A CORRELATION BETWEEN MASONRY COMPRESSIVE STRENGTH AND UNIT SPLITTING STRENGTH

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SUMMARY

Masonry compressive strength is a key material parameter for the design of masonry structures. The masonry compressive strength is usually obtained according to the procedures defined in test standards. The Swiss Structural Masonry Code SIA 266/1 defines, in addition, a so-called three-unit test to determine the splitting strength of a unit. It has been found that the values of the masonry compressive strength and the splitting strength of corresponding blocks or bricks correlate very well. Based on the test results from both experiments carried out at ETH Zurich and other tests, the abovementioned correlation is discussed and a simple relationship between the two strengths is proposed for practical use.

INTRODUCTION

The masonry compressive strength (perpendicular to the bed joints) is a key material parameter for the design of masonry structures. The masonry compressive strength is usually obtained according to the procedures defined in test standards. Such is the case in Europe where the European test standard EN 1052-1, 1998 is applied. The standard defines the specimen's dimensions, how to load the specimen up to failure as well as how to calculate the characteristic compressive strength. However, there are also other procedures for determining masonry compressive strength. Some of them, such as a procedure developed at the Institute of Structural Engineering at ETH Zurich, involve larger specimens (wall elements). On the other hand, there are procedures that use smaller specimens and whose aim is to obtain the splitting strength of units, which is later correlated to the masonry compressive strength. A good correlation can be expected since the same failure mechanism for both test types is observed. The Swiss Structural Masonry Code SIA 266/1, 2003 defines a so-called three-unit test to determine the splitting strength of a unit. The splitting strength is obtained from tests on a specimen consisting of three blocks or bricks separated by neoprene plates, which are meant to simulate the bed joints.

THREE-UNIT TEST ACCORDING TO SIA 266/1

According to the Swiss Structural Masonry Code SIA 266/1 the splitting strength of a masonry unit is determined from five compression tests on specified specimens. The specimen consists of three units and two neoprene plates that are placed between them, see also Figure 1. The length, height and thickness of the unit are denoted by l_u, h_u and t_u, respectively.

The bearing surfaces of the units must be ground to parallel planes, perpendicular to the vertical axis of specimen. After conditioning, the units are dried for at least two hours. The reusable neoprene plates must be 3±0.3 mm thick and have a density of 1500±50 kg/m^3. In addition, their hardness must be 70±5 Å (Angstrom) and their tensile strength must be at least 6 N/mm^2. Finally, they must allow for an ultimate strain of at least 3.

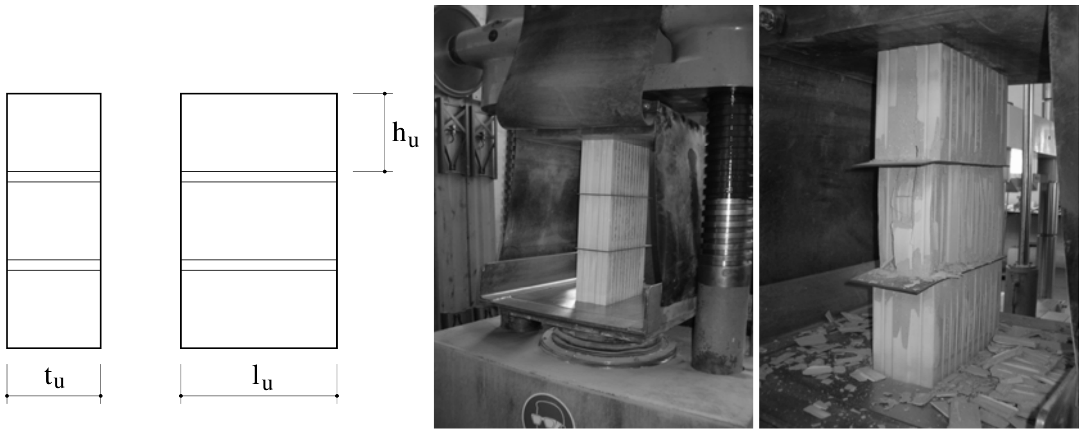


Figure 1. Three-Unit Test: Test Specimen, Test Set-up and Typical Failure

The specimen is placed centrally in the testing machine and must be in perfect contact with the loading platens of the testing apparatus. Furthermore, the upper loading plate must have a ball joint. The load has to be increased monotonically up to the failure of the specimen with a constant loading rate of 0.5 N/mm^2 per second.

The splitting strength of a specimen is obtained by dividing the failure load by the gross unit area of the middle unit. The characteristic splitting strength, f_{bq}, is obtained as a mean value, to the nearest 0.1 N/mm^2, of all five test results. The coefficient of variation shall be determined to the nearest 1%.

TESTING ACCORDING TO TEST STANDARD EN 1052-1

The determination of the masonry compressive strength perpendicular to the bed joints is defined by the test standard EN 1052-1. This standard gives details about the requirements for testing apparatus, preparation of specimens and the test procedure itself. These will be briefly described here. Figure 2 depicts the test specimen and test set-up and shows a typical failure of the specimen.

The specimen's dimensions are dependent on the unit's length, l_u, height, h_u, and thickness, t_u. Furthermore, the height of the specimen, h_s, its thickness, t_s, and length, l_s, depend on each other as shown in the Table 1.

Table 1. Specimen Dimensions according to EN 1052-1

Dimensions of the unit		Dimensions of the specimen			
l_u [mm]	h_u [mm]	l_s	h_s		t_s
≤ 300	≤ 150	≥ (2xl_u)	≥ 5h_u	≥ 3t_s and ≤ 15t_s and ≤ l_s	≥ t_u
	> 150		≥ 3h_u		
> 300	≤ 150	≥ (1.5xl_u)	≥ 5h_u		
	> 150		≥ 3h_u		

According to the EN 1052-1 standard, the compressive strength of masonry is determined on a set of at least three specimens, which have to be properly prepared and cured. The upper and lower faces of the specimen must be flat and parallel to one another and perpendicular to the main (vertical) axis of the specimen. The specimen is to be placed centrally in the testing apparatus. The load must be applied uniformly and increased monotonically so that failure of the specimen is reached after 15 min to 30 min from the commencement of loading. Depending on the strength of the units, the corresponding loading rate can vary between 0.15 N/mm^2 per min to 1.25 N/mm^2 per min.

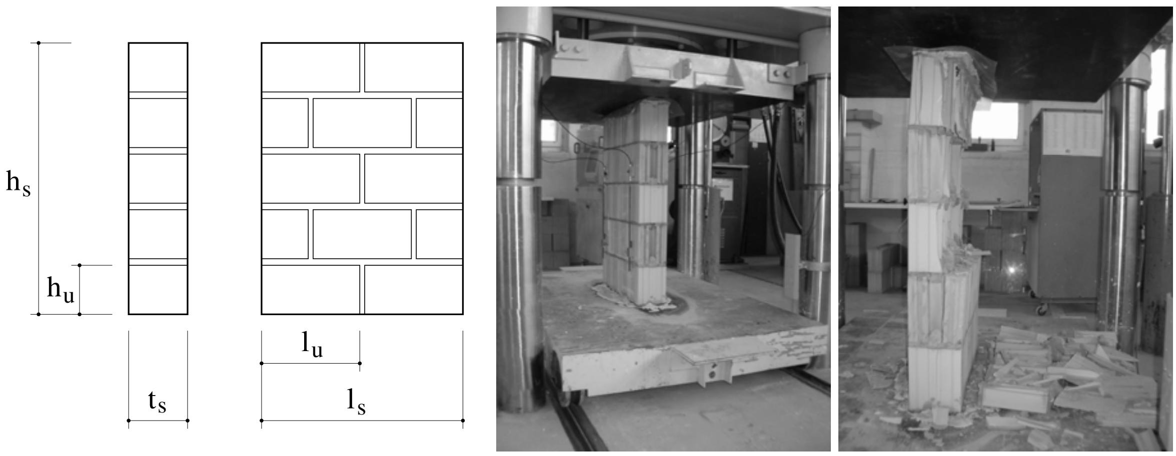
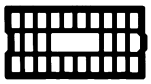
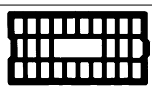
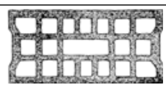
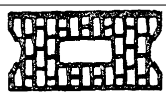
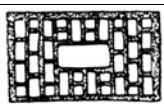
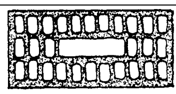


Figure 2. Test Standard EN 1052-1: Test Specimen, Test Set-up and Typical Failure

The compressive strength of the specimen is calculated to the nearest 0.1 N/mm^2 by dividing the maximal load by the loaded cross section of the specimen. The mean masonry compressive strength is calculated to the nearest 0.1 N/mm^2 from the measured values of all specimens. The characteristic compressive strength is obtained, again calculated to the nearest 0.1 N/mm^2, by dividing the mean compressive strength by 1.2 or, if there are five or more specimens, as the 5% fractile value based on a confidence level of 95%, whichever is greater. Depending on the strengths of units and mortar, it might be needed to perform some additional calculations, which are not discussed here.

Results from different test series which were conducted according to EN 1052-1 at Testing and Research Institute in Sursee and at ETH Zurich are presented in Table 2. This Table gives information about the reference and corresponding test series considered and shows the unit's shape, B denoting the clay brick units. Additionally, the obtained strengths are given: unit compressive strength (according to EN 772-1, 2000), f_b, mortar compressive strength (according to EN 1015-11, 1999), f_m, masonry compressive strength perpendicular to the bed joints (according to EN 1052-1), f_x, and finally, the splitting strength of the unit (according to SIA 266/1), f_{bq}. The masonry specimens were tested 28 days after preparation.

Table 2. Overview of Standard Tests

Unit	Reference	Series	Unit's shape	f_b [N/mm^2]	f_m [N/mm^2]	f_x [N/mm^2]	f_{bq} [N/mm^2]
B	p+f Sursee 2006	PF1	Standard brick	45.4	27.7	9.8	10.0
	p+f Sursee 2006	PF2	Facing brick	46.6	15.4	16.6*	14.2
	p+f Sursee 2006	PF3	Facing brick	53.6	16.6	19.5*	17.0
	p+f Sursee 2006	PF4	Thermal insulating brick	11.3	7.2	2.3	4.0
	p+f Sursee 2006	PF5	Thermal insulating brick	7.0	8.6	2.8	2.6
	p+f Sursee 2006	PF6	Thermal insulating brick	15.7	11.2	3.7	4.1
	p+f Sursee 2006	PF7	Thermal insulating brick	11.8	9.7	2.5	3.2
	Barth and Marti 1997	XC		36.2	22.3	8.3	8.1
	Barth and Marti 1997	XB		36.2	22.3	8.4	8.1
	Guggisberg and Thürlimann 1987	2R		37.4	27.9	7.7	9.1
	Guggisberg and Thürlimann 1987	3R		34.6	24.9	10.0	10.3
	Guggisberg and Thürlimann 1987	4R		16.4	22.3	5.7	5.6
	Guggisberg and Thürlimann 1987	8R		56.4	22.5	16.5	15.1
	*For facing brick tests, the specimens consisted of only three units.						

ETH TESTS ON WALL ELEMENTS

Figure 3 depicts the wall element specimen, the corresponding test set-up and a typical failure. The specimens were subjected to an axial load, which was increased in a deformation controlled manner up to failure of the test specimen.

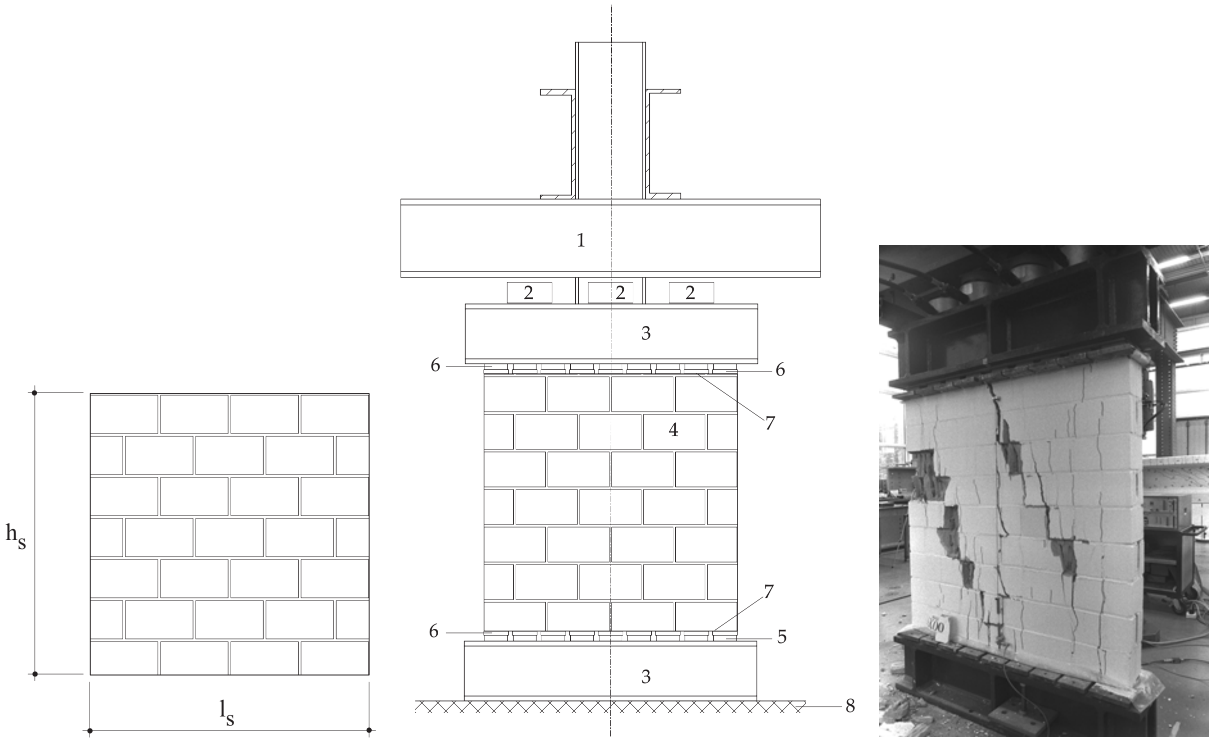


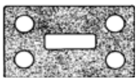
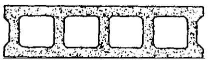
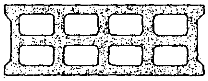
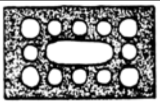
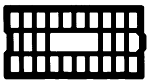
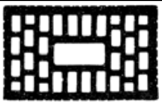
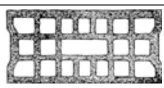
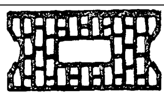
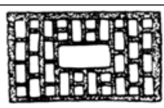
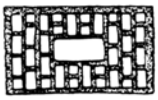
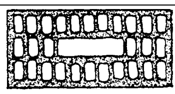
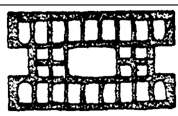
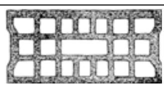
Figure 3. ETH Test: Wall Element, Test Set-up and Typical Failure

The test specimen dimensions were 1290 (length l_s) x 1300 (height h_s) mm. Both concrete (Z) and calcium-silicate (K) blocks as well as clay bricks (B) were used for tests. The brick and block shapes are shown in Table 3. The specimens were built in running bond and were tested 28 days after preparation. Dry, factory-made mortar was mixed with water at the test site to build the wall elements. Both bed and head joints were 10 mm thick and fully filled. All specimens were unreinforced.

Figure 3 shows the test set-up. The axial load was applied by means of three hydraulic jacks (2) that were placed between the support frame (1) and the upper spreader beam (3). The test specimen (4) was placed between two spreader beams (3) and two sets of steel plates (6) which provided good contact with the specimen. In this way an unrestrained lateral deformation of the specimen was ensured. To achieve the exact position of the steel plates, two thin plaster layers (7) were applied to both the upper and lower edges of the specimen. Additionally, a set of neoprene plates (5) were placed between the steel plates and lower spreader beam, which lay directly on the laboratory's strong floor (8). These neoprene plates ensured a uniform load distribution along the specimen. Both spreader beams had a thin teflon layer on the faces towards the test specimen.

Table 3 gives an overview of the tests which were performed at ETH Zurich. The results given are organised similarly to those in Table 2.

Table 3. Overview of ETH Tests

Unit	Reference	Series	Unit's shape	f_b [N/mm^2]	f_m [N/mm^2]	f_x [N/mm^2]	f_{bq} [N/mm^2]
Z	Mojsilović and Marti 1994	KZ		27.4	10.1	12.7	13.3
	Lurati et al. 1990	ZSW		16.5	16.9	9.1	9.9
	Lurati et al. 1990	B		11.8	25.2	8.4	7.5
	Lurati et al. 1990	M1		37.3	24.4	19.3	25.7
	Lurati et al. 1990	M2		33.7	24.4	17.8	21.8
	Lurati et al. 1990	F		19.8	25.2	13.9	13.1
K	Mojsilović and Marti 1994	KK		21.5	15.5	10.6	10.0
B	Barth and Marti 1997	KC		36.2	16.1	9.3	8.1
	Mojsilović and Marti 1994	KB		37.8	17.7	9.4	9.8
	Guggisberg and Thürlimann 1987	2		37.4	27.9	7.9	9.1
	Guggisberg and Thürlimann 1987	3		34.6	24.9	8.1	10.3
	Guggisberg and Thürlimann 1987	4		16.4	22.3	4.9	5.6
	Guggisberg and Thürlimann 1987	6		42.1	22.4	8.1	11.4
	Guggisberg and Thürlimann 1987	8		56.4	22.5	16.3	15.1
	Guggisberg and Thürlimann 1987	10		53.3	29.6	12.8	12.3
	Ganz and Thürlimann 1982	K		31.1	30.0	7.6	8.3

COMPARISON OF TWO STRENGTHS

Using values from the tests performed at ETH Zurich and at Testing and Research Institute in Sursee, which are presented in the last two columns of Tables 2 and 3, a relationship between the masonry compressive strength, f_x, and the splitting strength of corresponding block or brick, f_{bq}, can be established and these strengths can be compared to each other. Figure 4 shows this comparison. It can be seen that a simple relationship $f_x = f_{bq}$ (diagonal in the diagram) gives a fair approximation for masonry strength f_x. Furthermore, the data points are almost evenly distributed above and below the diagonal, i.e. they lie on both the safe and unsafe side, the safe side ($f_x > f_{bq}$) being represented in the diagram by the area under the diagonal.

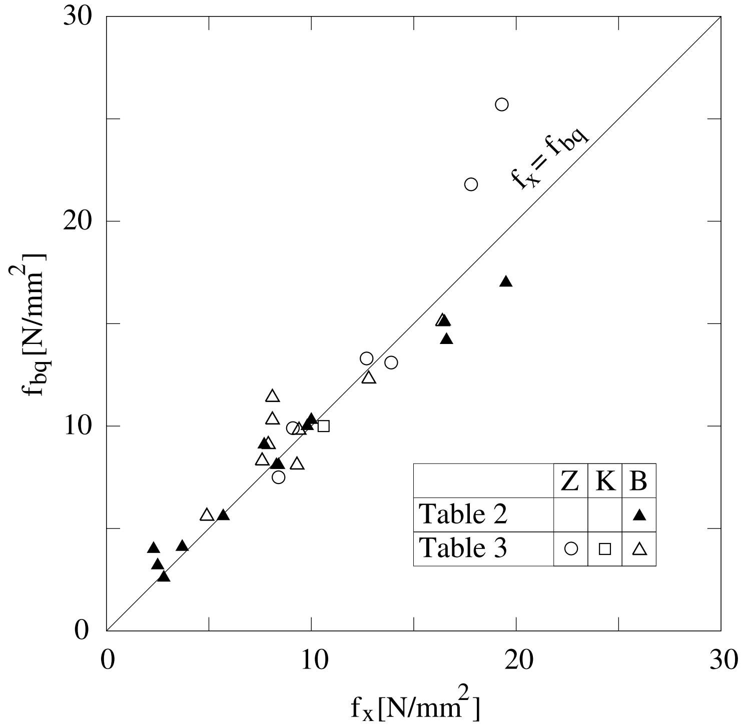


Figure 4. Relationship between Masonry Compressive Strength and Unit Splitting Strength

DISCUSSION

A general failure hypothesis for masonry under compression is based on the different material characteristics of units and mortar (Francis et al. 1971, Hilsdorf 1969). In general, the compressive strength of a unit is higher than the compressive strength of mortar whereas the coefficient of lateral expansion (Poisson's ratio) is higher for the mortar. Thus, under compression the mortar, i.e. bed joint, tends to expand laterally at a somewhat greater rate than the unit. In order to fulfil the compatibility conditions this lateral deformation of mortar is restrained (by the unit). Due to this confinement the mortar is able to resist the compressive stresses that are higher than its uniaxial strength. On the other hand, in order to maintain equilibrium, tensile stresses must be introduced into the unit. These tensile stresses induce the vertical cracking of the units and finally lead to the failure of the specimen.

The idea behind the three-unit test is to simulate the bed joints by using the neoprene plates. As it can be seen from Figure 4, this simulation is appropriate and the results obtained from

three-unit test for the splitting strength of a unit can be used to estimate the masonry compressive strength. However, somewhat larger deviation from the idealised relationship (diagonal in the diagram) is observed for concrete block masonry with very high masonry compressive strength. Bearing in mind the generally high overall safety factors prescribed by structural masonry codes this deviation can be traded off. To be on the safe side, an alternative relationship, which is rather conservative, can be used.

CONCLUSIONS

A simple and effective test method on a three-unit specimen for determining unit splitting strength can be used to estimate the masonry compressive strength. The values of the masonry compressive strength and the splitting strength of corresponding blocks or bricks have been found to correlate very well. Based on the test results from both experiments carried out at ETH Zurich and Testing and Research Institute in Sursee, the abovementioned correlation is discussed and a simple relation between these two strengths, $f_x = f_{bq}$, which gives a fair approximation of masonry strength, is proposed for practical use. Since some data points lie on the unsafe side ($f_x < f_{bq}$), an alternative but rather conservative relationship can be used. The concluding remarks apply specifically to the materials used in Switzerland, but should be of relevance for similar materials.

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