The effect of deep rejointing on the compressive strength of brick masonry

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ABSTRACT: The effect of deep rejointing on the behaviour of brick masonry subjected to axial compression is experimentally investigated. Nine masonry prisms were constructed using low strength lime mortar. Three of them were tested as constructed, whereas the remaining six were tested after the application of deep rejointing, using either a lime cement mortar or a cement mortar. Substantial increase of the compressive strength of prisms was achieved when the removed mortar was fully replaced by the new higher strength one. On the contrary, in cases where full replacement was not achieved, premature failure of masonry prisms has occurred due to extensive spalling of bricks.

1 INTRODUCTION

Deep rejointing consists in removing part of the existing mortar of masonry (from both sides of the element and as deep as possible) and replacing it with a mortar of improved mechanical properties. Deep rejointing is considered to be a mild intervention technique. Thus, it is acceptable also for monuments of high architectural value. Deep rejointing is often applied in combination with other intervention techniques (e.g. grouting). The study of the deep rejointing technique is composed of two issues: the first concerns materials- and the second mechanical compatibility between the existing and the new (repair) mortars.

The literature related to the analysis of existing (historic) mortars and the design of new materials, physico-chemically compatible to the in situ ones, is now quite rich. There exist recommendations (e.g. Rossi-Doria 1986), methodologies (e.g. Papayianni 1998) and many reported case studies (e.g. Bartos 1999). On the contrary, the issue regarding the effect of the mechanical properties of the repair mortars on the mechanical properties of masonry and, consequently, the range of acceptable mechanical properties of the repair mortars as a function of the in situ ones is not yet sufficiently raised.

It is normally assumed that deep rejointing, when applied to relatively small thickness masonries that have not suffered severe damage, leads to increased compressive and shear strength of masonry. Nevertheless, in the literature there is a lack of experimental results proving the effectiveness of deep rejointing. A first reference (Tassios et al. 1987) includes an empirical relationship allowing for the calculation of the improved mechanical characteristics of masonry after rejointing. However, no information is provided regarding the source material on the basis of which the relationship was derived. More recently, Binda et al. (1999) presented the results of flat jack tests obtained before and after repair of a stone wall by deep cement rejointing. The obtained stress-strain diagrammes clearly showed that the structure, at least locally, became stiffer. The effect on the wall strength is not however mentioned in this reference.

Thus, a preliminary research program was carried at the Laboratory of Reinforced Concrete, NTUA, with the aim to obtain basic information regarding the effect of deep rejointing on the compressive strength of brick masonry. In this paper, the program, the investigated parameters, as well as the experimental results are presented and commented.

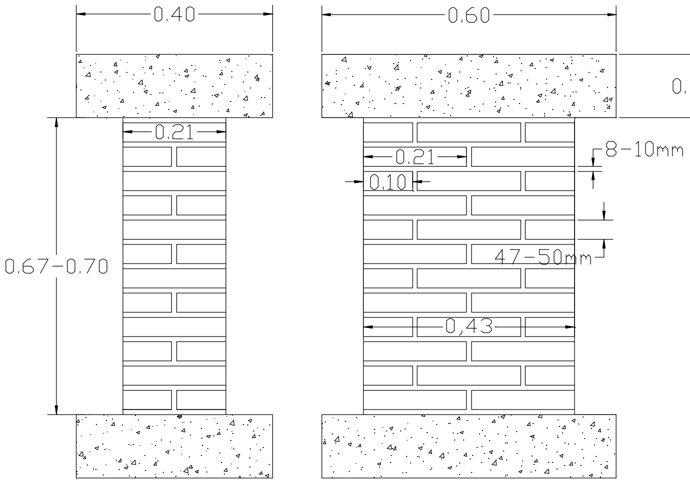


Figure 1: The geometry of specimens

2 THE EXPERIMENTAL PROGRAM

2.1 The specimens

Nine brick masonry prisms were constructed. The specimens were 0,43m long, 0,21m thick and 0,67m to 0,70m high, see Fig. 1. The masonry prisms were made of solid bricks 210mm long, 100mm wide and 47mm to 50mm high. Lime mortar was used for laying the bricks. The thickness of joints was equal to 8-10mm. Each masonry prism was constructed on a reinforced concrete prism (0,60m long, 0,40m wide, 0,13m high), whereas a RC prism of the same dimensions was provided at top of each specimen, to ensure uniform distribution of the applied compressive load on the masonry.

2.2 Application of deep rejointing

In order to determine the initial compressive strength of masonry prisms, three of the specimens (Prisms No 1, 2 and 3) were tested in axial compression as constructed. In the remaining prisms (Prisms 4 to 9), deep rejointing was applied as follows: The mortar was chiseled out of all horizontal joints along the four faces of the specimens, at a depth of approximately 40mm. Thus, almost 35% of the total volume of mortar was removed. Loose mortar pieces and dust were removed using air under pressure. Subsequently, the prisms were saturated. The rejointing mortar was mixed and introduced to the joints by hand. All prisms, both after construction and after application of deep rejointing were kept wet for one week. Afterwards, they were stored in the Laboratory until testing.

2.3 Materials

2.3.1 Brick

Solid bricks were used for the construction of specimens. Their mean compressive strength was equal to 51,5 N/mm^2.

2.3.2 Initial Mortar

The mix proportions (per volume) for the lime mortar used to construct the nine prisms were as follows: Hydrated Lime: Sand = 1:5. During construction, conventional prismatic specimens (40mmx40mmx160mm) were taken, in order to measure the mechanical properties of mortar. The mean value of its tensile strength under bending was measured to be equal to 0,35 N/mm^2, whereas its mean compressive strength was equal to 0,98 N/mm^2.

Table 1 : Mix proportions (per volume) and mechanical properties of mortars for deep rejointing

Prism	Mortar	Tensile strength in flexure N/mm^2	Compressive strength N/mm^2
4	1:0,25:4	1,92	5,97
5	1:0,25:4	2,27	9,23
6	1:0,25:4	0,97	5,49
7	1:4	3,50	13,85
8	1:4	3,67	17,13
9	1:4	3,67	17,01

2.3.3 Mortars for rejointing

A lime cement mortar was used for the rejointing of prisms 4, 5 and 6. The mix proportions (by volume) were: Cement: Hydrated Lime:Sand=1:0,25:4. For the rejointing of prisms 7, 8 and 9, a cement mortar was used. The mix proportions (by volume) were: Cement:Sand=1:4. In Table 1, the strengths of rejointing mortars the day of testing the respective masonry prism are listed. It should be noted that both construction of masonry prisms and deep rejointing were carried out under site (and not under Laboratory) conditions. The (experienced) worker who constructed the prisms and applied the rejointing used the quantity of water needed to produce a consistent and, at the same time, workable mortar. This is the reason why, as shown in Table 1, the mechanical properties of mortars are quite scattered. It is, however, believed, that such scatter is realistic for the application of deep rejointing on site. It should be mentioned that mortars for deep rejointing should comply with a set of requirements, such as reduced shrinkage, chemical compatibility with the existing materials, etc. However, at this preliminary stage, those requirements were not taken into account.

2.4 Constructional problems

After completion of each prism test, bricks were carefully removed layer by layer (from top of the prism to the bottom), in order to check whether rejointing mortar had filled all voids left after removal of the initial mortar. It was proved that, although deep rejointing was applied very carefully, only in prisms 8 and 9 full replacement was achieved.

On the contrary, in prisms 4 to 6, the rejointing mortar was introduced to a depth of 20mm approximately, leaving part of the horizontal joints void. In prism 7, only 6% of the total volume of joints was left void. It will be demonstrated in what follows that the presence of voids in the horizontal joints has affected both the compressive strength of masonry and its failure mode.

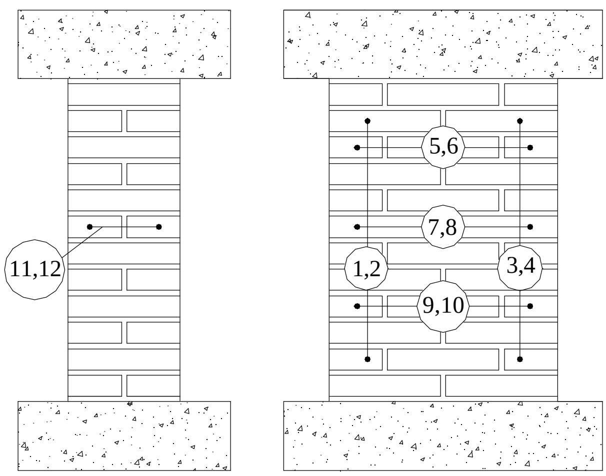


Figure 2 : Location of LVDTs for measuring horizontal and vertical deformations

2.5 Testing procedure and measurements

All masonry prisms were subjected to axial compression in a machine of 2000? ? maximum capacity. The prisms were tested one month after their construction (prisms 1, 2, 3) or after rejointing (prisms 4 to 9). Load controlled tests were performed at a rate of approximately 0,10N/mm^2/min. During testing, compressive load and deformation of prisms were measured at various locations. To this purpose, electrical transducers were used, as shown in Fig. 2. Vertical deformations were measured using two transducers at each prism face (transducers 1 to 4). Horizontal deformations were measured at three locations on both faces of prisms (transducers 5 to 10), whereas transverse deformations (along the thickness of prisms) were measured by means of transducers 11 and 12, placed at mid height of specimens.

3 EXPERIMENTAL RESULTS

3.1 Failure mode

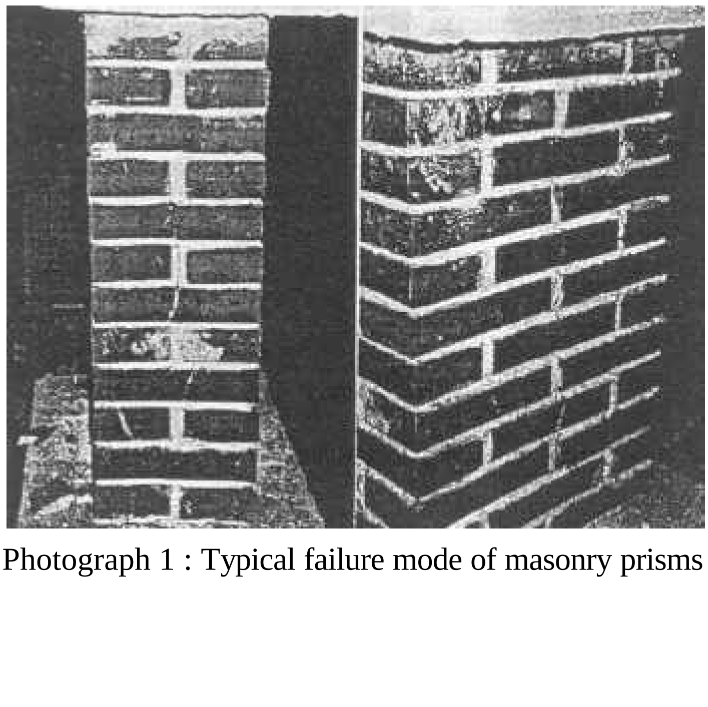
In all specimens, typical vertical cracks due to compression have appeared (see Photograph 1) both along the length and the width of prisms.

In addition to those cracks, spalling of bricks was observed (see Photograph 2) in prisms to which deep rejointing was applied. This feature was pronounced in prisms with partial replacement of the removed initial mortar, whereas spalling of bricks was negligible in prisms 8 and 9. As shown schematically in Fig. 3, the spalling of bricks is attributed to the concentration of stresses in the region of the new mortar having substantially higher strength and modulus of elasticity than the old one. Such a concentration of stresses is more pronounced in case of defective application of deep rejointing, in which case horizontal joints remain partly void.

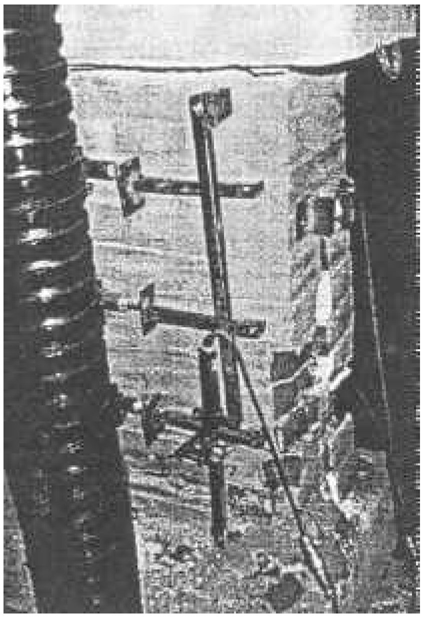
3.2 Stress-strain diagrams

Compressive stress vs. compressive strain curves for prisms 1 to 9 are given in Fig. 4, whereas a summary of experimental results is given in Table 2.

One may observe that masonry prisms 1 to 3, which were tested as constructed, exhibited a compressive strength approximately equal to 6,50 N/mm^2. Those prisms, due to the low strength (and, hence, low modulus of elasticity) of their mortar, reached their compressive strength for a strain larger than 0,007. Thus, the secant modulus of elasticity of masonry (calculated at a stress level of 1/3 of the compressive strength) is rather low, approximately equal to 200f_{wc} (f_{wc} being the compressive strength of masonry).



Photograph 1 : Typical failure mode of masonry prisms



Photograph 2 : Extensive spalling of bricks in prisms with partially void mortar joints

Masonry prisms 4 to 6, that were subjected to deep rejointing with partial filling of horizontal joints, exhibited a non satisfactory behaviour. In fact, despite of the substantially higher compressive strength of the new mortar, prisms 4 to 6 reached a compressive strength lower than that of prisms 1 to 3. This unfavourable result is attributed to the partially empty joits, as well as to premature spalling of the bricks, according to the mechanism qualitatively described in Fig. 3. Although the results of prisms 4 to 6 seem to be rather scattered, the mean value of the strain at which they failed, as well as the mean value of their modulus of elasticity seem to be close to the respective values for prisms 1 to 3.

On the contrary, prisms 7 to 9, in which perfect filling of the horizontal joints was achieved (with the exception of prism 7, in which-however-the percentage of voids was small), exhibited substantial increase of compressive strength, compared to prisms 1 to 3. They also exhibited an increased modulus of elasticity (from $200f_{wc}$ to $250f_{wc}$).

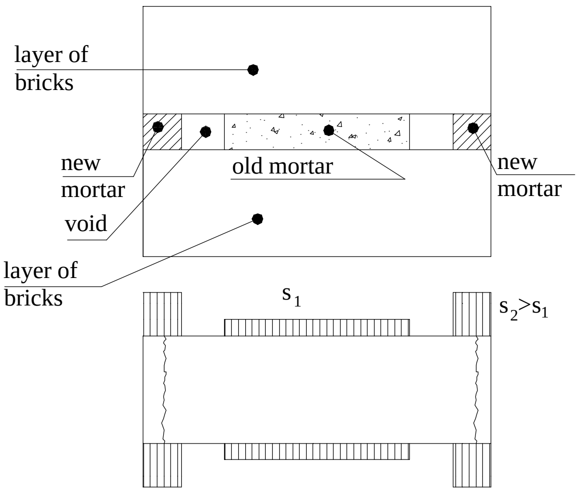


Figure 3 : Compressive stresses on a layer of bricks

3.3 Horizontal and transverse deformations

As mentioned before, during testing, horizontal and transverse deformations of prisms were also recorded (transducers 5 to 12). Obviously, the respective measurements include both the tensile deformations of masonry before cracking and the opening of vertical cracks after cracking of prisms. Nevertheless, as shown in Fig. 5, the tensile deformations of uncracked masonry being very small, they can be neglected. Thus, one can assume that measurements of transducers 5 to 12 represent the total opening of vertical cracks along the front and transverse faces of prisms.

Thus, in Table 2, the sum of openings of vertical cracks (w_u) is given for each prism, as well as the total crack opening along the width of each prism (w_{trans}). Although the results are rather scattered, it is obvious that the total crack opening at failure of prisms 7, 8 and 9 is substantially smaller than for prisms 1 to 6 (see also Fig. 5).

Table 2 : Summary of test results

Prism	Voids % mortar vol.	f_{wc} N/mm^2	e_u	E_{wc} N/mm^2	w_u mm	$w_{6,5}$ mm	w_{trans} mm	$w_{tr, 6.5}$ mm
1	-	6,55	0,0085	1038	1,78	1,78	**	**
2	-	6,51	0,0073	1409	7,26	7,26	4,13	4,13
3	-	6,52	0,0075	1550	2,24	2,24	1,08	1,08
4	17	4,50	0,0107	500	0,88	*	1,48	*
5	10	5,71	0,0082	1118	1,50	*	1,47	*
6	14	5,27	0,0043	1494	2,56	*	0,93	*
7	6	8,74	0,0071	1712	0,83	0,11	0,61	0
8	0	9,91	0,0072	3000	5,37	0,70	0,32	0
9	0	8,53	0,0047	2185	0,85	0,13	0,05	0

* The prism failed under a stress smaller than 6,5 N/mm^2
** Unreliable measurements

In addition, Table 2 shows the total opening of vertical cracks for a compressive stress equal to the compressive strength of prisms 1 to 3 ($w_{6,5}$?a? $w_{tr, 6.5}$). It may be observed that in prisms 7 to 9, the total vertical cracks opening at front faces varies between 0,11mm and 0,70mm, whereas the respective values for prisms 1, 2 and 3 varied between 1,78mm and 7,26mm. In addition, for the same level of compressive stress, vertical cracks on transverse faces were not yet opened in prisms 7 to 9.

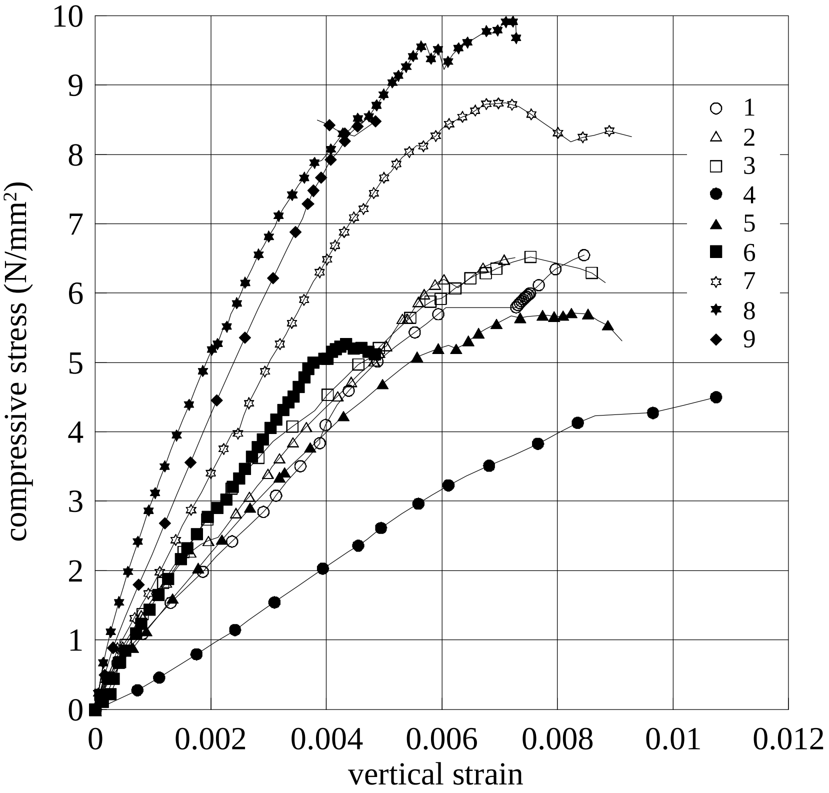


Figure 4 : Stress-strain diagrams for prisms 1 to 9

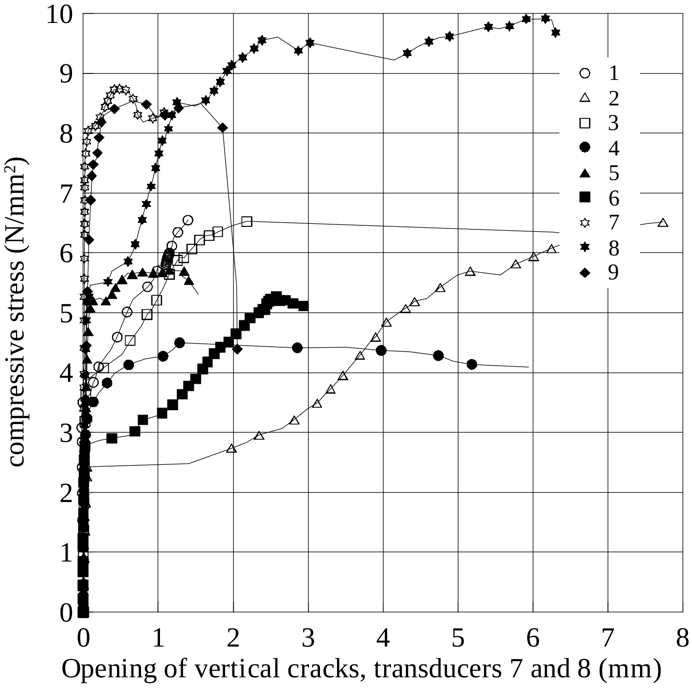


Figure 5 : Compressive stress-opening of vertical cracks curves for prisms 1 to 9

4 CALCULATION OF COMPRESSIVE STRENGTH OF MASONRY AFTER DEEP REJOINTING

In Rossi-Doria (1986), the following relationship is included for the calculation of compressive strength of masonry after the application of deep rejointing:

$$fwc = fwc{,}0\left[1 + k\,\frac{Vnew}{Vnew + Vold}\right] \qquad (1)$$

where $f_{wc,0}$ = the initial compressive strength of masonry (before deep rejointing), V_{new} = the volume of the new mortar, V_{old} = the volume of the initial mortar, and k = empirical constant, equal to 1÷2 for brick masonry (suggested value, k=1,50).

Equation (1) predicts an increase of the compressive strength of masonry, even for the case of prisms 4, 5 and 6, in which spalling of bricks has led to premature failure of masonry and, hence, to reduced compressive strength compared to that of prisms 1 to 3.

The application of Eq. 1 to prisms 7, 8 and 9 is shown in Table 3. One may observe that, although Eq. 1 does not take into account the compressive strength of either the old or the new mortar, the predicted values of compressive strength of masonry are very close to the experimental ones. It has to be noted, however, that the small number of specimens tested within this program does not allow for definitive conclusion to be drawn.

Table 3: Application of Eq. 1 for prisms 7, 8 and 9

Prism	V_{new} %	V_{old} %	f_{wc} N/mm^2, equ. (1)	exp. f_{wc} N/mm^2
7	22,8	71,2	8,86	8,74
8	28,1	71,9	9,24	9,91
9	24,6	75,4	8,90	8,53

5 CONCLUSIONS

The results of this preliminary research have shown that:

1. Deep rejointing leads to substantial increase of the compressive strength of masonry, provided that horizontal joints are completely filled. This increase in compressive strength seems to be quite accurately predicted using a simple empirical formula from the literature.
2. Nevertheless, it was proved that due to construction difficulties, complete filling of horizontal joints is not easily achieved.
3. In those cases, extensive spalling of bricks may lead even to a substantial reduction of the compressive strength of masonry after deep rejointing.
4. The results obtained up to now seem to be promising. However, further systematic research is needed to cover the issues related to mix design of new mortars, as well as the effect of deep rejointing on the behaviour of various types of (brick and stone) masonry under compression, tension and shear actions.

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