TENSILE STRENGTH OF MASONRY

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ABSTRACT The tensile strength of masonry parallel to the bed joints and its deformation behaviour (stress-strain-curve, modulus of elasticity, elongation at rupture) under tensile stress were investigated. The experimental work included analyses carried out on different types of brick and conventional mortars as well as shear tests carried out on brick mortar specimens and tensile tests on small masonry specimens. The investigation of the stress-deformation properties allowed an exact determination of the main deformation parameters. The correlations between tensile strength of masonry and properties of brick and mortar were analysed.

1. INTRODUCTION

The safety against cracking of masonry depends on its stress by influence of exterior loadings, temperature and humidity as well as on the strength- and deformation properties. These are essentially determined by the properties of the components brick and mortar and their bonding properties. The impediment of deformation causes tensile stress, which means an increased cracking risk because of the relatively low tensile and shear strength. Today there are very much improved calculation charges which protect the safety against cracking (see (1)); their exactness, however, depends substantially on the precision, with which the characteristic properties of masonry and the characteristics of deformation impediment can be given. Up to now for estimations according to safety against cracking the modulus of elasticity in compression vertically to the bed joints had to be used instead of the modulus of elasticity in tension; also the tensile strength of masonry approximately had to be determined by the tensile strength of bricks or the shear strength between brick and mortar. This compulsorily caused considerable uncertainty of statement about measures, which are too far on the safe side and thus uneconomically.

This is why the tensile strength, the stress-strain-curve and the elongation at rupture of masonry under tensile stress have been determined experimentally for the purpose of a research project (2) in the Institute for Building Research of the Technical University of Aachen. The tensile stress worked parallel to the bed joints of masonry, because on the one hand this kind of stress is the reason for the frequent damage called "vertical cracks in relative long masonry walls" (case of deformation: horizontal deformations, comp. (1)), and on the other hand it is admitted to be the only way of tensile stress of masonry in the projected standard DIN 1053 part 2.

2. STATE OF RESEARCH CONCERNING THE TENSILE STRENGTH OF MASONRY

Only those investigations ((3)...(9)) have been taken into consideration from the literature, which contained results about the

tensile strength of masonry (tensile-, diagonal tensile- and splitting tensile strength). The evaluation of the several test results was complicated by the different test conditions and the terminology partly varying from that one of the strength theory. The shape of the test specimens and the way of bearing and loading differed very much. Furthermore important informations were missing, e.g. a description of the test and measuring device, testing age of the specimens, mortar's composition and strength values of bricks and mortar.

Up to now the tensile strength of masonry made of concrete or sand-lime bricks being loaded parallel to the bed joints has been determined - as is known - only by (3), (4), (10) and (12). By further investigations the diagonal tensile strength, the splitting tensile strength and the shear strength related to the whole crack surface have been found out according to different methods. Altogether the tensile strength of masonry grows tendentiously due to its increasing strength of bricks and mortar, as it can be seen by means of the strength values, which are given by the publications in hand. A lot of material and test-bound influences have to be considered, which are described insufficiently in most reports.

3. TEST PROGRAMME

The masonry tensile tests were carried out within the scope of a larger research project (2). Masonry made of brick - mortar combinations was tested, for which extremely low or high tensile strength values were expected (see Table 1).

Table 1: Programme for the Testing of Tensile Strength

Bricks			Number of Specimens	
Type of Brick	Standard DIN	Compression Strength Class N/mm^2	Mortar Type MG II	MG III
HLz (Vertical coring clay brick)	105	12	3	3
		60		3
KS (Solid sand-lime brick)	106	12[2]	3	3
		36[3]		3
KS L (Cored sand-lime brick)	106	12	3	3
G (Gas aerated concrete brick)	4165	2	3	
		6		3
V (Light weight concrete brick)	18152	2	3	
		12		3

1) Standard mortar specified in DIN 1953 part 1

2) With handling device

3) Without handling device

The test arrangements and the realization have already been described in (13). Figure 1 shows details of the test arrangement for tensile testing of masonry wallettes. The type of bricks was varied as well as the brick strength and the mortar strength (-type). The brick size (240 mm x 115 mm x 113 mm), the state of humidity of the bricks when being layed (air dry) and the test moment were kept constantly (test moment: coming up to the mortar's minimum compressive strength).

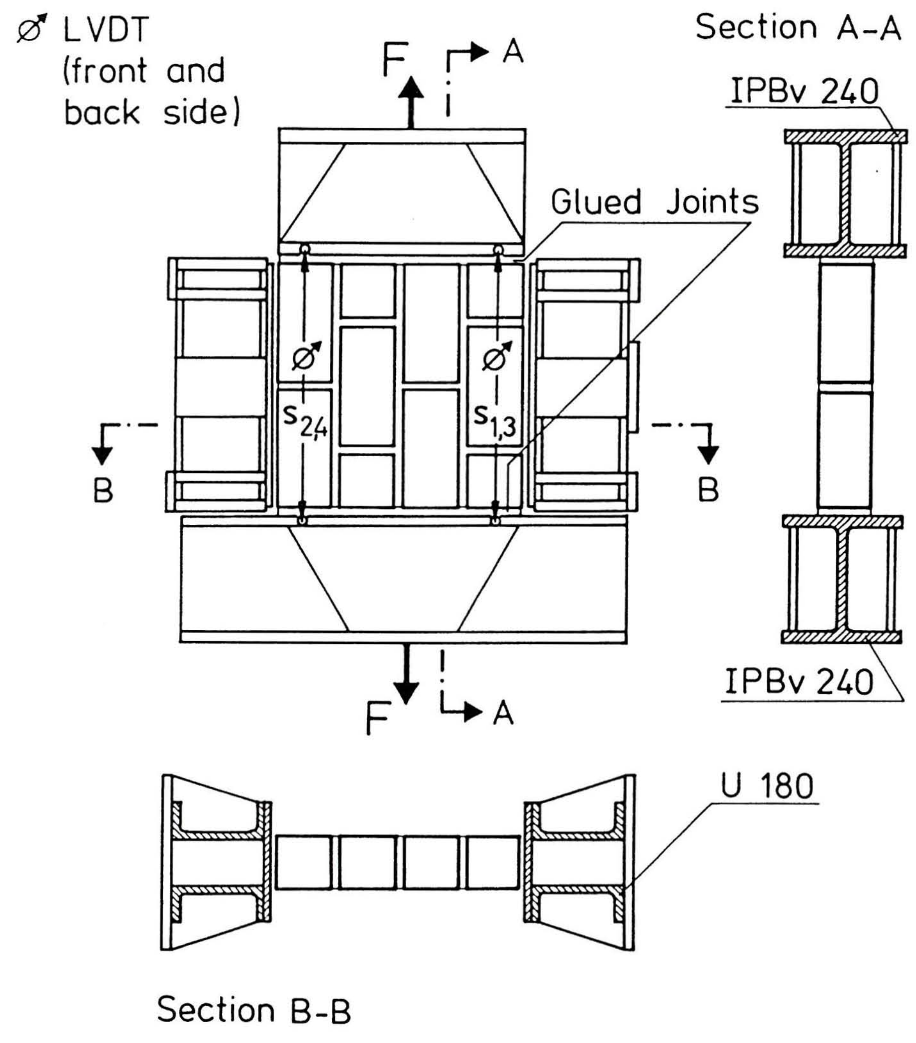

Fig. 1 Test Set-up for Tensile Testing of Masonry Wallettes

The main aim of the research project was the determination of the tensile strength of masonry caused by tensile stress depending on some essential influencing values. Furthermore the relations between tensile strength of masonry and brick-/mortar properties had to be investigated, resp. those between the bonding properties of bricks and mortar.

4. TEST RESULTS

4.1 Shearing Tests

The tests were carried out on test specimens consisting out of 3 masonry bricks. The specimens broke down in most cases because of a exceeding of the bonding shear strength between brick and mortar. The bonding shear strength values vary from each other according to the type of brick. They can be classified into two groups: β_{SB} = 0,1...0,2 N/mm² (sand-lime and gas aerated concrete bricks) and β_{SB} = 0,2...0,9 N/mm² (vertical coring clay and light weight concrete bricks; see Table 2). There was no determination of a definite influence of the bricks strength. The application of mortar MG III instead of MG II caused in most cases an increase up to a doubling of the β_{SB} values.

Table 2: Tensile Strength of Masonry and Strain at Maximum Tensile Stress for the Tested Combinations

Bricks				Mortar		Masonry	
Type of Brick	Compression Strength Class N/mm²	β_C N/mm²	β_{ST} N/mm²	Type	β_C N/mm²	β_T N/mm²	ε_T [1)] mm/m
HLz	12	23,3	0,90	II	3,50	0,122	0,074 0,106 0,225
HLz	12	23,3	0,90	III	9,86	0,205	0,137 0,102 0,105
HLz	60	95,2	3,28	III	9,86	0,822	0,153 0,168 0,286
KS	12	23,2	1,44	II	3,50	0,154	0,133 0,062 0,050
KS	12	23,2	1,44	III	9,86	0,192	0,047 0,072 0,100
KS L	12	26,4	1,61	II	3,50	0,069	0,048 0,807 0,471
KS L	12	26,4	1,61	III	9,86	0,092	0,087 0,081 0,063
KS	36	46,0	3,24	III	9,86	0,150	0,060 0,050 0,082
G	2	4,16	0,59	II	3,50	0,092	0,062 0,170 0,114
G	6	9,78	0,66	III	9,86	0,120	0,068 0,266 0,043
V	2	3,10	0,34	II	3,50	0,162	0,170 0,103 0,153
V	12	17,0	1,64	III	9,86	0,576	0,130 0,114 0,168

1) Indication of single values due to the large scattering

4.2 Masonry Tensile Tests

The failure depending on the applied type of brick occured basically by either a tensile debonding and shear debonding between brick and mortar in the joint area or by a tensile debonding in the joint and brick area (see also (1)). All the cracks of masonry wallettes made of the vertical coring clay and light weight concrete bricks passed along the head joints of bricks at alternate courses and through the centre of the brick at the intervening courses (Fig. 2). On the other hand all cracks of the wallettes made of sand-lime bricks passed along the head joints of the bricks and the length of bed joint between staggered head joints (Fig. 3). Diverging from these two failure modes the cracks in all gas aerated concrete specimens were to be seen inside the head and bed joints as well as across the masonry bricks.

Fig. 2 Failure Mode of a Wallette made of HLz 12 and Mortar MG II

Fig. 3   Failure Mode of a Wallette
          made of KS 12 and Mortar MG III

Essential differences between the determined stress-strain-curves are the initial rise, characterized by the modulus of elasticity, and the longitudinal strain ε_T at the moment of maximum load resp. of tensile strength β_T . A classification of the stress-strain-curves into two groups is possible; these can be adjointed to the two failure modes as described above:

I) stress-strain-curves, going steeply and largely linear up to the maximum tensile stress σ_T and then going down very fast to nearly $\sigma_T = 0$ (Fig. 4).

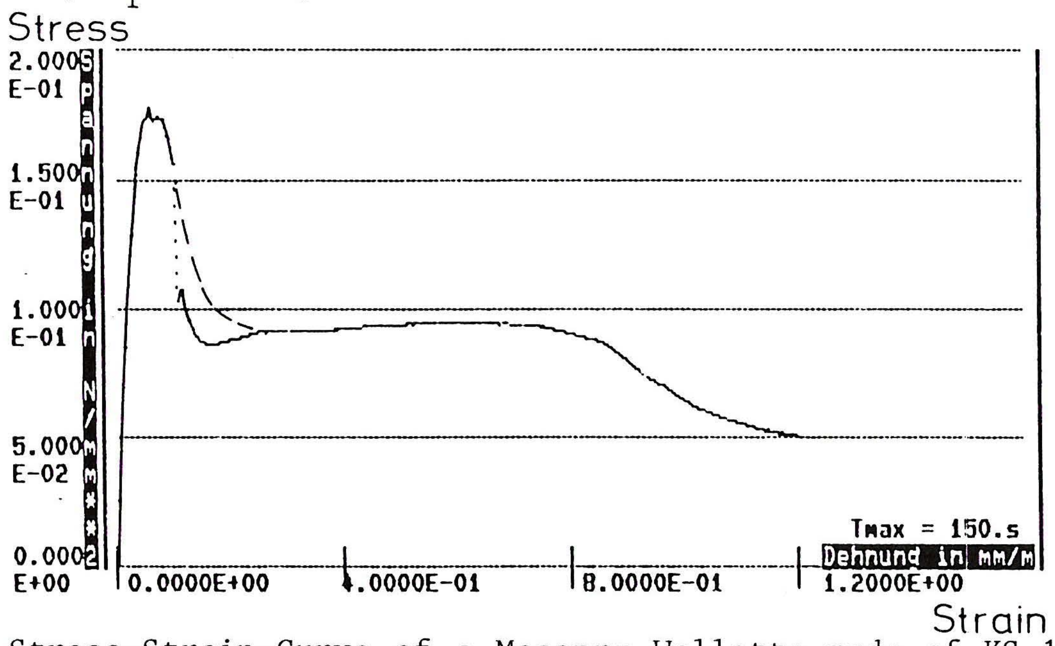

Fig. 4   Stress-Strain-Curve of a Masonry Wallette made of KS 12 and Mortar MG II

II) stress-strain-curves, going steeply and largely linear up to max σ_T, but then in some cases going down to a stress amounting approximately 50 % of the maximum stress, and which does not change very much with an increasing strain (Fig. 5).

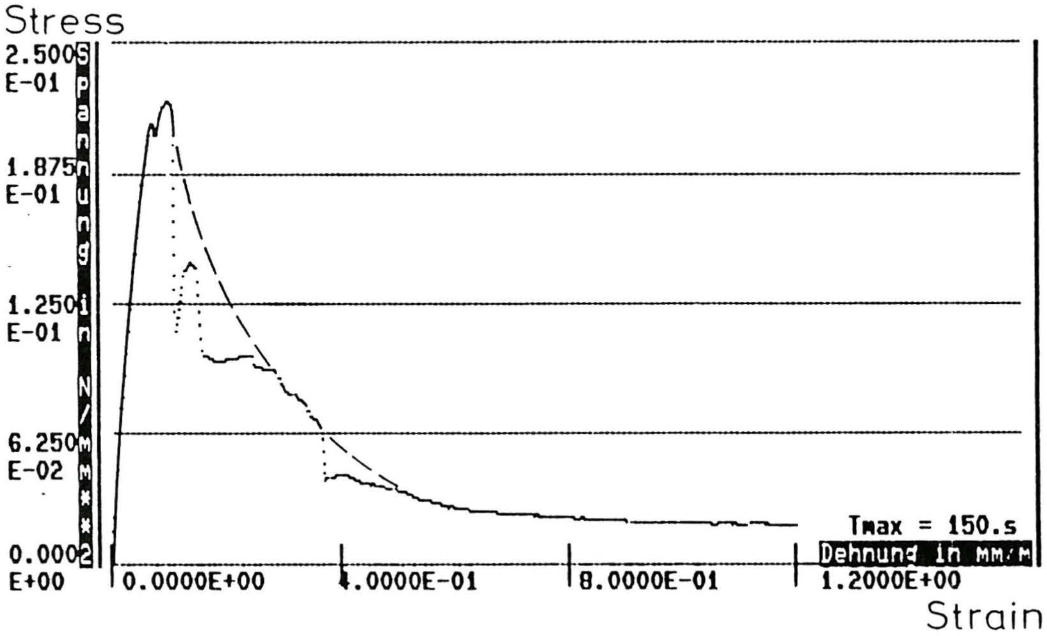

Fig. 5 Stress-Strain-Curve of a Masonry Wallette made of HLz 12 and Mortar MG III

Type I belongs to the test specimens showing a tension failure by tensile debonding along the brick's head joint at alternate courses and tensile failure of the brick in the intervening courses, type II belongs to those with a step-wise debonding failure in the joint area.

In Table 2 and Figure 5 a survey and an outline can be seen of the measured average strains at maximum tensile stress and tensile strength values. The dimension of the longitudinal strains appearing parallel to the masonry's bed joints and caused by tensile stress depends on both the deformation behaviour of bricks and mortar and their bonding properties. The average longitudinal strain of the test specimens HLz 12, KS 12 and KS L 12 decreased with an increasing mortar strength - the decrease was insignificant in most of the cases.

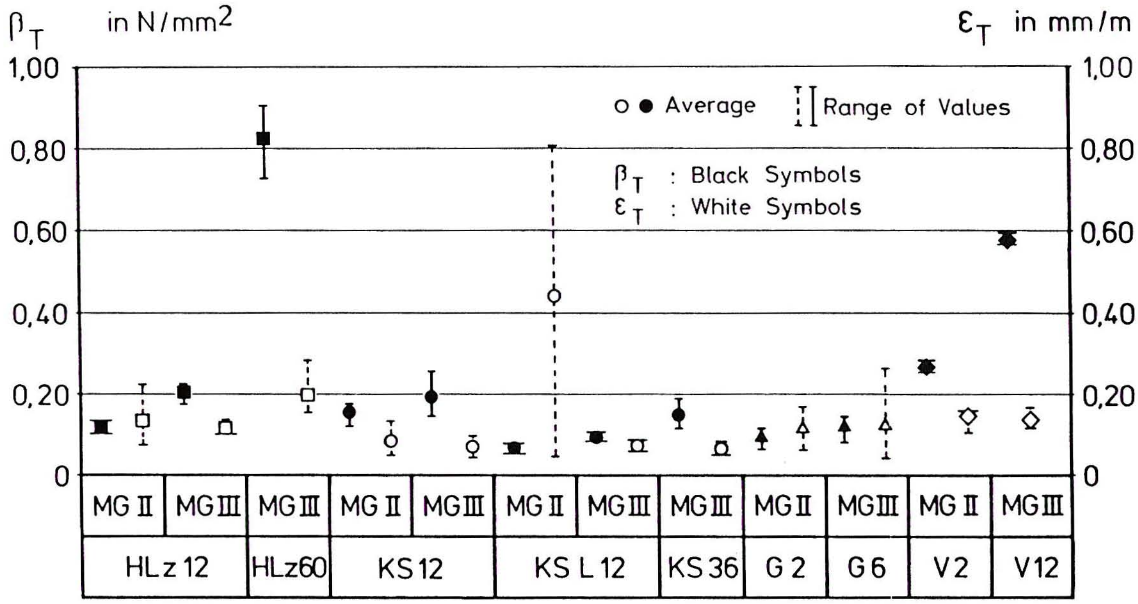

Fig. 6 Tensile Strength of Masonry β_T and Strain at Maximum Tensile Stress ε_T for Different Brick-Mortar Combinations

The scattering of the ε_T values was less with the mortar MG III than with MG II. The average ε_T values generally were between about 0.05 and 0.20 mm/m. There is no safe opinion about influences of the type of brick and its strength. The average tensile strength values β_T of masonry made of vertical coring clay bricks were between 0.122 and 0.822 N/mm². The tensile strength values increased with rising brick and mortar strength. The average β_T values of sand-lime brick masonry have a relatively close area, from 0.069 to 0.192 N/mm². The KS L 12 test specimens had the lowest and the KS 12 the highest values. The KS 12 and KS L 12 test specimens had a rising tensile strength in connection with an increasing mortar strength. The average tensile strength values of the gas aerated concrete masonry were 0.092 and 0.120 N/mm² and are inside those of the sand-lime brick masonry. In comparison to that - especially to the gas aerated concrete masonry (V 2 - G 2) - the tensile strength of light weight concrete brick masonry has got high values, on an average of 0.162 and 0.576 N/mm².

The generally same shaped stress-strain-curves made it possible to determine mathematically just that point of the curve, from which on the curve differed over proportionally from the straigth-lined run. The coordinates of this point were called critical tensile stress $\sigma_{T,c}$ and accompanying critical strain $\varepsilon_{T,c}$; the proportionality factor $\sigma_{T,c}/\varepsilon_{T,c}$ was called modulus of elasticity in tension $E_{T,c}$. The $E_{T,c}$-moduli and the E_T-moduli being determined as secant moduli with $\varepsilon_T = 0.33 \cdot \beta_T$ were opposed to each other (see Table 3). The proportionality factors $E_{T,c}/E_T$ are between 0.58 and 0.85, generally between 0.70 and 0.80. There has not been any comparison between the modulus of elasticity - up to now used for the estimation of the safety

against cracking - and the modulus of elasticity in tension being determined under tensile stress parallel to the bed joints. Nevertheless even these values were opposed to each other. It was to be seen that the values differed very much from each other, depending on the brick-mortar combination. The determined moduli of elasticity in tension permit - at least partly - an adequate correction of the up to now substitutionally used modulus of elasticity in compression; thus a more applicable mathematical estimation of the safety against cracking is possible.

Table 3: Modulus of Elasticity of Masonry in Tension and in Compression

Bricks		Mortar	Masonry		
Type of Brick	Compression Strength Class N/mm²	Type	$E_{T,c}$ N/mm²	E_T N/mm²	E_C [1] N/mm²
HLz	12	II	1857	2467	3500
HLz	12	III	2590	3273	4500 [2]
HLz	60	III	9083	12470	25000
KS	12	II	2733	3870	5000
KS	12	III	3897	4943	6000 [2]
KS L	12	II	1607	2293	5000
KS L	12	III	1463	2007	6000 [2]
KS	36	III	3530	6127	11000
G	2	II	1267	1487	1000
G	6	III	2437	2990	2500
V	2	II	1917	2273	1500
V	12	III	6813	8917	12000 [2]

1) Calculated values according to (1)
2) Estimated value

For both cases of failure investigations have been carried out concerning the relations between the masonry's tensile strength and the brick and mortar properties or the bonding properties between brick and mortar. These investigations were described and discussed in (2). Between the modulus of elasticity in tension $E_{T,c}$ and the brick and mortar tensile strength or the bonding shear strength there is a relation too, which can be described exactly by adequate functions.

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6. NOTATION

The following symbols are used in this paper:

σ_C compressive stress

σ_T tensile stress

β_C compressive strength

β_{SB} shear bond strength

β_{ST} splitting tensile strength

β_T tensile strength

ε_T strain at maximum tensile stress

E_C modulus of elasticity of masonry in compression ($\sigma_C = 0.33 \cdot \beta_C$)

E_T modulus of elasticity of masonry in tension ($\sigma_T = 0.33 \cdot \beta_T$)

$E_{T,c}$ modulus of elasticity of masonry in tension at the critical stress