13th International Brick and
Block Masonry Conference
Amsterdam, July 4-7, 2004

EXPERIMENTAL DETERMINATION AND NUMERICAL MODELLING OF THE FAILURE BEHAVIOUR OF HISTORICAL MASONRY

F.A.Veer[1], G.J.Hobbelman[1], M. van Dijken[1],
A.C.B. Schuurman[1],J. Rots[1], M. Janssen[2]

Abstract

Currently several infrastructural and building projects are going on which potentially affect historical masonry buildings. One of these is the project building a tunnel under the existing Amsterdam central station which will in all probability cause some subsidence. The building is made of masonry using bricks and lime mortar. As a listed building damage to the façade is not allowed. Thus a research programme was started to determine the allowable subsidence. Samples of the historical brickwork have been taken from the foundations of the building. These samples have been cut into beam shaped specimens and tested in three point bending to determine failure criteria. Finite element models of the experiments have been made of several levels of sophistication.

Key Words

Historical buildings, failure criteria, masonry

1 Introduction

One of the problems of modern society is that the continuous changes that occur in the development of cities conflict with the desire to keep the historical character intact. Especially in the case of listed buildings a conflict can arise with the necessary changes in urban infrastructure. An example is the central railway station in Amsterdam, shown in figure 1. Since it's building in the second half of the 19th century the amount of rail traffic has increased significantly while the requirement of moving the passengers from the city to the station and from the station into the city requires considerable transportation facilities. As these have reached the saturation point additional capacity is sought by building a new metro line from the north to the south of Amsterdam. This line is being build under the existing central railway station. In practice this means tunnelling under a listed building, replacing its foundations, while

[1] faculty of architecture, Delft University of Technology
[2] laboratory of materials science, Delft University of Technology

the building continues to function as Amsterdam's main connection hub. A good description of the project is given by Vlijm and Snel (2004).

Subsidence is unavoidable and the only question is how much subsidence the building can tolerate before cracks form in the historical masonry. The façade of the building cannot be used to take samples. However during the building cores have been drilled out of the foundation walls, to place steel beams. These cores have been used to manufacture specimens. Figure 2 shows the drilled holes in the foundation wall with the steel beams protruding from the surface.

Figure 1 : Historical façade of Amsterdam central station

Figure 2: Location of drilled out cores

2 Specimen preparation

The cylindrical cores are illustrated in figure 3. These cores were cut into rectangular beam specimens using a water cooled laser controlled diamond wheel saw usually used to cut marble into tombstones. The cutting revealed a rather heterogeneous structure composed of several qualities of brick and also quite irregular lime joints. The specimens were washed with demineralised water after cutting and left to dry for a week.

Figure 3 : Drilled cores before cutting

Figure 4 : heterogeneous structure revealed after cutting

3 Experimental methodology

From the two cylindrical cores 8 rectangular specimens with size approximately 130 mm wide, 150 mm high and a length of 400 mm were made. These were tested in 3 point bending on a ZWICK Z100, 100kN, electromechanical universal testing machine. The test was under displacement control using a test speed of 0.1 mm/minute. The dimensions of the specimens, the maximum load and the maximum bending stress are given in table 1. Of the eight specimens one was lost due to an irrecoverable control error during the test.

Table 1: dimensions of specimens, maximum load and maximum bending stress

Test number	h (mm)	W (mm)	F_m (kN)	σ_m (MPa)
1	153	132	7.25	1.04
2	132	150	12.9	2.22
3	152	133	4.63	0.68
4	131	150	10.4	1.81
5	152	135	14.3	2.07
6	132	153	7.00	1.16
7	131	147	9.50	1.69
average			9.43	1.52

4 Experimental results

As only seven experimental results were available statistical analysis is impossible. The results show significant deviation and will be analysed on a specimen by specimen basis to determine what can be learned.

4.1 Experiment 1

Specimen 1 started to fail at the boundary of the lime and the brick. A crack grew along the bottom brick layer, arrested momentarily and the crack grew through the second bricklayer. The stress-displacement curve is given in figure 4 and the initial failure is shown in figure 5.

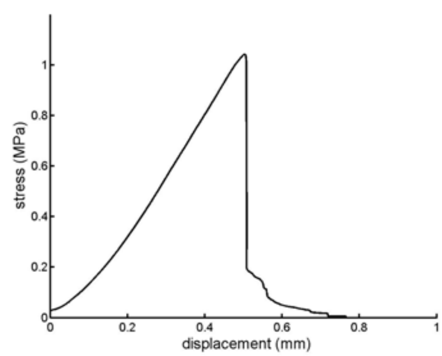

Figure 4: stress-displacement plot for specimen 1

Figure 5: beginning of failure process of specimen 1.

4.2 Experiment 2

Specimen 2 had a thin lime mortar layer on the bottom. This was well supported by a brick spanning the centre section. The specimen failed suddenly as the brick that carried all of the load failed. The stress-displacement curve is given in figure 6 and the initial failure is shown in figure 7.

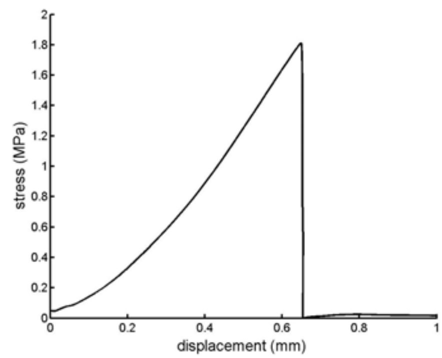

Figure 6: stress-displacement plot for specimen 2

Figure 7: beginning of failure process of specimen 2

4.2 Experiment 3

Specimen 3 was the weakest. A crack grew along the brick mortar interface a the bottom. The second layer contained a damaged brick already containing cracks which could not carry any load. The stress-displacement curve is given in figure 8 and the initial failure is shown in figure 9.

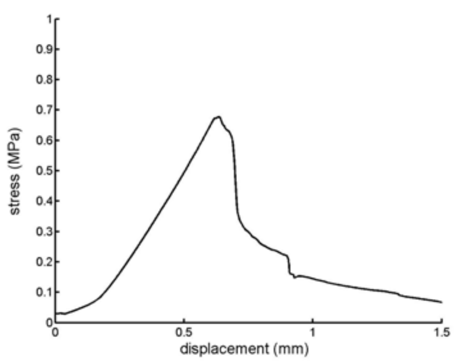

Figure 8: stress-displacement plot for specimen 3

Figure 9: beginning of failure process of specimen 3

4.3 Experiment 4

Specimen 4 was well supported by bricks in the centre section. Failure started along the brick-mortar interface with the crack immediately running through the supporting bricks leading to total failure. The stress-displacement curve is given in figure 10 and the initial failure is shown in figure 11.

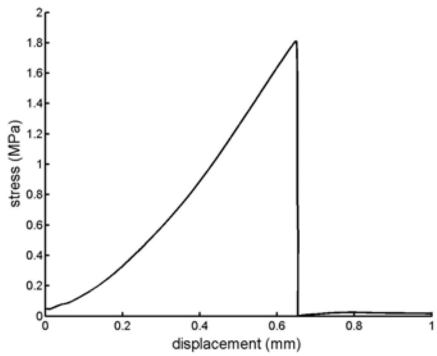

Figure 10: stress-displacement plot for specimen 4


Figure 11: beginning of failure process of specimen 4

4.4 Experiment 5

Specimen 5 had a thin mortar layer on the bottom supported by a brick. Failure started in the mortar interface with the crack immediately running through the supporting bricks leading to total failure. The stress-displacement curve is given in figure 12 and the initial failure is shown in figure 13.

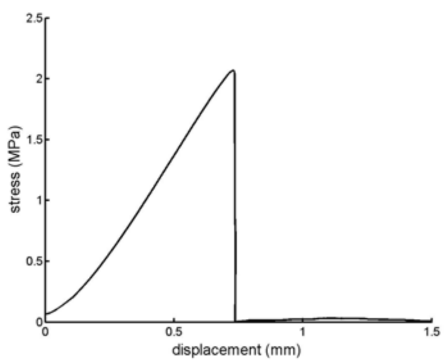

Figure 12: stress-displacement plot for specimen 5


Figure 13: beginning of failure process of specimen 5

4.5 Experiment 6

Specimen 6 was well supported by bricks in the centre section. Failure started along the brick-mortar interface with the crack immediately running through the supporting bricks leading to total failure. The stress-displacement curve is given in figure 14 and the initial failure is shown in figure 15.

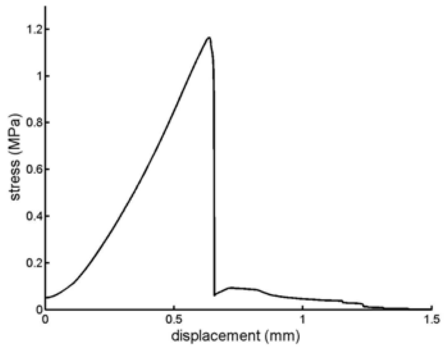

Figure 14: stress-displacement plot for specimen 6

Figure 15: beginning of failure process of specimen 6

4.6 Experiment 7

Specimen 7 was well supported by bricks in the centre section. Failure started along the brick-mortar interface with the crack immediately running through the supporting bricks leading to total failure. The stress-displacement curve is given in figure 16 and the initial failure is shown in figure 17.

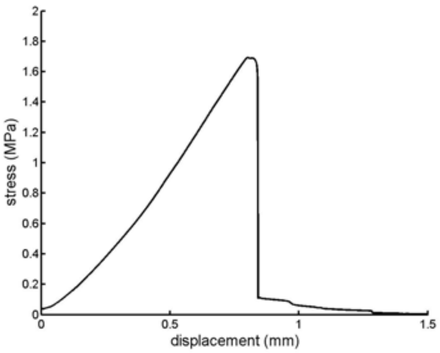

Figure 16: stress-displacement plot for specimen 7

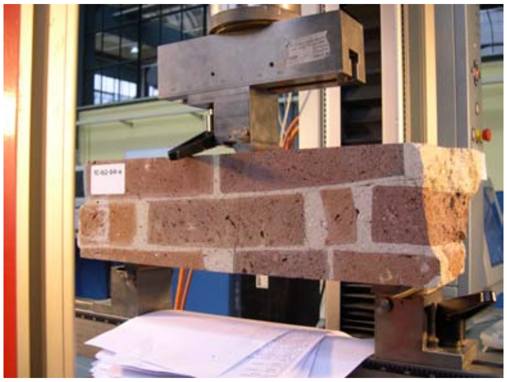

Figure 17: beginning of failure process of specimen 7

4.8 **Discussion of experimental results**

The experimental results can be divided into three groups :

A Experiment 3, where the brick in the second layer was broken and the mortar had to carry all the tensile loads. The specimen fails at low stress.

B Experiments 1, 6 and 7. Here a full brick layer is at the bottom and the maximum bending stress is at a joint. The supporting second brick layer is on the neutral line of the specimen and thus cannot carry a lot of the load. A crack starts at the bottom by debonding of the mortar brick interface. A slight form of softening can be seen in the stress-displacement curve as the crack arrests on reaching the supporting brick.

C Experiments 2, 4 and 5 where a thin layer of mortar/brick is at the bottom with a good brick layer supporting the specimen in the centre. As the brick is mostly in the tensile zone higher strengths are obtained. Once the supporting brick fails the specimen fails in a totally brittle fashion.

This division into three group rationalizes the results. It also shows a major weakness. Specimen 3 should have fallen into the C category but because the critical brick had an initial crack before the test the actual strength was only about one third of what would be expected. How these results can be applied to the façade of the Amsterdam central station is at this moment uncertain and is being researched further. It should be noted that these results seem to be better than those obtained earlier under comparable conditions by van der Pluijm (2000)

5 Numerical analysis

The propagation of the crack in specimen 1 was studied numerically using the DIANA version 7.2 FEM software package. The guidelines given by CUR 1994 were followed. Specimen 1 was selected for modelling because it did not fail completely at the start of cracking, but showed crack arrest, followed by crack propagation, crack arrest and crack propagation to final failure. 2 and 3 dimensional models were made using cq16m and cte30 elements respectively. Young's moduli for the brick of 2.38 GPa and for the lime mortar of 1.19 GPa were used. The crack as actually grew in specimen 1 was modelled into the specimen, with the crack faces being uncoupled in stages to model the progressive cracking of the specimen. More advanced methods such as used by Giambanco and Mroz (2001) were considered but not used at this stage because they were not deemed to provide sufficient benefits for this particular case. Results were calculated at the point of initial crack growth, the point of subsequent crack propagation and the point where the crack propagated to final failure. The numerical results of the 2D calculations are summarised in table 2. The 3-D calculations are more complicated and results are not available at the time of writing. The results suggest that there is no single stress or strain criterion that can describe the crack initiation/propagation process. Further work on modelling the other specimens in 2-D and 3-D is continuing. It is hoped to extend this to modelling the whole façade analogous to the work done by Pegon et al. (2001). This work will be published later.

Table 2: Summary of results of 2D-FEM calculations

	First crack growth	First crack propagation	Final crack propagation
σ_1 (MPa)	0.94	0.71	1.62
$\sigma_{von\ mises}$ (MPa)	0.94	0.69	1.68
$\varepsilon_{von\ mises}$	0.001	0.0007	0.0009

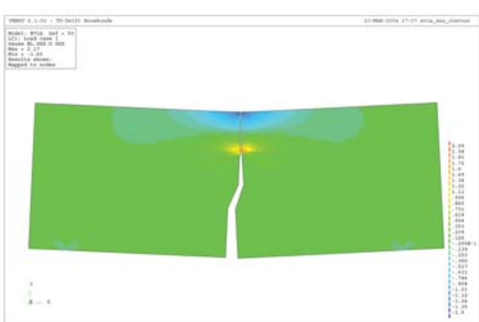

Figure 18 : FEM calculated stress distribution at moment pf onset of final failure

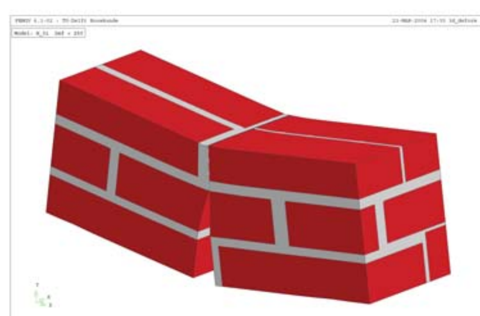

Figure 19: 3D model of specimen 1

6 Conclusions

From the results it is concluded that :

- failure takes preferentially place along the lime mortar-brick boundary
- specimens which have intact bricks in the tension zone are considerably stronger, these specimens however fail immediately due to the release of the stored elastic energy.
- specimens where the lime mortar joint allows initial cracking at low stress fail by cracking of successive layers
- this last failure mode involves considerably more displacement but as the stresses are low the failure energy is actually less than in the stronger specimens the numerical analysis suggests that there is no single criterion that determines crack initiation and propagation
- these results should only be considered as a lower boundary for the brickwork in the façade of the Amsterdam central station which is of higher quality.

References

Civieltechnisch centrum uitvoering research en regelgeving
Constructief metselwerk, rapport 171, CUR 1994

Gianbanco.G , Mroz. Z
The interphase model for the analysis of joints in rock masses and masonry structures, mecccanica vol 36 , p 111, 2001

Lourenco. P.B. , Barros. J.O. , Oliveira. J.T.
Shear testing of stack bonded masonry, Construction and building materials

Pegon. P , Pinto, A.V. , Geradin. M
Numerical modelling of stone-block monumental structures
Computers and structures vol 79, p 2165, 2001

Pluijm, R van der
Gedrag en sterkte van het metselwerk van het CS Amsterdam evenwijdig aan de lintvoeg, TNO-rapport, 2000-CON-BM-R3030, 2000

Salerno, G., Bilotta. A. , Porco. F
A finite element wit masony-scale effects for the linear analysis of masonry brickwork
Computer Methods in applied mechanics and engineering, vol 190, p 4365, 2001

Vlijm, H.M. , Snel, A.J.M.
Complexe technieken voor de stad, cement 2004 , no 2