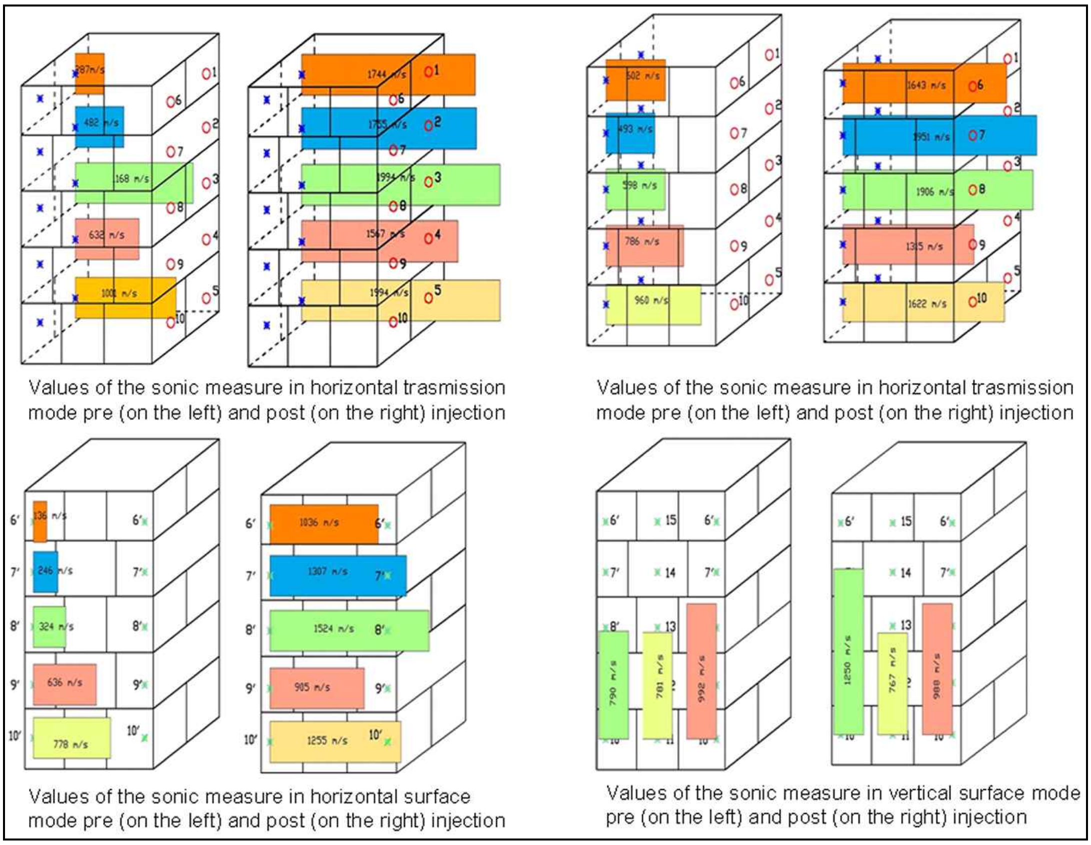


Figure 12. Values of sonic velocity pre and post injection acquired with different geometry on wall PN40.

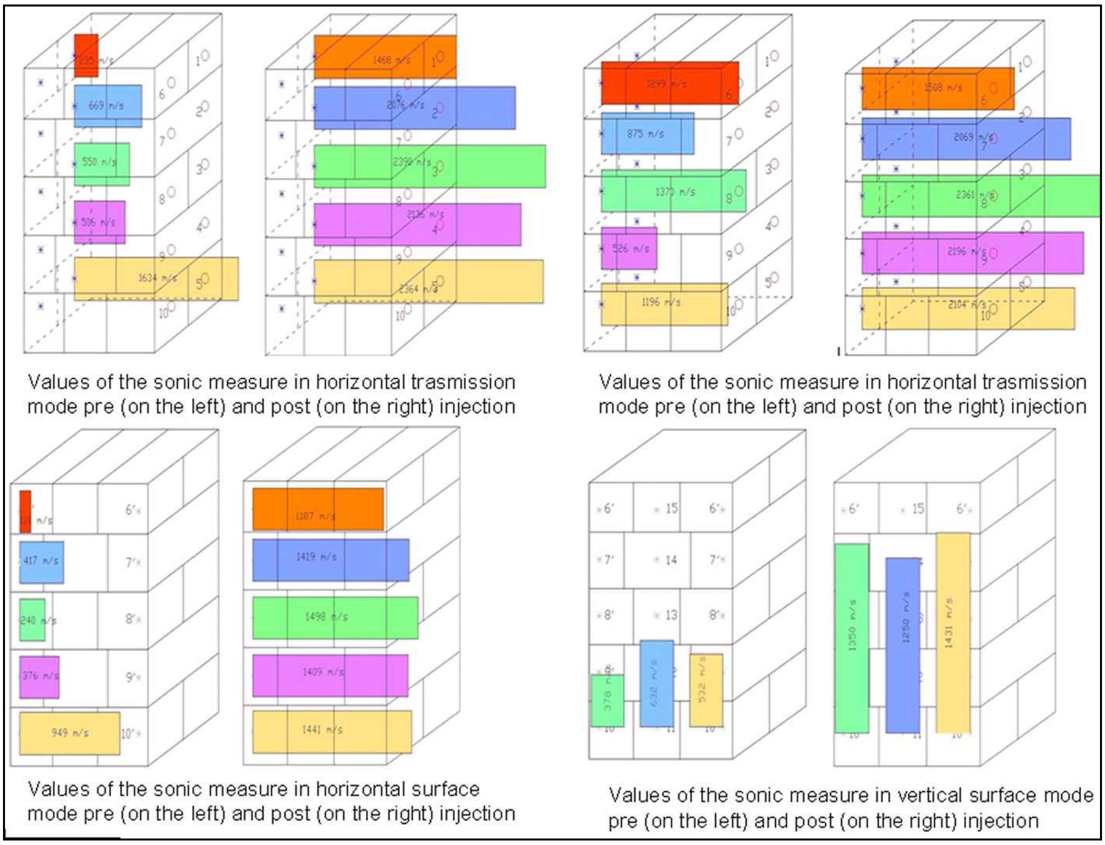


Figure 13. Values of sonic velocity pre and post injection acquired with different geometry on wall PN60.

High frequency radar measurements can be used in order to qualify the material that constitutes the wall in order to optimize the choice of the position of the points of injection. It helps in discriminating between the zones of the masonry interested by macro fractures and voids, those characterized by smaller, diffuse fractures and areas of compact material so to better program the drilling positions.

Acknowledgements

M. Ciano, M. Carsana, F. Cappellini, I. Mecca, S. Rampoldi are gratefully acknowledged for their assistance in the experimental activity, M. Antico and M. Iscandri for the technical support.

References

[1] Binda L., Anzani A., Fontana A., Mechanical behaviour of multiple-leaf stone masonry: experimental research, 3-Day Int. Conf. Structural Faults & Repair, London, 1-3/7/2003, MC Forde (Ed.), Engineering Technics Press, Edinburgh, ISBN 0-947644-53-9, CD-ROM, Keynote Lecture, 2003.

[2] Binda L., Fontana A., Anzani A., Multi-leaf Masonry: Shear Transfer at Interfaces, 6th Int. Symp. Computer Methods in Structural Masonry (STRUMAS VI), Ed. T.G.Hughes & G.N. Pande, Computers & Geotechnics Ltd, ISBN 0-9510380-3-6, Roma 22-24/09/2003, pp. 142-148, 2003.

[3] Anzani A., Binda L., Fontana A., Pina-Henriques J., An experimental investigation on multiple-leaf stone masonry13th International Brick/Block Masonry Conference RAI Amsterdam, July 4- 7, CD-ROM, 2004.

[4] Anzani A., Binda L., Ramalho M.A., Taliercio A., Historical Multi-Leaf Masonry Walls: Experimental and Numerical Research, Masonry International, ISSN: 0950-2289, Vol. 18, n.3, pp. 101-114, 2005.

[5] Ramalho M., Papa E., Taliercio A., Binda L., A Numerical Model for Multi-Leaf Stone Masonry, Conv. 11th Int. Conf. on Fracture (ICF11), Torino, March 20-25, CD-ROM, 2005.

[6] Ramalho M., Taliercio A., Anzani A., Binda L., Papa E., Experimental and numerical study of multi-leaf masonry walls, Ninth Int. Conf. on Structural Studies, Repairs and Maintenance of Heritage Architecture (STREMAH), Eds. C.A. Brebbia, A. Torpiano, 22-24/06/2005, Malta, Section 4, ISBN 1743-3509, pp. 333-342, 2005.

[7] Baronio G., Tedeschi C., Binda L., Restoration of A Tower: Choice of Mortars and Grouts for Repointing and Injection, 9th Int. Conf. and Exhibition, Structural Faults + Repair, 4-6 July, CD-ROM, 2001.

[8] Laefer D., Baronio G., Anzani A., Binda L., Measurement of grout injection efficacy for stone masonry walls, Conv. 7NAMC, Notre Dame, USA, Vol. 1, pp. 484-496, 1996.

[9] Binda L., Cardani G., Penazzi D., Saisi, A., Performance of some repair and strengthening techniques applied to historical stone masonries is seismic areas, ICPCM a New Era of Building, Cairo, Egypt, 18-20/2/2003, Vol. 2, pp. 1195-1204, 2003.

[10] Modena C., Valluzzi M.R., Tongini Folli R., Binda L., Design Choices and Intervention Techniques for Repairing and Strengthening of the Monza Cathedral Bell-Tower, Construction Building Materials, ISSN 0950-0618, Special Issue, 16(7), pp. 385-395, 2002.