TESTS ON REPRODUCED BYZANTINE MASONRY

VERSUCHE AN NACHGESTELLTEM BYZANTINISCHEM MAUERWERK

ESSAIS SUR MAÇONNERIE BYZANTINE REPRODUITE

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SUMMARY

Tests have been performed on reproduced Byzantine masonry with one type of brick and one mortar composition. The joint thickness has been varied between 20 and 60 mm. The storage conditions either standard climate 20°C/65% RH or sealed in aluminium foil. Incremental loading shows a strong plastic behaviour of the joints. Short term loading reveals clearly the influence of joint thickness on the mechanical behaviour.

ZUSAMMENFASSUNG

An nachgestelltem byzantinischem Mauerwerk mit einer Ziegelart und einer Mörtelzusammensetzung wurden Versuche durchgeführt. Die Fugendichte variierte zwischen 20 und 60 mm. Die Lagerungsbedingungen waren entweder Normklima 20°C/65% r.F. oder versiegelte Lagerung in Aluminiumfolie. Die Versuche mit stufenweiser Belastung zeigen ein stark plastisches Verhalten der Fugen. Kurzzeitbelastung enthüllt den Einfluß der Fugendichte auf das mechanische Verhalten.

RESUME

Des essais ont été réalisés sur une maçonnerie byzantine reproduite avec un type de brique et une composition de mortier. L'épaisseur des joints a été variée entre 20 et 60 millimètres. Le stockage des spécimens a eu lieu soit sous climat standard 20°C/65% d'humidité relative, soit sous enveloppe hermétique en papier d'aluminium. Le chargement par paliers montre un fort comportement plastique des joints. Le chargement de courte durée révèle clairement l'influence de l'épaisseur des joints sur le comportement mécanique.

KEYWORDS: ancient masonry, testing, strength, deformation, Byzantine church, San Vitale

1. MOTIVE

In Roman times and later during the Byzantine period (Vth to XIVth century), thick joint loadbearing brickwork was the general building techniques in representative buildings. Many of these buildings survived and are still in operation such as S. Michele in Africisco and San Vitale in Ravenna. There is not much knowledge about the structural behaviour of brickwork with thick joints and there is even less known about the effect of this building technique on the structure during construction. Therefore a project was started in cooperation with the Politecnico di Milano which was aimed at the experimental investigation of reproduced Byzantine masonry. The material was reproduced in Italy and the mechanical testing was carried out in the Otto-Graf-Institute in Stuttgart. The short report deals with the latter. For more information see [FALTER ET AL., 1998].

2. TESTING PROGRAMME

The testing programme was designed to simulate the construction procedure of a main column in San Vitale. The dead load is increased in steps of 20 kg during the first week, in steps of 30 kg in the 2nd week, in steps of 60 kg every 48 hours from the 30th day, and, finally, 120 kg steps every 48 hours from the 60th day. The maximum load was supposed to be 6 t or 60 kN.

The mortar consists of lime as the binder, quartzitic sand and crushed fired clay brick. It has been demonstrated that the crushed brick is puzzolanic. Great emphasis was placed on the workability which should be plastic. It was measured on the DIN 1048 spread table and should amount to 320 mm. However, some mortars were a little stiffer, others a little softer.

Bricks were reproduced with the dimensions 510 mm x 310 mm x 40 mm. The specimens consisted of 4 bricks and 3 mortar joints. The joint thickness varied between 20 and 60 mm. The storage conditions were either standard climate of 20°C and 65% RH or wrapped in aluminium foils. Table 1 shows the variation of parameters.

Table 1: *Testing variables*

Specimen nr.	Joint thickness mm	Environment	Consistency [1)]
1	20	20°C/65% RH	0
2/1	40	20°C/65% RH	-
2/2	40	20°C/65% RH	+
2/3	40	20°C, wrapped	0
3/1	60	20°C/65% RH	-
3/2	60	20°C/65% RH	+

[1)] 0 as anticipated
\+ a little softer
\- a little stiffer

The loading rig consisted of a lever and a loading weight. The magnification of load was 1:5 in the lower range and could be changed to 1:40 in the higher range. Fig. 1 shows a schematic of the loading equipment. Dial gauges with a resolution of 1 µm were mounted on the four corners of the specimens.

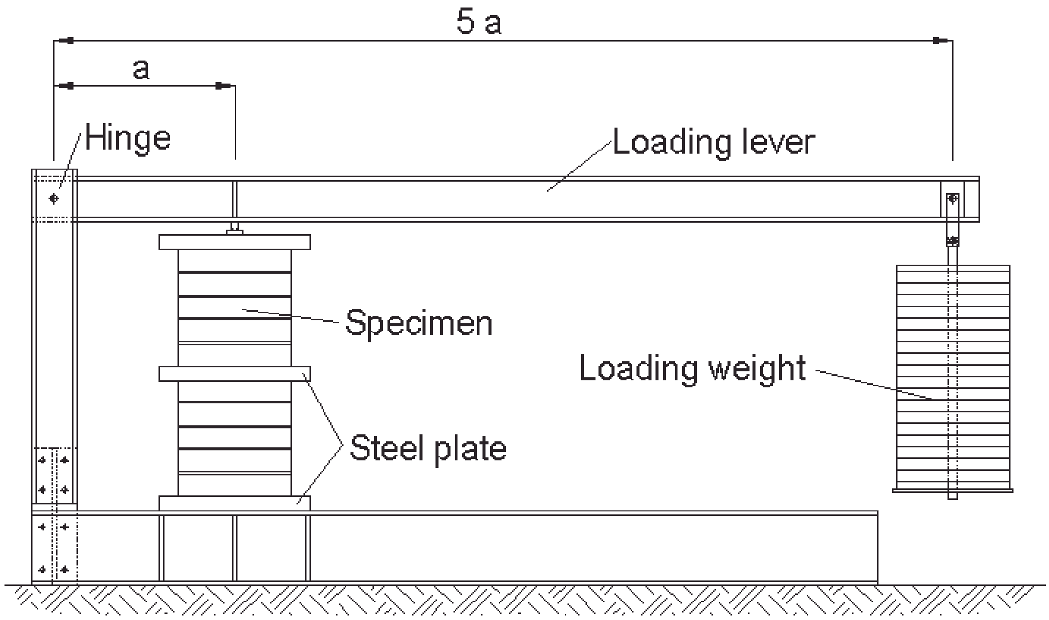


Fig. 1: *Mechanical loading equipment*

After the tests with incremental loading, four specimens were subjected to monotic loading until failure. These tests were carried out in a displacement-controlled hydraulic testing machine with displacement rate of 0.02 mm/s. The displacement was recorded at the corners of the specimens by four LVDTs.

3. TEST RESULTS

3.1 Incremental loading

The results of the incremental loading are summarized in Fig. 2. The horizontal axis shows the time from beginning of loading. The left vertical axis shows the strain with respect to the joints, i. e. it is assumed that the brick deformation is negligible with respect to the deformation of the joints. The right vertical axis shows the stress which increases incrementally. It can be seen that the strain increases very fast in the first 20 days despite the rather small stress. Prisms 3/2 and 3/1 deform most because the joint in thicker than of prisms 2/1 and 2/2 and 1.

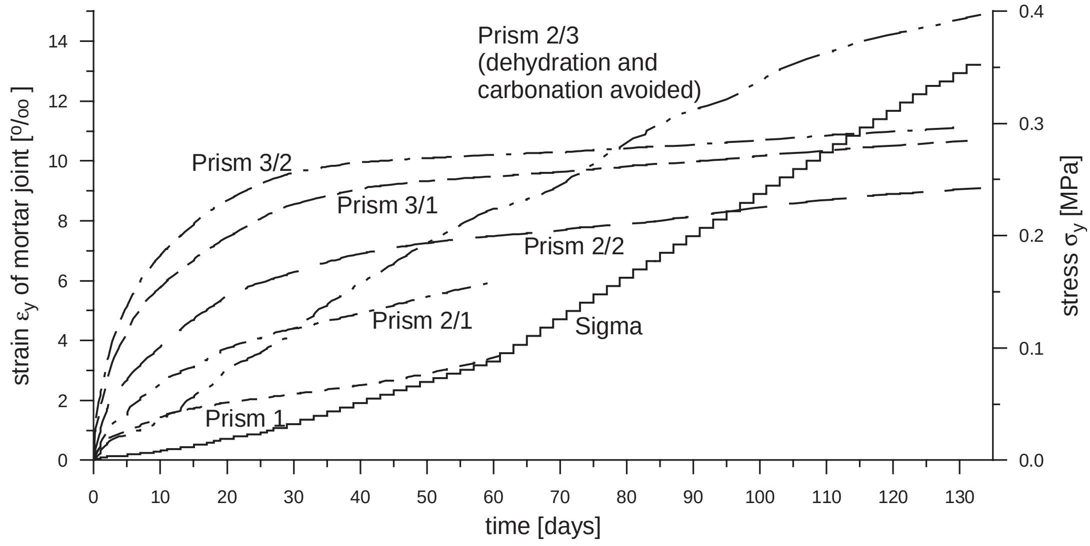


Fig. 2: *Stress vs. time and strain vs. time relation of incremental loading*

Since prism 2/3 is lacking behind prisms 2/1 and 2/2 it should be assumed that drying shrinkage plays a major part in the deformation during the first 20 days. When stress increases, the joints of prism 2/3 are still water saturated and deformation increases more than that of prism 1, 2/1, 2/2, 3/1 and 3/2. The stress-strain behaviour of the mortar in the joint is the effect of various phenomena: compaction due to water absorption of the bricks, consolidation due to seepage of water, shrinkage due to drying, carbonation, plastic deformation in the fresh state, elastic deformation, and viscous creep in the early age and later on. It is really a complex behaviour which has to be studied more carfully in the future.

The large plastic deformation in the fresh state, i. e. during construction, have the gread advantage that masonry could settle and could adjust itself to a state almost free of stresses due to imposed deformation. This is important because the brittle bricks did not encounter stress concentrations and did not break.

3.2 Short term loading to failure

When a layered structure is loaded it is important to know the individual properties of the layers. In the case of Byzantine masonry the joint is rather soft compared to the brick. The brick is brittle and has a low tensile strength. In this combination it is well known that the joint expands due to Poisson´s effect and imposes tensile stresses on the brick. On the other hand, the brick reduces horizontal expansion of the joint and induces compressive stresses in the joint. It is a typical interaction of two completely different materials.

Fig. 3 shows the stress-strain response of four prisms loaded after 1 year preloaded in the incremental loading test.

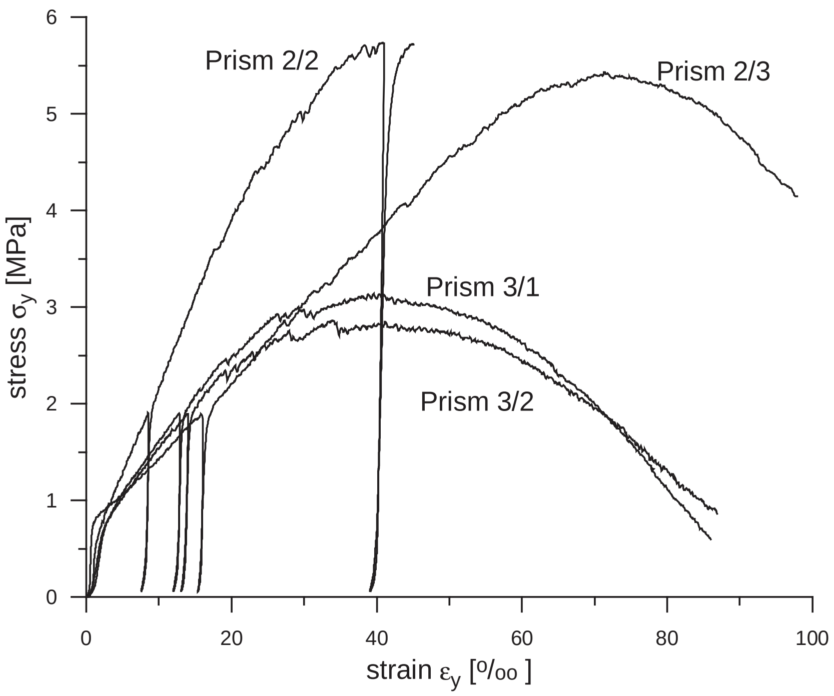
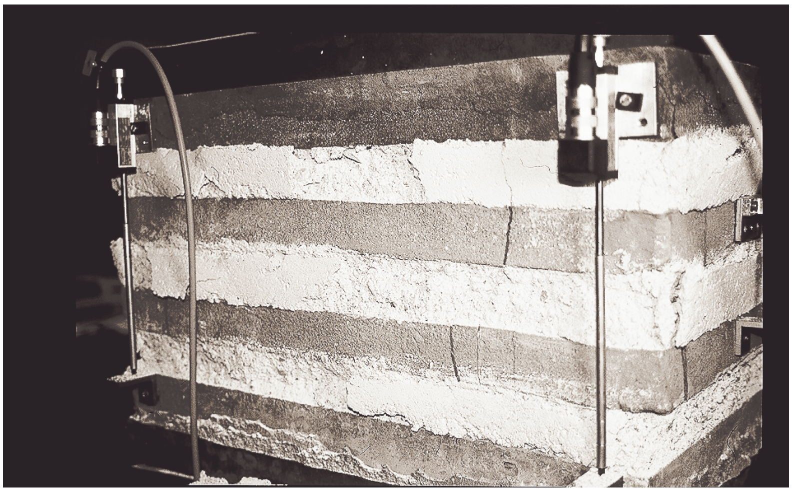


Fig. 3: *Stress strain response of prisms during monotonic loading*

Prism 3/1 and 3/2 with 60 mm mortar joint show a rather weak behaviour. Prism 2/3 which was wrapped and could not dry and not carbonate is very similar to the prisms with 60 mm mortar joint. Prism 2/2 is much stiffer than the others. It can be concluded that joint thickness and environment have a distinct influence on the stress-strain behaviour of masonry.

The sequence of pictures 4a to 4c shows the failure of masonry prisms.

a)



b)

c)

Fig. 4: *Cracking and failure patten of masonry prisms*
a) Prism 2/2 at σ = 2.5 MPa
b) Prism 3/1 at σ = 2.9 MPa, prepeak
c) Prism 3/1 at σ = 2.8 MPa, postpeak

Fig. 4a shows the beginning of splitting cracks in the brick due to transverse expansion of the mortar. Picture 4b illustrates a situation when splitting cracks in the brick coincide with spalling of the mortar joint. Finally, picture 4c is a typical core shaped fracture due to friction on the loading platens and expansion of the mortar joint. However, it should be mentioned that the stresses reached at failure are far beyond the stresses in a real Byzantine structure. For example, the stress in the main column of San Vitale does not reach more than 0.4 MPa. The failure stress of prism 3/1 was about 3 MPa.

The results of incremental tests and short term tests have been discussed broadly and the effects on construction and long term structural behaviour have also been shown in [FALTER, 1998].

4. CONCLUSIONS

Tests on reproduced Byzantine masonry has shown that the plastic behaviour of lime mortar with crushed brick has a rather favourable effect on the structural behaviour during construction and long term. The very good state of preservation of churches and other buildings after more than thousand years is certainly due to the ancient building technology which used thick joints in masonry structures. The reported investigation should give rise to more thorough and systematic treatment of the subject which would help understanding the structural behaviour of durable ancient structures.

ACKNOWLEDGEMENT

The cooperation with Prof. Binda and Prof. Baronio of Politecnico di Milano is gratefully acknowledged.

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