1. ABSTRACT

Knowledge about the tensile strength of masonry is necessary for the estimation of the crack resistance of masonry under tensile stress due to drying shrinkage and thermal movements. The tensile strength of masonry can be calculated from properties of masonry units and mortar. The correlation between calculated values and test results is strong.

The modulus of elasticity under tensile stress is another important material property. Regression analysis gives a good correlation between the modulus of elasticity and the tensile strength of masonry. Test results and different regression analyses are presented. A test method for the determination of the tensile strength and the E-value is described.

The flexural strength of masonry is important for the estimation of the resistance of walls subjected to lateral loads (wind, earth pressure). Influences, calculation method and test methods are described. An evaluation of the available German test results worked out by the author is presented.

Keywords: masonry tensile strength, masonry flexural strength, E-values, influences calculation, test methods

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2. TENSILE STRENGTH

2.1 Definition, Importance

In the following, masonry tensile strength is understood as centric, uniaxial tensile strength parallel or perpendicular to the bed joints.

A knowledge of tensile strength is required for assessment of the crack resistance of masonry walls without significant loads, in which tensile stresses occur due to impeded shrinkage and temperature strains. This may be the case with veneer and non-loadbearing walls (tensile stresses parallel to the bed joints) and in external walls joined to internal cross walls (tensile stresses perpendicular to the bed joints). Apart from a knowledge of masonry tensile strength, a knowledge of stress-strain behaviour (modulus of elasticity, ultimate strain) is also significant for the assessment of crack resistance (cf. /1, 2/).

2.2 Stress Model, Influencing Variables, Mathematical Representation

2.2.1 Stress Model

The stress model is depicted in Fig. 1 for the two cases of tensile stress parallel and perpendicular to the bed joints. In this simplified form it is valid for masonry with a thickness of a single unit, used in the cases noted in Section 2.1. Two basic failure cases should be differentiated for tensile stress parallel and perpendicular to the bed joints, namely:

Case 1: Stress exceeding the tensile strength of the unit and
Case 2: Stress exceeding the unit-mortar bond strength.

With tensile stress parallel to the bed joints and Failure Case 1, cracks run almost vertically through the unit and in the head joint zone.

In Failure Case 2 it is necessary to differentiate between head joints which are fully mortared and those which are partly or wholly unmortared. In the latter case, masonry tensile strength is determined by the initial shear strength between the bed joint mortar and the unit. In fully mortared head joints, a distinction must be drawn according to the type of mortar employed. In masonry with general purpose and lightweight mortar, the ability to withstand tensile stressing (tensile bond strength) in the head joint zone is generally very slight (low adhesive strength between the mortar and the unit, edge disbonding of the mortar due to shrinkage, incomplete mortaring of the head joint) and may therefore be neglected. In masonry with thin layer mortar, a significant tensile stress is generally possible in the head joint zone, due to the substantially greater adhesive strength between the thin layer mortar and the unit.

With tensile stressing perpendicular to the bed joints, failure is generally caused by stresses exceeding the comparatively low tensile bond strength between the bed joint mortar and the unit. In masonry with greater tensile bond strength between the bed joint mortar and the unit - thin layer mortar, higher-strength general purpose mortar and units
with numerous smaller perforations (dowelling effect) - and units in lower strength classes, failure may occur as a result of stresses exceeding unit tensile strength in the axis of unit height.

2.2.2 Influencing Variables

Significant influencing variables affecting masonry tensile strength are
- in the case of tensile stressing parallel to the bed joints
  - unit tensile strength parallel to the bed joints (axis of unit length or width), usually the unit longitudinal tensile strength $f_{tl,u}$
  - initial shear strength between the bed joint mortar and masonry units $f_{sh,b}$ and possibly
  - tensile bond strength between the head joint mortar and the unit $f_{b,h}$:
- in the case of tensile stressing perpendicular to the bed joints
  - the adhesive strength between the bed joint mortar and the unit perpendicular to the bed joints and possibly
  - the unit tensile strength in the axis of unit height.

The magnitude of unit tensile strength is determined mainly by the type of unit, the degree of perforation and the perforation pattern. Other influences may be: moisture content, uneven moisture distribution across the unit cross-section (shrinkage stresses) and age-related effects (carbonation).

The following values were determined for the relationship between unit longitudinal tensile strength $f_{tl,u}$ and standard compressive strength $f_c$ (with shape factor) /3/:

- calcium-silicate units: $f_{tl,u} = 0.051 \cdot f_c$ (coefficient of correlation: 0.85)
- clay-units: $f_{tl,u} = 0.026 \cdot f_c$ (coefficient of correlation: 0.73)
- lightweight concrete units: $f_{tl,u} = 0.086 \cdot f_c$ (coefficient of correlation: 0.79)
- autoclaved aerated concrete units: $f_{tl,u} = 0.118 \cdot f_c$ (coefficient of correlation: 0.97)

It should be noted that the spread of the single values is extremely wide.

Initial shear $f_{sh,b}$ and tensile bond strength $f_{b,h}$ between the mortar and the unit are determined by numerous factors. The most important are: the type of masonry units and presence of perforations, together with their characteristics (surface structure, pore size distribution), the moisture content of the units during laying, the composition and setting characteristics of the masonry mortar and the possibility of "dowelling" the joint mortar with the units by means of the perforations, Owing to the wide variety of influencing variables and the relatively high process-dependent scatter of test results, accurate universal "characteristic strengths" for the various unit-mortar combinations cannot be provided at present. If it is necessary to use initial shear strength values for calculation in individual cases, corresponding test results or sufficiently reliable empirical values should be available. This applies equally to tensile bond strength values.
2.2.3 Mathematical Representation

Mathematical determination of masonry tensile strength \( f_{t,ma} \) can be performed with sufficient accuracy for the stress case parallel to the bed joints by reference to the 2 failure cases discussed above (cf. Fig. 1 and /2, 4/);

Case 1: Stress exceeding unit tensile strength

\[
f_{t,ma} \cdot (hu + hmo) = f_{tl,u} \cdot hu/2 \quad \text{(1)}
\]

\[
f_{t,ma} = f_{tl,u} \cdot \frac{hu}{2 (hu + hmo)} \approx f_{tl,u}/2 \quad \text{(2)}
\]

where

- \( f_{tl,u} \): unit tensile strength parallel to the bed joints
- \( hu, hmo \): unit height, height (thickness) of the bed joints,

Case 2: Stress exceeding mortar-unit bond strength (without mortar-unit adhesive tensile strength in head joint zone)

\[
f_{t,ma} \cdot (hu + hmo) = f_{sh} \cdot o \quad \text{(3)}
\]

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Fig. 1: Tensile strength of masonry parallel and perpendicular to the bed joints types of failure.
\[ f_{t,ma} = \frac{f_{sh}}{2 (h_u + h_{mo})} \approx f_{sh} \cdot \frac{o}{h_u} \approx (f_{ish} + \mu \cdot \sigma_c) \frac{o}{h_u} \] (4)

where

- \( f_{sh}, f_{ish} \): shear strength, initial shear strength between bed joint mortar/masonry unit
- \( \mu \): coefficient of friction
- \( \sigma_c \): compressive stress perpendicular to the bed joint
- \( o \): overbonding factor

Tensile strength values of masonry calculated from these equations agree very well with test results - mainly from /5/. The only values required to determine masonry tensile strength for an individual case are therefore the unit tensile strength, the initial shear strength and the envisaged overbonding factor.

There is currently no function reliably confirmed by comparative tests for determining tensile bond strength perpendicular to the bed joints. As a very rough approximation, masonry tensile strength for Failure Case 1 may be equated with the tensile strength of the units in the axis of unit height and masonry tensile strength for Failure Case 2 with the tensile bond strength between the bed joint mortar and the unit.

2.3 Test Methods

At present, there is no standard DIN, CEN or ISO test method for the determination of masonry tensile strength. The methods used in /5/ are recommended as test methods (cf. Fig. 2).

![Fig. 2: Testing tensile strength of masonry (according /5/)
   a) building of the test specimen
   b) test specimen before installation into the testing machine
   c) test specimen ready for testing
   The specimen consists of four courses, initially laid in the usual manner. A special device attached to the specimen turns it through 90° in the intended direction of testing shortly before the test time. The load is applied via steel plates resp. beams attached to](image-url)
the top and bottom of the specimen by a special glue. It is advisable to determine the entire stress-strain curve under tensile stress, using inductive displacement sensors.

Advice on test methods for determining unit tensile strength, initial shear strength and tensile bond strength is available in [6].

2.4 Test Results

Fig. 3 shows the characteristic tensile strength values (stress parallel to the bed joints) inferred from the test values.

![Graph](image)

**Fig. 3: Characteristic tensile strength/(5 %-fractile) \( f_{tk} \) of masonry versus the compressive strength of the units \( f_{c,u} \)**

The test values (mean values) were reduced by a factor of 0.7, on the assumption that this reduction yields the approximate nominal strength (5 % quantile). It is evident from the figure that there are often substantial differences between different unit types and grades. The main reasons are the differing initial shear strength and unit tensile strength values (see Section 2.2.2). Figures 4 and 5 indicate the relationship between the tensile modulus of elasticity (secant modulus at roughly one-third maximum stress) and tensile strength for masonry composed of different masonry units with general purpose mortar.

The secant modulus of elasticity at maximum tensile strength is some 30 to 70 % of \( E_{t,ma} \).
3. FLEXURAL TENSILE STRENGTH

3.1 Definition, Importance

In the following, masonry flexural tensile strength will be understood as flexural tensile strength under uniaxial flexural stress parallel or perpendicular to the bed joints (cf. Fig. 6).

The flexural tensile strength of masonry is of special importance for unloaded or slightly-loaded flexurally stressed components such as cellar walls beneath patios, veneer, non-loading and freestanding walls.
3.2 Stress Model, Influencing Variables, Mathematical Representation

3.2.1 Stress Model

Stress models for flexural tensile strength parallel to the bed joints are given in /7/. According to /7/, the corresponding equations for the two failure cases in masonry subjected to uniaxial tensile stresses parallel to the bed joints (see Section 2.2.3) may be used for masonry with unmortared or partially mortared head joints, in which the head joint zone can transmit only small tensile or compressive forces.

In masonry with fully mortared head joints, it is necessary to differentiate between the two failure cases - Case 1 "stresses exceeding the unit tensile strength" and Case 2 "stresses exceeding the mortar-unit bond strength. In Case 1, compressive stresses can be transmitted throughout the wall height, tensile stresses - according to the conditions - only via the masonry units, i.e. only in every second course.

According to /7/, it may be assumed for Failure Case 2 that the tensile bond strength in the head joint zone is lower than the shear strength in the bed joint zone. This is allowed for in mathematical determination by a reduction factor k.

For flexural stresses perpendicular to the bed joints, the tensile bond strength between the bed joint mortar and the masonry units will usually be decisive for masonry with general purpose and lightweight mortars. Only in the case of masonry with low-strength masonry units and high tensile bond strength (thin layer mortar, "dowelling" of the bed joint mortar in favourably perforated units) will failure occur due to stress exceeding the unit tensile or flexural tensile strength in the axis of unit height.

3.2.2 Influencing Variables

Significant influencing variables for masonry flexural tensile strength are:
- for flexural tensile stress parallel to the bed joints ($f_{x,p}$)
  - the unit flexural tensile strength parallel to the bed joints (axis of unit length or width),
  - the unit longitudinal compressive strength parallel to the bed joints (axis of unit length or width), \(\Rightarrow\) flexural compression zone,
- the shear strength between the bed joint mortar and the masonry units and possibly
- the tensile bond strength between the head joint mortar and the masonry units ⇒
given higher bonding strength (thin layer mortar);
- for flexural tensile stress perpendicular to the bed joints \( f_{x,v} \),
- the tensile bond strength between the bed joint mortar and the units perpendicular to
the bed joints under flexural stress,
- the unit tensile or flexural tensile strength in the axis of unit height.

The influences on unit flexural tensile strength and on unit-mortar tensile bond and
shear strength are essentially the same as for uniaxial masonry tensile strength (see
Section 2.2.2).

Compressive strength in the axis of unit length or width is influenced mainly by the
degree of perforation and the perforation pattern. Especially where there is a high degree
of perforation and a perforation pattern unfavourable for this type of stress (no conti­
nuous webs in the stress axis), the compressive strength values may be extremely low in
relation to the standard compressive strength. Table 1 contains values in relation to
standard compressive strength.

### Table 1: Masonry units; compressive strength in the direction of the unit length \( f_{c,l} \) and
unit width \( f_{c,w} \) related to the standard compressive strength \( f_c \) (without shape
factor), from /3/

<table>
<thead>
<tr>
<th>unit</th>
<th>number of test values</th>
<th>( f_c ) range of values N/mm²</th>
<th>( f_{c,l} / f_c ) mean value range of values</th>
<th>( f_{c,w} / f_c ) mean value range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-solid</td>
<td>8</td>
<td>21..60</td>
<td>0,9</td>
<td>0,6..1,2</td>
</tr>
<tr>
<td>CS-perforated</td>
<td>4</td>
<td>10..18</td>
<td>0,4</td>
<td>0,3..0,4</td>
</tr>
<tr>
<td>Clay-solid</td>
<td>10</td>
<td>22..131</td>
<td>0,6</td>
<td>0,4..0,8</td>
</tr>
<tr>
<td>- without holes</td>
<td>7</td>
<td>23..82</td>
<td>0,3</td>
<td>0,2..0,5</td>
</tr>
<tr>
<td>Clay-perforated</td>
<td>28/22</td>
<td>17..96</td>
<td>0,2</td>
<td>0,04..0,6</td>
</tr>
<tr>
<td>AAC</td>
<td>13</td>
<td>3..9</td>
<td>0,7</td>
<td>0,5..1,3</td>
</tr>
<tr>
<td>LC solid</td>
<td>4</td>
<td>3..23</td>
<td>0,8</td>
<td>0,6..1,0</td>
</tr>
<tr>
<td>LC hollow-blocks</td>
<td>6</td>
<td>2..8</td>
<td>0,6</td>
<td>0,4..1,0</td>
</tr>
<tr>
<td>Concrete</td>
<td>1</td>
<td>16</td>
<td>-</td>
<td>0,5</td>
</tr>
</tbody>
</table>

### 3.2.3 Mathematical Representation

Mathematical functions for the determination of masonry flexural tensile strength parallel
to the bed joints were inferred from /7/.

According to /7/, the equations for centric masonry tensile strength parallel to the bed
joints (see Section 2.2.3) may be used for masonry with unmortared or partially
mortared head joints (where the low bond strength may be neglected).

For masonry with fully mortared head joints and according to /7/, it may be stated for
Failure Case 1 (stress exceeding the unit tensile strength) that
\[ f_{x,p} = 0.59 \cdot f_{t,u} \]  

and for Failure Case 2 (stress exceeding the unit-mortar bond strength) that

\[ f_{x,p} = \frac{f_{ish} + \mu \cdot \sigma_c + 1.24 \cdot k \cdot f_{ish} \cdot h_u / w_u}{0.71 - 0.75 \cdot \mu \cdot \sigma_c / w_u} \cdot \frac{o}{w_u} \]  

where

- \( k \): reduction factor for the lower adhesive strength in the head joint zone,
- \( w_u \): unit width;

see Section 2.2.3 for other symbols.

The flexural tensile strength values obtained with these equations agree well with test results - mainly from /8/. The masonry flexural tensile strength parallel to the bed joint can therefore be calculated in good approximation if the unit tensile strength, the shear or tensile bond strength and the geometrical conditions are known.

The comments in Section 2.2.3 apply analogously to flexural tensile strength perpendicular to the bed joints.

3.3 Test Methods

There is no standardized German test method for determining the flexural tensile strength of masonry. Flexural tensile test methods, referred to in EC 6 /9/, are standardized in EN /10/ or ISO /11/. They are currently available in draft form. Fig. 7 shows the test set-up for tests parallel to the bed joint according to /10/ or /11/.

![Equipment for testing the flexural strength of masonry parallel to the bed joints](image)

Fig. 7: Equipment for testing the flexural strength of masonry parallel to the bed joints

a) cross section, b) longitudinal section

3.4 Test Results

Fig. 8 shows available German test results for flexural tensile strength parallel and perpendicular to the bed joints, indicating the range of mean values (usually 3 individual tests in each case) for various types of unit and mortar (general purpose mortar: NM,
lightweight mortar: LM, thin layer mortar: DM) and the suggested characteristic strength.

The characteristic flexural tensile strength $f_{xk}$ was set at 70% of the mean values (test values). It was assumed that this reduction yields the approximate nominal strength (5% quantile).

It is evident from fig. 8 that

- as expected, the $f_{xk}$ values differ very widely according to the type and grade of unit, the unit strength class and the type and group of mortar;

- in most cases, the flexural tensile strength values parallel to the bed joints are, in accordance with previous knowledge, significantly greater than those perpendicular to the bed joints;

- the spread of test values is generally large, due mainly to different unit flexural tensile and longitudinal compressive strength and shear strength;

- as expected, flexural tensile strength values for masonry with thin layer mortar are significantly higher than those for masonry with general purpose mortar, provided that the unit strength is not too low (masonry of AAC precision units in Strength Class 2);

- the suggested characteristic flexural tensile strengths parallel to the bed joints are between 0.1 and 0.5 N/mm²; characteristic strengths of 0.05 to 0.2 - in one case 0.4 N/mm² were obtained for flexural tensile strength perpendicular to the bed joints.

![Diagram](image)

**Fig. 8:** Characteristic flexural strength $f_{xk}$ from german test results
(NM: general purpose mortar, LM: lightweight mortar, DM: thin layer mortar)
Because of the wide range of influences affecting flexural tensile strength and the large resulting differences in flexural tensile strength values for the various unit-mortar combinations, it is difficult to establish accurate characteristic values. Conceivable is the definition of a uniform characteristic value amounting in the present case to 0.1 N/mm² for flexural tensile strength parallel to the bed joints, with the option of test checks in individual cases.

It would, however, be much more advantageous to represent the characteristic flexural tensile strength of masonry in mathematical form, e.g. according to /7/. The mathematical representation contained in /7/ is also based on a well-founded and reproducible theoretical approach. If necessary, further improvements or adaptations to test results can be made.

Figures 9 and 10 illustrate the way in which useful relationships between values for different properties can be determined. Fig. 9 shows the anticipated relationship between flexural tensile strength perpendicular to the bed joints and tensile bond strength (bond wrench method), though this is based on relatively few test values.

**Fig. 9:** Correlation between the flexural strength vertical to the bed joints \( f_{x,v} \) and the tensile bond strength \( f_{b,t} \) - Masonry of lightweight concrete units

\[ f_{x,v} = 1.05 \cdot f_{x} \]
\[ c = 92.6\% \]

**Fig. 10:** Correlation between the flexural strength vertical \( f_{x,v} \) and parallel \( f_{x,p} \) to the bed joints - Masonry of lightweight concrete units

\[ f_{x,p} = 0.54 \cdot f_{x} \]
\[ c = 88.3\% \]
According to the analysis in Fig. 10, the flexural tensile strength perpendicular to the bed joints for lightweight concrete masonry is roughly half that parallel to the bed joints.

It may be possible to simplify the available mathematical functions and place them on a firmer basis by determining such relationships.

4. REFERENCES


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