NON DESTRUCTIVE EVALUATION OF THE EFFICACY OF MASONRY STRENGTHENING BY GROUTING TECHNIQUES

M. Berra*, L. Binda**, L. Anti**, A. Fatticcioni*
* ENEL-CRIS, Milano, Italy
** Dept. of Structural Engineering, Politecnico di Milano, Italy

ABSTRACT

A research program has been developed by the authors in the past four years to study the efficacy of strengthening decayed masonry walls by injection of grouts. Brick masonry prisms were built in laboratory, cracked and subsequently injected with epoxy resins, polymeric and cementitious grouts; advantages and disadvantages of the technique were shown. Sonic and ultrasonic tests were carried out to detect the improvement of the material properties after injection. The results obtained encourage to prefer the use of sonic tests in the diagnosis of masonry when a repair needs to be made; moreover the sonic tests can be satisfactorily used to control the penetration and diffusion of grout inside the masonry. Some new experience has been made on prisms cut out of blocks recovered from the ruins of a Medieval Tower collapsed in 1989. It was also possible to apply the investigation procedure in-situ to brick masonry.

1. INTRODUCTION

The effectiveness of strengthening damaged masonries needs to be evaluated, especially when the use of materials and techniques is not based on a long experience. Repair and strengthening of masonries by reinforced and unreinforced injections of grout has been largely used in Europe during these last decades; nevertheless there is a lack of criteria useful to state whether the intervention was successful. Moreover it is also difficult to decide previously whether the repair is really needed, if it has to be limited or extensive. In other words an evaluation of the safety factor of the structure is required before any decision is taken for the repair, strengthening, conservation or even demolition of the masonry walls. 

Destructive tests are often unreliable because of the difficulty of sampling representative specimens, the high cost of repair which must follow the sampling and the poor correlation that may exist for samples which are disturbed during the extraction. However technology for non-destructive evaluation of masonry structures cannot yet be used with confidence due to the lack of correlation between data of non-destructive tests and parameters representing the state of the structure. Among the procedures applied for non-destructive evaluation of masonry structures, ultrasonic and sonic pulse tests have been proposed and applied since a long time with different purposes such as correlation between velocity and compressive strength [1], evaluation of the degree of deterioration of stone and brick masonry elements [2], detection of defects and flows [3], assessment of condition and detection of the uniformity of the walls [4]; nevertheless their reliability is still under discussion. Since this type of investigation allows to obtain low cost and quick information, attempts have to be made to improve its application to masonry.
structures. The authors have investigated on the reliability of sonic and ultrasonic tests as a mean to follow the procedure of repair by injection of grouts and to measure its degree of strengthening.

2. RESEARCH DEVELOPMENT AND PROCEDURES

The experimental research was developed as follows: (i) construction of brick masonry prisms, (ii) subjection of the prisms to compressive tests beyond the peak stress, (iii) injection of the damaged masonries with epoxy resins, polymeric or cementitious grouts, (iv) subjection of the repaired specimens to compressive tests and research of correlations between the different steps [5]. The prisms were built in laboratory with solid softmud facing bricks and cement, cement-lime, lime-pozzolana, and hydraulic lime mortars. The dimensions of the prisms were: 250x500x600 mm or 250x500x1100 mm. Ultrasonic and sonic tests were performed during the four phases of the experimental study. The pulse transmission was monitored along horizontal paths: 9 in the transverse direction, between the larger faces and 3 in the longitudinal direction [6]. Measurement of the wave parameters (velocity, amplitude and frequency) and evaluation of the properties of the masonry in the different phases of the research have been done [6]. The ultrasonic equipment was composed by two P-wave piezo-electric transducers, a pulse generator, a preamplifier, a waveform analyser coupled with a computer and a floppy disk recorder and two load cells with digital indicators. The natural frequency of the transducers used for both transmission and reception was 90 kHz. A coupling material (silicone) was applied between the masonry prisms and the transducers for a better pulse transmission. The couplant was always directly applied on brick surface previously cleaned and smoothed. A constant pressure of 10N have been always applied to hold the transducers against the surface of the masonry wall through a load cell.

The sonic equipment was composed by an impulse force hammer instrumented with a small load cell, an accelerometer, a preamplifier and a waveform analyser coupled with a computer and a floppy disk recorder. The impulse force hammer used to initiate the stress wave allowed to repeat the same force of impact for all situations and test locations. In fact it was used as a pendulum, having a mass of about 0.35 kg, always fallen down on the masonry wall with an angle of 61°, with reference to the vertical line (Fig. 1). The impact hammer generated an impulse force with a nominal frequency of approximately 3.5 kHz. The small vibrations of the wall, resulting from the propagating stress waves, were measured by an accelerometer positioned in a magnetic way to a small steel plate which was then mounted with epoxy to the masonry wall surface.

The surface condition of the bricks has less effect on the sonic pulse test than on the ultrasonic one. The steel plate for the accelerometer can be attached with epoxy to the brick regardless of roughness of wall and the area impacted by the hammer is less than the area of ultrasonic transducers. For both ultrasonic and sonic pulse tests the waveforms obtained along each path of measure and in all the 4 conditions considered were displayed and then stored in the floppy disk recorder for further processing.

3. INTERPRETATION OF THE RESULTS

Masonry is an heterogeneous material whose characteristics depend upon the individual properties of mortars and units. Not only the mortar joints constitute significant material discontinuities, but also the volume ratio of units to mortar varies with height, length and depth of masonry walls.
For new walls or existing well preserved walls, made with solid bricks or cut stones, physical and mechanical properties can be assumed as homogeneous. While in damaged masonry, dishomogeneity of properties due to deterioration of mortars can be found together with cracks and voids. These flaws cause an attenuation of the waves and difficulties in the interpretation of the collected data. Furthermore, much more attenuation of the waves can be caused by the presence of large voids inside multiple leaf brick or stone-masonry, which represent a large part of our historic inheritance. A good correlation has been found between ultrasonic and sonic velocities. However the waveform obtained with sonic tests is generally more well defined and clear than the corresponding ultrasonic waveform, especially for damaged masonry. In fact the ultrasonic waveform is usually quite attenuated and sometimes even a large amplification cannot allow a good reading. The attenuation of a waveform is related to the wavelength of the transmitted pulse and to the number and size of flaws in the material the pulse passes through. The short wavelength ultrasonic pulse is overly sensitive to the presence of even minor flaws and then suffers considerably energy loss resulting in extremely rapid attenuation. Therefore greater transmission distances may be possible with sonic. Moreover, as mentioned above, ultrasonic tests have greater sensitivity to the surface conditions of brick. All these considerations lead to prefer the sonic tests.

In Fig. 2 the compressive strength of the undamaged, damaged, injected and collapsed masonry prisms (250x500x600 mm) is reported versus the average sonic pulse velocity. A rough linear correlation between the two parameters has been attempted obtaining very low correlation coefficient, with value of about 0.5.

Then the conclusion was that, in this case, the compressive strength cannot be taken into consideration as a good parameter to evaluate the reliability
of sonic tests. In fact while the sonic velocity gives local information on material properties, the strength obtained by the compressive tests on small walls is actually a ratio between the peak load and the area of the transversal section, according to the rough assumption of a uniformly distributed load. While the strength highly depends on the dimensions of the specimens, the velocity seems to be unaffected by them. In Fig. 3 the strength versus the sonic velocity is presented for two types of prisms with the following dimensions: type 1: 250x500x600 mm, type 2: 250x500x1100 mm.

Other attempts which had been done to correlate dynamic elastic moduli, obtained through sonic tests, and static elastic moduli, obtained during compression tests, gave even less reliable results.

An alternative criterion to interpret the results of the sonic tests is described in the following.

Two different stages of application of the sonic tests were detected: a) evaluation of the damaged masonry in order to decide on the opportunity of applying the injection technique, b) evaluation of the efficacy of strengthening.

4. EVALUATION OF THE DAMAGED MASONRY

A preliminary evaluation of the masonry and of its state of damage has always to be done, in order to decide whether a repairing or strengthening intervention is necessary. This difficult task cannot be accomplished as it was explained before, with destructive tests; moreover cracks and voids or other signs of damage are often hidden inside the masonry. Therefore non destructive tests which allow to know the interior of the masonry, as endoscopy, x-ray, etc. are better used. Sonic tests represent the easiest among non destructive tests.

The results of the laboratory sonic tests on undamaged and damaged prisms allowed to detect two levels of the sonic velocity $V$ corresponding to the two different situations: 1) $V < 1000$ m/s for the damaged masonries, 2) $V > 2000$ m/s for the undamaged masonries (Fig. 4). The intermediate level $1000 < V < 2000$ m/s represents the range between a badly damaged and a new good masonry.

The damages detected in practice can have different origin: mechanical or chemico-physical. In the second case the decay may be connected to salt crystallization, then to a growth of salt crystals inside the masonry.

In Fig. 4 the black marks represent two different situations of masonry prisms subjected to salt crystallization tests: damaged ($V=1909, 2179$ m/s),...
undamaged (V=3355 m/s). Fig. 5 shows the local increasing of velocity when a prism is subjected to salt crystallization by partial immersion. This possibility has to be considered when evaluating in situ masonry walls in aggressive environments.

The sonic velocity can also be used to investigate the crack pattern of damaged masonries. Fig. 6 shows a typical example of correlation: the values of the different velocities match in a real satisfactory way the crack pattern, i.e. the higher is the measured velocity the lower is the number of cracks.

Sonic tests were carried out on some real masonries. A new solid brick masonry made with hydraulic lime gave a good average velocity of 2778 m/s. Some prisms taken from the ruins of a collapsed tower gave an average velocity of 1565 m/s. An other in-situ investigation was carried on two parts of an historic building with the following average results: V=1130 and 876 m/s respectively on a pier and on a load bearing wall (Fig. 1). A comment can be done as follows: the load bearing wall might be very damaged and with big voids inside, being its velocity much less than 1000 m/s. The pier seems instead to be in lightly better condition (V > 1000 m/s).

The in-situ measured velocities are inserted in Fig. 4.

5. EVALUATION OF THE EFFICACY OF INJECTION TECHNIQUES

The improvement of the situation of cracked masonries after injection was detected both by compression tests and sonic tests. Fig. 7 shows the compressive strength of the prisms versus the sonic velocity before and after injection. The compressive strength before injection was taken as the residual stress measured after the compressive test. The velocity V after injection is greater than 2000 m/s, that is approximately all the specimen belong, after repair, to the best level of velocity. Nevertheless there is a difference between specimen injected with epoxy resin, cementitious or polymeric grout. Both strength and velocity are lower in the second case showing a better performance of the injection with epoxy resin. Once again the prisms subjected to crystallization tests show higher velocities than the others, both before and after injection.

However locally an increase of velocity not always corresponds to an effective amelioration of the masonry properties [7], as it is shown by the waveforms. They were analyzed through the FFT (Fast Fourier Transform). For the prisms in the undamaged or repaired situation, a general increase of signal components with higher frequencies was observed. Amplitude A and frequency F of the fundamental wave were considered in order to identify a waveform parameter able to characterize the masonry, and the product of amplitude and frequency was calculated.

It is very interesting to observe, as a typical example, the sonic waveforms (Fig. 8) at a specific location (point 1 of Fig. 9) where the sonic test indicated an increase in velocity value from undamaged to repaired situation. In the undamaged situation the waveform shows a transit time $t_u$ with a good high frequency. In the repaired situation, the transit time $t_1$ is decreased, but the waveform is flatter and has a lower frequency than in the undamaged situation. Therefore, probably, the cracks corresponding to the considered point 1, are not completely filled. The sonic pulse quickly crossed the masonry section through a sort of "bridge", but the elastic response of the masonry is not as good as it was in the undamaged situation. This behaviour is not detected by the pulse velocity but it is well represented by the product between amplitude A and frequency F of the fundamental wave (see Fig. 9, left).
Fig. 4 Compressive strength versus sonic velocity: comparison between undamaged and damaged situations. In-situ measured velocities are also reported.

Fig. 5 Local velocities measured before and after crystallization treatment.

Fig. 6 Correlation between velocity and crack pattern of a damaged prism.

Fig. 7 Compressive strength versus sonic velocity: comparison between damaged and repaired situation.
6. CONCLUSIONS

For the masonry studied, both sonic and ultrasonic tests appear to be sufficiently reliable to assess the degree of physical and mechanical damage of existing masonry structures and to evaluate the effectiveness of the repair technique. Sonic tests appear particularly suitable to: (i) detect large voids, flaws, cracks and delaminated bed joints, (ii) evaluate walls of great thickness, due to the strength and robustness of the signal, (iii) obtain clear waveforms for further processing. Direct empirical correlation between masonry strength and sonic pulse velocity are typically limited by specific masonry conditions and high degree of scatter in the data. However a rough guide for masonry quality can be established based on different levels of pulse velocity values. Sonic waveforms contain information on the material properties. The product of amplitude and frequency of the fundamental wave (AxF) as obtained from the FFT analysis of the waveform, can be considered as a good parameter of the local effectiveness of the injection.

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