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EXPERIMENTAL INVESTIGATIONS ON THE BEHAVIOUR OF UNREINFORCED MASONRY WALLS UNDER SEISMICALLY INDUCED LOADS AND LESSONS DERIVED

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SUMMARY

Shaking table and quasistatic tests have been performed to identify the fundamental response mechanisms of unreinforced masonry walls subjected to cyclic in-plane shear forces. Changing the axial load level, the brick type and the material strength different types of cracking and post-cracking response have been identified. Both the post-cracking strength and the plastic deformation capacity depend on the crack pattern. Walls with solid and strong units under low axial load perform deformations in a ductile manner, whereas brittle failure with almost no plastic deformation capacity is observed on walls under high axial load and on walls composed of highly perforated bricks with discontinuous inner webs.

INTRODUCTION

For building structural systems where masonry walls predominantly or entirely resist the forces induced by earthquakes, sufficient shear strength has to be provided by appropriate design and construction. The strength design of masonry buildings, in general, is associated with a number of uncertainties. Because of the inhomogenity of the material and the variety of the units, mortar and bond the analytical prediction of the shear strength is complicated. Further difficulties may arise due to the irregularities in geometry and vertical load distribution. Since the seismic actions also raise questions regarding the prediction of their intensity, it is difficult to satisfy the requirement of safe and economic aseismic design of masonry walls.

Regarding the "no collapse requirement" as the basic rule of the earthquake resistant design, it is essential to provide for means which improve the strength and the post-cracking resistance. The latter feature is of importance, since it is needed for the stability of the cracked wall. In this connection, a well-mannered post-elastic response, i.e. stable plastic deformations without considerable loss of strength, is especially desirable. Such a ductile performance could, on the other hand side, be used for more economy in design. For example, in Eurocode 8 the latter aspect is taken into account by introducing behaviour factors according to the different types of masonry.

The specific objective of the investigations (1), supported by Institut für Bautechnik, Berlin, is aimed at gaining of more knowledge about the ultimate-limit-state properties of unreinforced masonry shear walls under seismic actions.

The ultimate objective is the establishment of sufficient analytical and experimental data in order to derive realistic parameters for the aseismic design of unreinforced masonry buildings, complying with the format of Eurocode 8.

ANALYTICAL BACKGROUND

The starting point of the investigations is the shear-failure model described in Reference 2. In this model the shear strength capacity of a masonry wall under static loads is evaluated considering various failure criteria. According to (2) the level of the axial load significantly controls the type of failure as well as the corresponding strength capacity (Fig. 1):

Low Axial Load - Failure in the Horizontal Bed Joint   The effective friction is a minimum with the smaller stress σ_2, so that the unit halves subjected to σ_2 tend to slide due to shear. Since σ_2 is located on the diagonal of the unit, a stepped crack appears in the wall following the joints (Fig. 1a).

Moderate Axial Load - Tensile Cracking of the Unit   With a larger vertical load the friction resistance in the joint also becomes larger. In this case a crack may develop at the center of the unit due to the inclined principal tensile stresses if these exceed the tensile strength of the unit (Fig. 1b).

High Axial Load - Compressive Failure of the Wall   Large vertical stresses in combination with shear stresses may result in large principal compressive stresses which lead to compressive failure as shown in Fig. 1c.

The ultimate shear capacity of a wall can be described by an envelope curve composed of the above outlined failure curves reflecting the influence of the axial load (Fig. 1).

The quality of the analytical prediction is correlated with the compliance of the model assumptions with the specific case. Further it is associated with the accuracy of capturing the material properties such as cohesion, friction coefficient and the tensile strength of the units.

Based on the principles of the above analytical model, design factors such as axial load, strength of materials and type of the units are selected as the main parameters of the study.
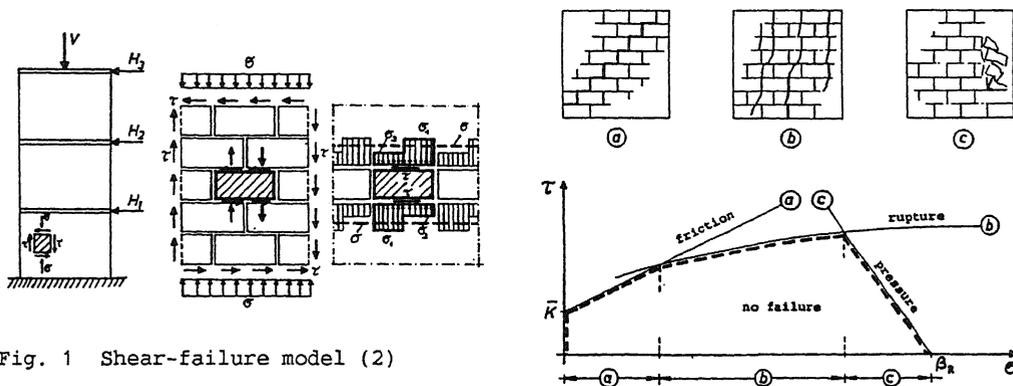
Fig. 1   Shear-failure model (2)

Series of wall elements (Fig. 2) with L/H/t = 1.24/1.24/0.115 m were tested on the Earthquake Simulator of Institut für Massivbau, THD. For the base acceleration a real time history recorded in Tolmezzo during the Friuli Earthquake, 1976, was used. In successive steps the test structures were subjected to different numbers of the base excitation with constant or increased intensities. In some cases, quasistatic tests were performed in order to study the response in more detail.
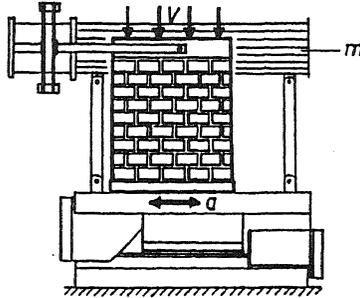
Fig. 2 Experimental Set-up

The experimental program is presented in Table 1. Three different types of units, however, having the same dimensions (l:w:h = 240:115:113 mm) were used. In the first two series solid calcium silicate units with three holes and no hole, respectively, were used, whereas in the third series perforated bricks with staggered longitudinal webs were investigated. The vertical joints were always filled with mortar.

In each series the axial load level was changed in order to study the different failure patterns. The axial loads were introduced through vertical prestressing. Using soft springs between the test structure and prestressing rods, the sensitivity of prestressing to deformations could be effectively minimized.

Series No. Exp. No.	Unit	Strength of unit / mortar type	Vertical stress (N/mm²)
Series 0		12 N/mm²/M5-10	
V01 D			-0,3
V02 D			-0,6
V03 D	KSV 12		-1,0
V04 D			-1,5
V02 ·S			-0,6
V04 S			-1,5
Series 1		28 N/mm²/M5-10	
V11 D			-1,0
V12 D	KSV 28		-0,8
Series 2		12 N/mm²/M5-10	
V21 D			-1,0
V22 D	HLZ 12		-0,6

D: Dynamic Test   S: Static Test

Table 1 Experimental Program

TEST RESULTS

With reference to the interaction between crack pattern, plastic deformability and failure type following results were obtained:

The Crack Pattern Strongly Depends on the Axial Load Level (Series No. 0)   Under low axial load (V01, V02) cracking occurs in the mortar joints along the diagonals. With increasing axial load straight diagonal cracks are formed which pass through the units (V03, V04).

The Plastic Deformability of the Wall Depends on the Crack Pattern   In   cases where solely or primarily mortar joint cracking occured (V02, V11 and V12) a considerable potential of plastic deformability could be observed (Fig. 3).   The individual partitions of the wall seperated by joint cracks slide on each other resulting in large relative deformations. The strength degradation is small, since the strength capacity is governed by the friction resistance which remains nearly unchanged. If unit cracking governs, the individual partitions seperated by cracks are not stable and tend to slide downwards along the straight diagonal crack surfaces (V03). This brittle type behaviour is more pronounced with increasing axial load finally resulting in an explosive-type failure without any plastic deformability (V04) (Fig. 4).
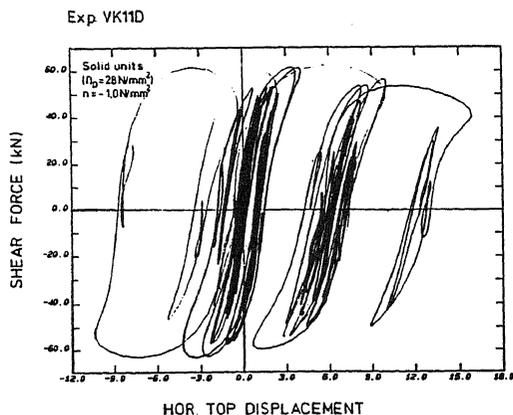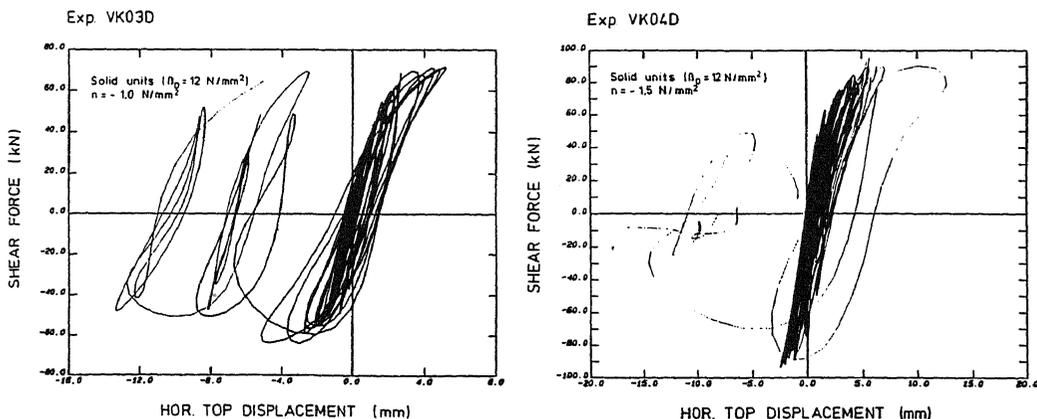

Fig. 3   Test V11D

Fig. 4   Tests V03D and V04D

Unit Strength/Mortar Strength Ratio is a Substantial Parameter to Control the
Cracking Pattern and the Plastic Deformability   Using units of higher strength
(Series No. 1) tensile unit cracking could be reduced to only a few cracks in the
lower corners of the specimen. With joint cracking governing the plastic deforma-
tion capability improved as shown in Figure 3.

Highly Perforated Units with Discontinuous Webs Fail Abruptly (Series No. 2)   In
both cases V21 and V22 a sudden failure was observed, prior to which practically
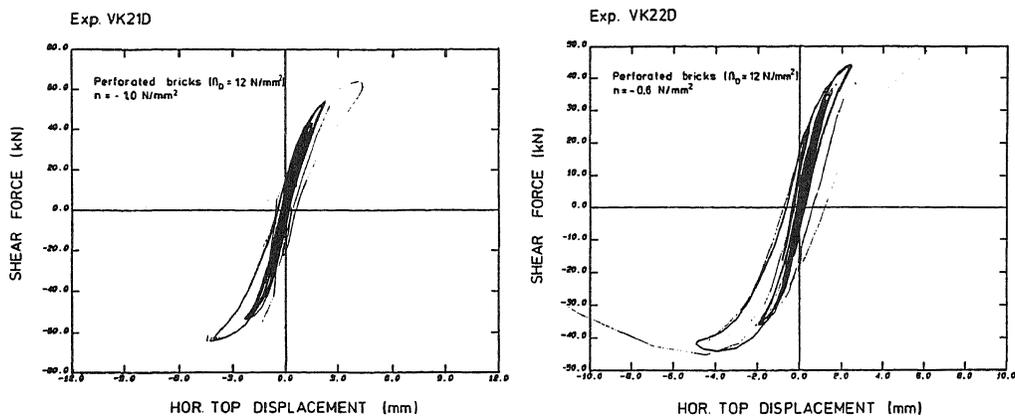no cracking occured (Fig. 5).

Fig. 5   Tests VK21D and VK22D

COMPARISON WITH ANALYSIS

In order to gain a better insight into the individual response mechanisms,
the recorded response data has been further evaluated and compared with the
analytical predictions.

Strength Assessment   As for the series No. 0 and No. 1 the results of strength
capacity and crack pattern principally show a good agreement with the analytical
predictions based on Reference 2. Considering the fact, that the test structure
has a number of pecularities such as large bending effects, extreme good workman-
ship with reference to the construction of the vertical joints and the relative
small size causing disturbances at the boundaries, adequate modelling features
had to be added in order to achieve a better agreement.

Regarding the assessment of the shear strength capacity of the walls with
perforated bricks (Series No. 2) detailed stress analyses for the bricks were
necessary. Assuming the axial load as uniformly distributed on the entire web
section in the compression zone and regarding the outer webs as the only shear
resisting elements, the principal stresses were calculated. The results indicate
that the principal tensile stresses in the outer webs are considerable. However,
due to the imperfections of the brick geometry and due to the uncertainties
associated with the material properties, it is difficult to outline a clear fail-
ure pattern. The cruical point is, that the weak and discontinuous inner webs do
not provide any resistance to shear which might be introduced by sliding of the
bricks in the bed joints. Through their abrupt failure the outer webs lose the
horizontal support and also fail under the compression they are subjected to.

Ductility Properties   In Fig. 6 the measured maximum shear force for each test
run is compared with the maximum linear-elastic response of a SDOF-model of the

test wall with 5 % viscous damping. Following relationships can be recognized:
- Walls under high axial loads (VO4) and walls composed of highly perforated bricks (V21) respond almost linear-elastically up to their abrupt failure.
- Walls composed of solid units under moderate to high axial loads, where cracks mainly pass through the units (VO3), show an unstable post-cracking response. The maximum shear force is smaller than the analytical linear-elastic response, but solely due to the fact, that the strength undergoes a significant degradation.
- Walls composed of strong solid units under low to moderate axial load, where the mortar joint cracks dominate, respond in a ductile manner (V11, V12). After cracking the strength remains nearly constant controlled by the friction resistance in the joints. An increase of the earthquake intensity only results in larger deformations of stable reversible type with substantial energy dissipating capability.

Nonlinear analyses assuming a perfectly elastoplastic behaviour resulted in an excellent agreement with the measured displacements.
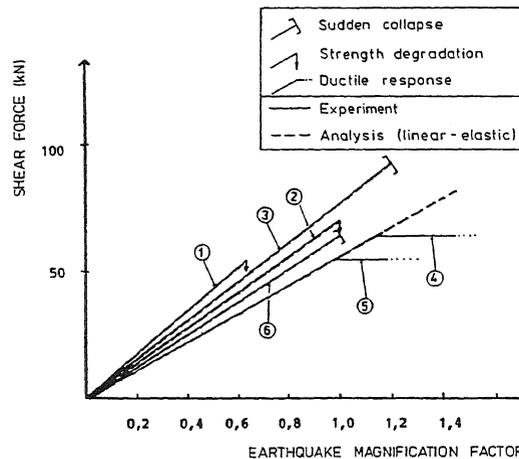

Fig. 6 Comparison with Analysis

CONCLUSIONS

The experimental findings clearly underline the essential role of the axial load level on both the type of cracking and the post-cracking seismic behaviour of unreinforced masonry walls. The combination of strong solid units with low or moderate axial compression result in a ductile response whereas high axial loads with weak units are associated with brittle failure. An other essential parameter investigated is the type and degree of perforation of bricks. High degree perforation and discontinuous webs in the wall plane lead to brittle failures.

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