Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 70 (1993)

Artikel: Investigation on the load bearing behaviour of multiple leaf masonry

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DOI: https://doi.org/10.5169/seals-53311

Investigations on the Load Bearing Behaviour of Multiple Leaf Masonry

Études sur le comportement des éléments multiplans en maçonnerie

Untersuchungen zum Tragverhalten mehrschaligen Mauerwerks

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SUMMARY

The aim of the research has been to minimise the amount of strengthening and repair of multiple leaf masonry by a better understanding of its bearing and failure behaviour. By simplified mechanical models, finite element analysis and compressive tests on small size walls, it is shown that the deformation process of multiple leaf masonry has two phases. From a knowledge of the crushing strength of the outer skins, the infill, as well as the relative volume proportions of each, the ultimate carrying capacity of the composite system can be estimated with sufficient accuracy.

RÉSUMÉ

Cet article fait le point sur des travaux de recherche dont le but est de minimiser les mesures de restauration grâce à une meilleure connaissance du comportement mécanique des éléments multiplans en maçonnerie. A l'aide de modèles simplifiés, de calculs d'éléments finis et d'essais de compression sur modèles, il a été démontré que les éléments multiplans suivent deux phases de déformation. En connaissant les résistances à la compression des parois extérieures et intérieures, ainsi que la répartition de leurs volumes, les charges de rupture de ce type de mur peuvent être déterminées avec une bonne précision.

ZUSAMMENFASSUNG

Es wird aus einer Forschungsarbeit berichtet, deren Ziel es ist, durch möglichst genaue Kenntnis des Trag- und Bruchverhaltens mehrschaligen Mauerwerks sanierende Eingriffe auf ein Minimum zu beschränken. Mit Hilfe von einfachen Tragmodellen, Finite-Elementberechnungen und Modellversuchen wird dargelegt, dass mehrschalige Mauerwerkswände ein zweistufiges Verformungsverhalten aufweisen. Die Bruchlasten derartiger Wände lassen sich bei Kenntnis der Bruchfestigkeiten von Aussenschalen und Zwischenschicht sowie der Volumenanteile dieser Komponenten mit hinreichender Genauigkeit vorhersagen.

1 INTRODUCTION

When dealing with preservation or restoration of historic buildings the question frequently arises as to how to assess the residual strength of the existing masonry. In order to evaluate the residual structural capacity the manner of response to loading of the structure in question must be understood. Detailed knowledge of the structural behaviour only permits a static check; but together with testing of the building materials it allows the safety level of the structure to be assessed.

Historic masonry was commonly built using multiple leaf walls consisting in general of two outer walls and a more or less heterogeneous infill; the total thickness being not less than 50 cm. This method of building is around 4000 years old and exists in a variety of forms. Therefore a detailed understanding of the behaviour of these structures is essential, in order to reduce any intervention for the purpose of strengthening or repair to a minimum. Thereby can historic buildings be maintained as authentic as possible.

In this respect the aim of the presented research was to analyse the load bearing and failure behaviour of multiple leaf masonry walls as well as to estimate the ultimate strength.

2 INVESTIGATION METHOD

The load bearing behaviour of multiple leaf masonry was investigated by a three-way approach:

- theoretical identification of the loading of the components by simplified mechanical models
- linear and non-linear finite element analysis
- experimental analysis of multiple leaf masonry wallets under vertical loading

The overlay of the results provided an idea of the load path through the cross sections and enabled a prediction to be made of the ultimate strength of these constructions.

The investigations presumed that all loadings were vertical and uniformly applied. Additional (eccentric) loads caused by wind, hogging or sagging, shaking by traffic or earthquake, are the subject of future research work.

2.1 Mechanical models

2.1.1 Multi-material model

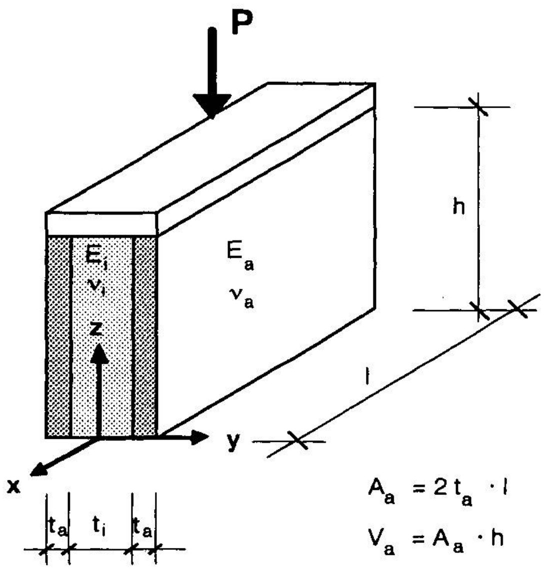

Fig. 1 Multi material model

The following conditions were presumed for the validity of the model:

- the system is formed by two parallel situated components (outer skins, infill),
- the outer skins are of similar geometry and materials,
- a stiff loading platen distributes load to the components (uniform vertical strain: $\varepsilon_a = \varepsilon_i = \varepsilon_z$),
- the wall is restrained from rotation about the lines of external loading,
- the wall is "long" (■ plain strain conditions apply: $\varepsilon_x = 0$),
- all components are linear elastic.

If the influence of lateral strain is neglected, the multi-material model can be simplified to the *spring model* [1]. The mechanical behaviour of the components can be described by different springs so that the stresses of outer skins ($\sigma_{zz,a}$) and infill ($\sigma_{zz,i}$) only depend on the ratios of stiffness (E) and geometry (t, A):

$$\sigma_{zz,a} = \frac{E_a}{E_l} \cdot \sigma_{zz,l} \tag{1}$$

$$\sigma_{zz,l} = \frac{P}{A_l} \cdot \frac{1}{1 + 2\frac{E_a \cdot t_a}{E_l \cdot t_l}} \tag{2}$$

The modulus of elasticity of the multiple leaf wall can be calculated as:

$$E_{ml} = \frac{A_a}{A} \cdot E_a + \frac{A_l}{A} \cdot E_l \tag{3}$$

The formula forms the basis of predicting the ultimate strength. The condition of compatibility requires the same vertical strains in all components and with the knowledge of the stress-strain behaviour of the components the actual stress of the system can be generally derived from the component stresses and their volume ratios:

$$\sigma = \frac{V_1}{V} \cdot \sigma_1 + \frac{V_2}{V} \cdot \sigma_2 \tag{4}$$

The upper limit of strength is reached if the ultimate strains of the components are equal. In the normal case the ultimate strength of the system depends on the crushing strength of the component with the lower peak strain and the relating stress level of the remainder:

$$f = \frac{V_1}{V} \cdot f_1 + \frac{V_2}{V} \cdot \sigma_2 \tag{5}$$

with

$$\sigma_2 = E_2 \cdot \varepsilon_{u,1} \tag{6}$$

If the influence of the lateral strain is considered the bending moments in the outer skins can be qualitatively calculated by the use of the analogy of the elasticly bedded beam [2].

2.1.2 Silo model

In a endless high silo compartment the cohesionless infill causes a horizontal pressure ($p_{h,a}$) on the outer skins:

$$\max p_{h,a} = \frac{\gamma_l \cdot A_l}{\mu \cdot U_l} \tag{7}$$

If the silo model is valid the load bearing capacity of multiple leaf masonry would directly depend on the density (γ_l), the friction coefficient (μ) and the geometric ratio of area / perimeter (A_l/U_l): the thicker the infill the lower the crushing strength of the wall. One aim of the experiments therefore was to check this hypothesis. Certain features of silo theory bring its veracity into question as a suitable analogue for multiple leaf masonry:

- masonry cannot be filled with a cohesionless material without tilting of the outer skins at a critical filling height [2]
- the silo pressure causes high bending moments in the outer skins; the resulting tension stresses cannot be suppressed by the compressive stresses induced by vertical loads. Therefore multiple leaf masonry walls could not exist if the silo pressure ($p_{h,a}$) is acting [2].

2.2 Finite element analysis

The aim of the finite element analysis was to investigate how different parameters influenced the stresses of the outer skins. The sensitivity study varied the following:

- the ratios of the elastic constants (Young's modulus E, Poisson ratios ν)
- boundary conditions at the wall crest
- application of the vertical loading: deformation or average applied stress
- bond between outer skins and infill

- thickness ratio of the components
- stress-strain behaviour of the infill (material law)

A selection of the results will be presented later for comparison with the experimental work.

The FE-Program ADINA 5.0 was used on the mainframe. Outer skins and infill were modelled by quadratic 2-D-SOLID elements (9 integration points). The material of the outer skins was considered homogeneous with linear elastic stress-strain behaviour. By the use of the symmetry and the plain strain condition the number of elements varied between 318 and 742 depending on the thickness ratio (t_i/t_a = 1, 3, 5). The geometry of the models provided an analogue of the test specimens. For the non-linear analysis the Drucker-Prager material law was applied to the infill as a generalised version of the Mohr-Coulomb failure criterion.

2.3 Experimental analysis

The testing programme was run on the basis of a developed typology [2] with:

- the thickness and the properties of the outer shells held invariant
- the thickness and the stiffness of the infill varied as standard parameters.

Five different infills were used for the specimens:

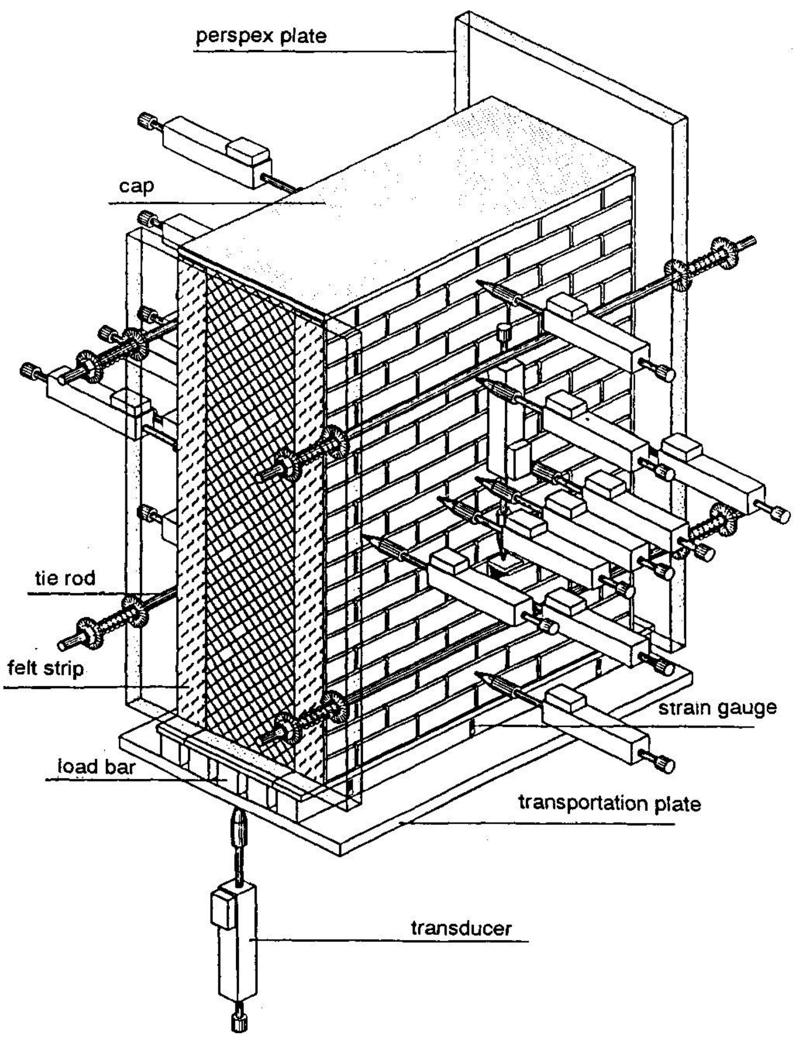

Fig. 2 specimen (t_i/t_a = 3) with the measure equipment

infill *L*: 3 reference-specimens (t_i/t_a = 3) kept unfilled (= infill air) and were tested under the same conditions as the other wallets.

infill *B*: 5 specimens (t_i/t_a = 3) were filled with mortar of a high binder content. The compressive strength and the stiffness of the infill were higher than the relating properties of the outer skins.

infill *F*: 1 specimen (t_i/t_a = 1), 6 specimens (t_i/t_a = 3), and 1 specimen (t_i/t_a = 5) were filled with mortar of a extremely low binder content. The compressive strength and the stiffness of the infill were lower than the relating properties of the outer skins.

infill *K*: 5 specimens (t_i/t_a = 3) were filled in a sandwich pattern: layers of mortar followed layers of gravel, giving cohesionless zones in the infill and a high specific volume.

infill Z: four specimens each (t_i/t_a = 1, 3, 5) were filled with a mixture of crushed bricks and mortar. The mechanical properties of the infill were similar to the characteristics of infill *K*.

All 33 specimens were built as quarter scale masonry wallets. The thickness of the specimens varies between 90 mm (t_i/t_a = 1) and 210 mm (t_i/t_a = 5), the height was 400 mm and length 313 mm. The model-brick skins had a slenderness of 13,4. There was a simple bond only between the outer skins and infill; consequently the tests investigated the worst scenario to give the lower limit of the bearing capacity. The mortar capped specimens were continuously loaded up to the failure by means of a 600 kN hydraulic test machine. Nine transducers on each outer shell measured the horizontal deformations during the test. Further measurements were taken of longitudinal deformations and the load distribution within the outer and inner layers at the base of the specimens (fig 2). A data logger and computer stored all measurements at five-second intervals.

Test cubes were made up from the material of the outer skins (masonry pillars) and the infill. The pulse velocity was measured ultrasonically and the results are used to determine the dynamic modulus of elasticity. The separate component behaviour was studied through compression tests on the cubes. Their stress-strain curves formed the basis of the comparison with their behaviour in the composite system.

3 RESULTS AND THEIR INTERPRETATIONS

3.1 Load bearing behaviour

The deformation behaviour of central loaded multiple leaf masonry is seen to have two phases:

Phase I: There is complete bonding between the outer skins and the infill, with the lateral deformations increasing linearly with vertical load. The normal stresses in the components are estimated by the use of the dynamic modulus and geometry of the components (spring model). In this load phase no damage in the outer skins can be recognised, cracks in the stones, gaping or squeezing bed joints, horizontal deformations or bending.

Phase II: This starts with the onset a bond failure between outer skins and infill (outer skins tear off). Because of the reduced lateral restraint (ε_q) the linear increase of the lateral deformations is higher than in phase I. The beginning of phase II depends on geometry and the ratio of the elastic constants between components, the boundary conditions of the outer skins, the load application and the structural bond between the components.

At a definitive load level the infill starts to yield, at the same time lateral deformations increase disproportionally (compare fig. 3 and fig. 4). The yield-load depends on the triaxial stress-state in the infill influenced by the normal vertical stress and the resistance to lateral strain. The yielding effects an increase of the normal stress and a constant horizontal loading of the outer skins. The height of the edge pressure results from the normal load and the bending moments. In that load step the outer skins clearly belly out. According to the spread-direction these deflections either cause an opening-up of the bed joints or vertical bending cracks.

3.2 Behaviour at failure

The behaviour at failure depends on the stiffness ratio of the components:

- If the infill is stiffer than the outer skins the collapse of the system is caused by the compressive failure of the infill. The vertically low-stressed skins are not able to bear the load transfer from the infill to the outer layers and the horizontal loading arising immediately before failure. The failure of the composite system occurs suddenly and without advance warning.

lateral strains depending on the area load **stress rate curves**

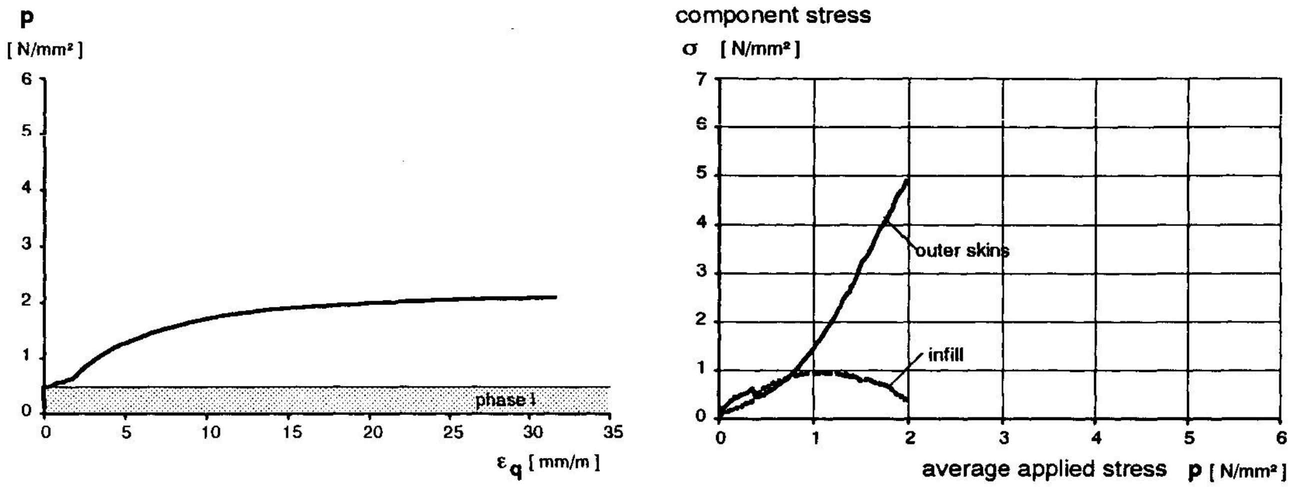

Fig. 3a specimen with weak infill *F*

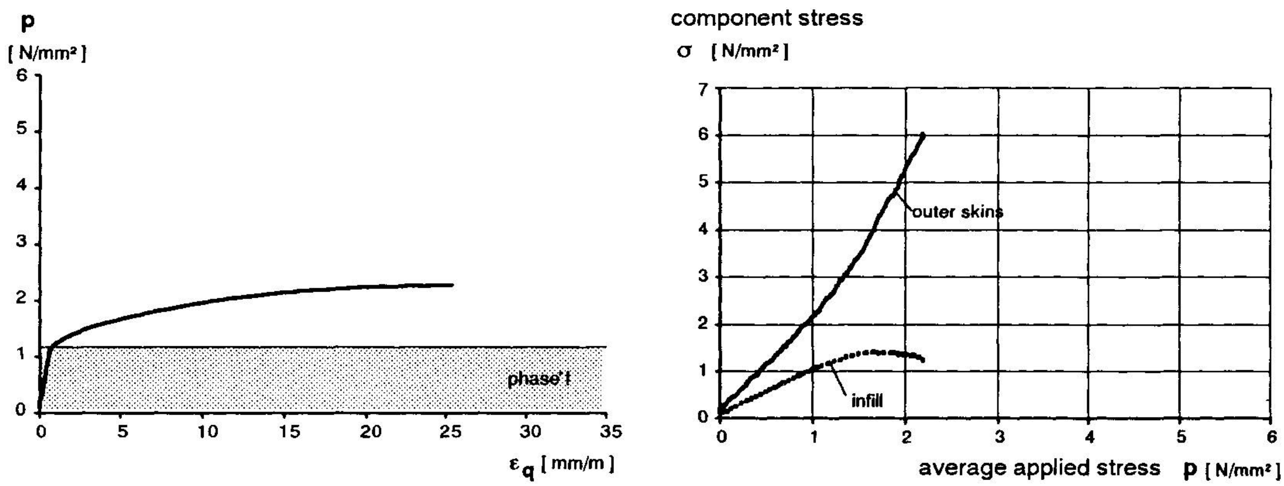

Fig. 3b specimen with heterogeneous infill *K*

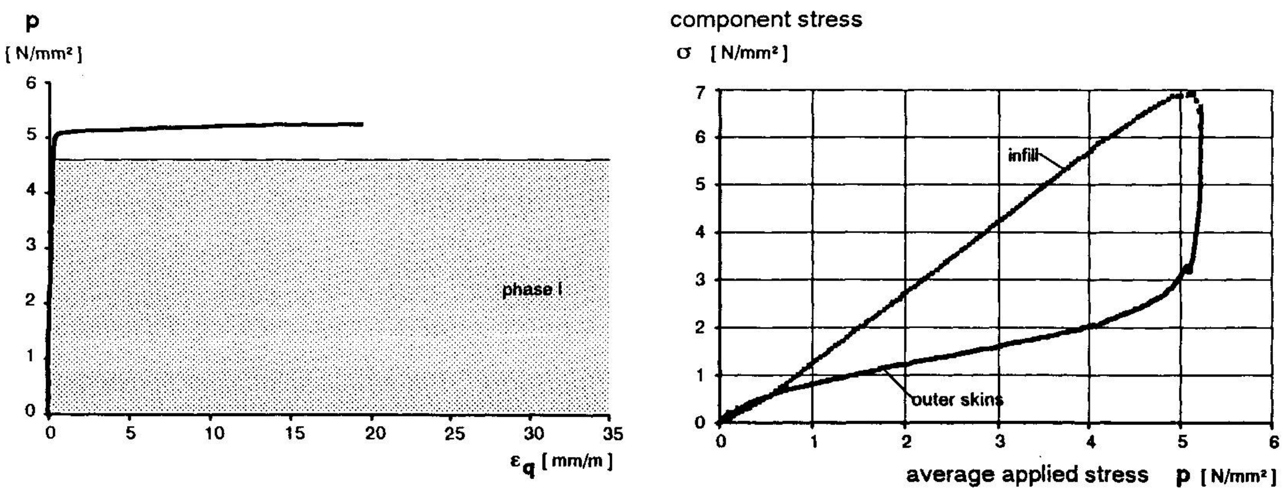

Fig. 3c specimen with stiff infill *B*

Fig. 3 Lateral strain curvature and stress rate curves of three specimens with different infills

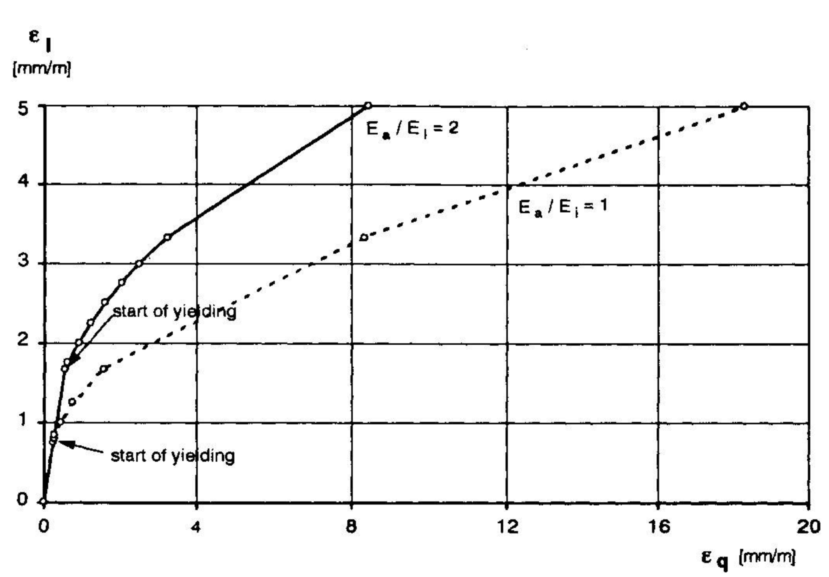

Fig. 4: Relation between the vertical (ε_l) and the lateral strain (ε_q) of the FE-model (at $h/2$)

- In the case of a weaker infill the collapse of the system is caused by a compressive edge failure due to bending of the outer skins. Large bending deflections combined with gapping of the bed joints or bending cracks announce the failure long time before. The slenderness and the boundary conditions of the outer skins have an important influence of the load bearing capacity of multiple leaf masonry.

3.3 Estimation of the load bearing capacity

The finite element analysis together with the experimental results showed that the thickness ratio (t_i/t_a) and the compressive strength of the components are the most important parameters to influence the load bearing capacity. By a linear finite element analysis for different thickness ratios and ratios of the elastic constants (E_a/E_i) the average applied stress p was computed which caused an edge pressure of 5 N/mm² in the outer skins (fig. 5). The dashed curve represents the air-filled cross-section. Fig. 6 shows the results of the experiments on three air-filled specimens plus one specimen with the infill F and four specimens with the infill Z in which properties vary slightly. Notice that the linear elastic calculation lies close to the experimental results. Although the load bearing behaviour can only be simulated by a non-linear calculation a linear analysis suffices to describe failure behaviour in qualitative terms. Even in the case of very weak infills the experiments concluded that the thicker the infill the higher is the ultimate strength of the specimen; that is in fact a contradiction to the silo theory which would anticipate lower ultimate strengths for thicker infills. Therefore the silo model is inappropriate for estimating the horizontal loading on the outer skins, its use would lead to an overprediction of the stresses and therefore to inadequate repairing methods.

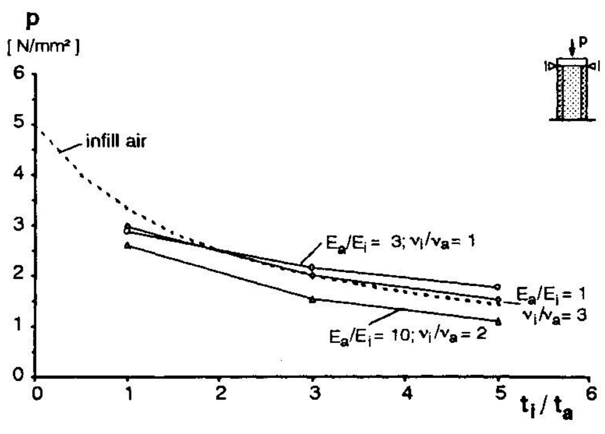

Fig. 5 FE-analysis: maximum of average applied stress (p) for reaching the critical edge stress at different thickness ratios (t_i/t_a)

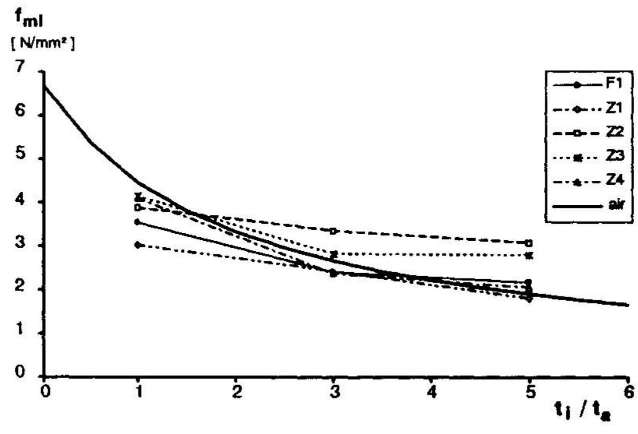

Fig. 6 Experiments: crushing strengths (f_{ml}) of filled and unfilled specimens of different thickness ratios (t_i/t_a)

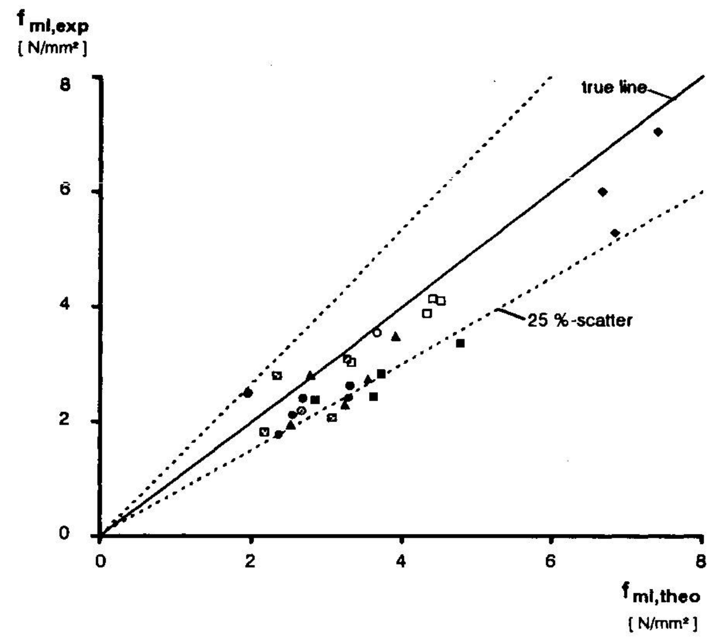

Fig. 7 Relation between the calculated and the measured crushing strength of the wallets

Through *load bars* at the base of the specimens the normal stresses in the components could be measured (fig. 2). So it became possible to check the validity of the multi-material model by the use of equation (4). For σ_1 we put in the measured strength of the outer skins at the failure ($\sigma_{a,u}$) and for σ_2 the corresponding value of the infill ($\sigma_{l,u}$). Fig. 7 presents the comparison between the theoretic crushing strength ($f_{ml,\ theo}$) according to eq. (4) and the experimental results ($f_{ml,\ exp}$). The 45°-line gives the stress path for conformity and the diagram shows points lying near to that line, with only 14 % are outside a masonry-usual scatter of 25 %.

Equation (4) is not suitable for the structural analysis because the component stresses at the failure load are not known. Therefore a failure criterion was developed which estimates the crushing strength of a multiple masonry wall (f_{ml}) on the basis of the failure loads of its components ($f_{a,k}$, f'_l). The comparison of the stress-strain relationships between the components in- and outside of the composite system showed that the criterion can be derived out of the triaxial stress relationships:

- In the composite system the infill reaches a higher compressive strength than under uniaxial loading. The reason is the triaxial compressive stress state caused by the vertical stress and the hindered lateral deformations. The correcting factor (Θ_l) which describes the ratio between the component stress at failure ($\sigma_{l,u}$) and the uniaxial compressive strength (f'_l) generally is larger than one and depends on the structure of the infill.
- The compressive strength of the outer skins in an unfilled system ($f_{a,k}$) are never reached in a multiple leaf cross section, because of the horizontal loading through the yielding infill. The correcting factor (Θ_a) depends on the bending stiffness, the boundary conditions and the bending moments. Its value is smaller than one.

The crushing strength of a multiple leaf masonry wall can be estimated as:

$$f_{ml} = \frac{V_a}{V} \cdot \Theta_a \cdot f_{a,k} + \frac{V_l}{V} \cdot \Theta_l \cdot f'_l \qquad (8)$$

4 OUTLOOK

Continuing research work will investigate the amounts of the correcting factors in relation to different types of multiple leaf masonry wall [2]. Then low-destructive test methods will be developed to identify the determining parameters for structural analysis.

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