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A DISCUSSION OF MASONRY CHARACTERISTICS DERIVED FROM COMPRESSION TESTS

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ABSTRACT

This paper discusses masonry characteristics derived from compression tests. The stress-strain relationship and the applicability of orthotropic elasticity to masonry are examined. It is concluded that masonry behaves more or less as a linear-elastic material, in particular for working loads (loads up to 30% of the failure load). For higher loads, concrete and calcium-silicate block masonry exhibit nonlinear behaviour, while clay brick masonry remains linear-elastic up to failure. At the same time concrete block masonry can be considered as isotropic, and calcium-silicate block and clay brick masonry as orthotropic materials. Based on the test results, a set of simple linear relationships between masonry characteristics is proposed for practical use.

KEYWORDS: in-plane forces, orthotropy, stiffness, tests, walls

INTRODUCTION

In general, masonry walls are primarily subjected to in-plane forces. This emphasises the importance of knowing reliably the stiffness and strength of masonry for this type of loading.

The research on structural masonry at the ETH Zurich (conducted since 1975) included 130 compression tests on wall elements [1, 2, 3, 4, 5]. As part of this research, within the framework of the project "Masonry under Combined Actions", 20 compression tests were conducted by the author [4]. The tests included concrete and calcium-silicate blocks as well as clay brick masonry in common use in Switzerland. This paper discusses some aspects of the stiffness of masonry based on characteristics derived from the author's own tests. The stress-strain relationship and the applicability of orthotropic elasticity to masonry will be examined. In addition, based on a comprehensive review of test data [6] derived from the all ETH tests, some simplified relationships between masonry characteristics are presented. The concluding remarks apply specifically to the materials used in Switzerland, but should be of use for similar materials.

COMPRESSION TESTS ON MASONRY

Figure 1 (a) illustrates the principle of the tests. The specimens were subjected to an axial load which was increased in a deformation controlled manner up to failure of the test specimen. Figure 1 (b) shows the corresponding Mohr's circle of the stress state in the specimen and the convention used for stresses.

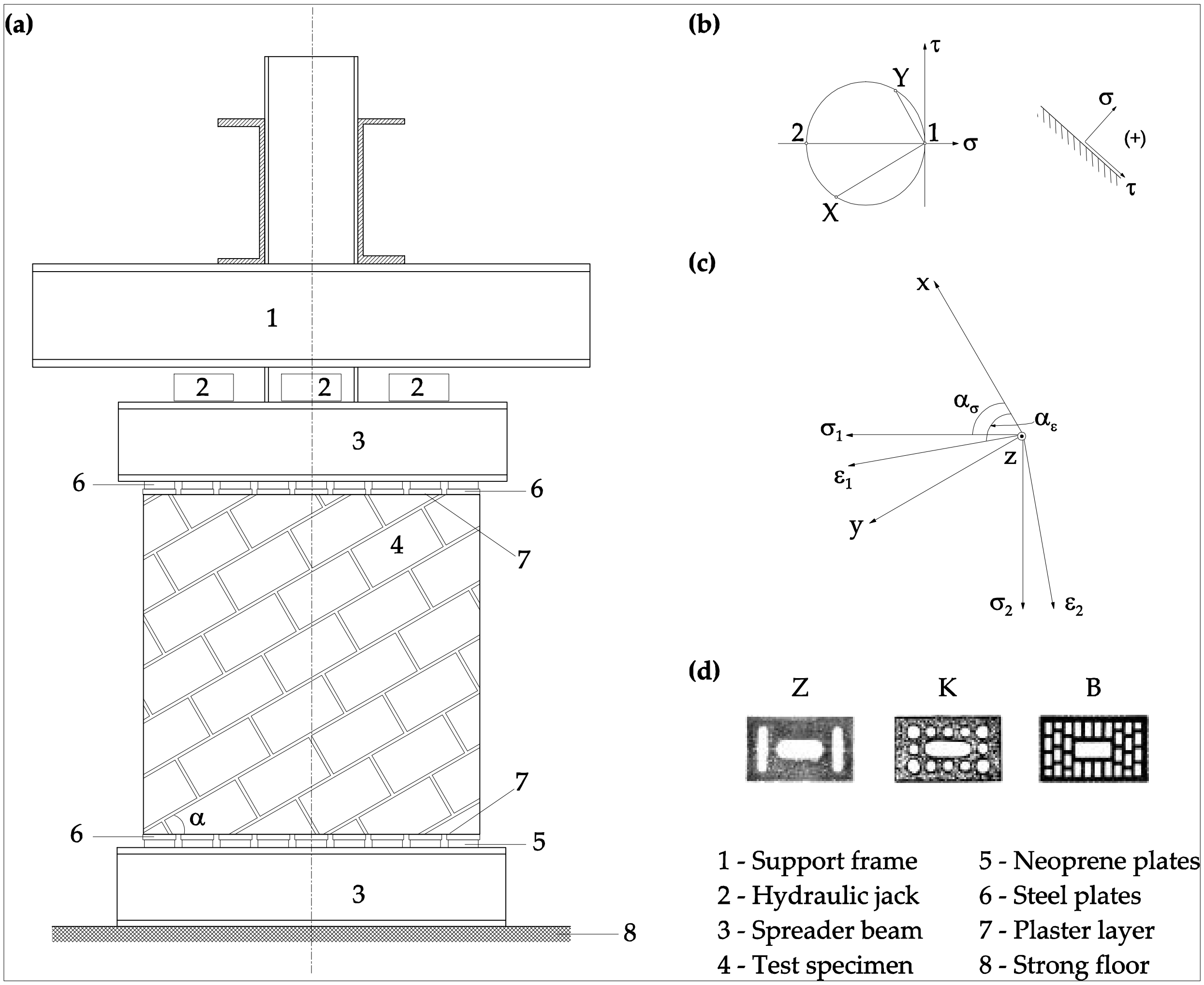

Figure 1 – Compression tests: (a) Principle and test set-up; (b) Mohr's circles for stresses; (c) Principal directions; (d) Brick and block form

Table 1 – Test programme

a **[deg]**	**0**	**15**	**30**	**45**	**60**	**75**	**90**
Z	KZ00	KZ15	KZ30	KZ45	KZ60		
K	KK00	KK15	KK30	KK45	KK60		KK90
B	KB00	KB15	KB30	KB45	KB60	KB75	KB90

The test programme and test parameters of the author's own tests are summarized in Table 1. The main test parameter, the angle of inclination of the bed joints relative to the horizontal, a, was varied from 0 to 90 degrees. The test specimen dimensions were 1290 (length) x 1300 (height) mm. Both concrete blocks (Z) and clay bricks (B) had dimensions of 150 (width) x 250 (length) x 135 (height) mm and void ratios of 20% and 40%, respectively. Calcium-silicate blocks (K) had dimensions of 145 (width) x 250 (length) x 135 (height) mm and a void ratio of 20%. The brick and block forms are shown in Figure 1 (d). Unit compressive strengths for Z, K and B were 27.4, 21.5 and 37.8 MPa, respectively and the average compressive strengths of the mortar used with them were 9.7, 16.1 and 16.7 MPa, respectively. The specimens were built in running bond and were tested 28 days after construction. 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, except two which were provided with bed joint reinforcement (KB30B and KB45B) were unreinforced.

Figure 1 (a) also shows the test set-up. The axial load was applied by means of three hydraulic jacks that were placed between the support frame and the upper spreader beam. The test specimen was placed between two spreader beams and two sets of steel plates which provided 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 were placed on both the upper and lower edges of the specimen. Additionally, a set of small neoprene plates were placed between the steel plates and lower spreader beam, which lay directly on the laboratory's strong floor. These neoprene plates ensured the uniform load distribution along the specimen. Both spreader beams had a thin teflon layer on the faces towards the test specimen.

The described test principle and set-up as well as the specimen's dimensions were adopted from the previous compression tests performed at ETH in Zurich. This allows a comprehensive comparison of the test results and theoretical predictions. Apart from the applied loads, measurements included strains on the front surface of the specimen, relative shortening of the specimen on both front and back surfaces and crack widths.

STRESS-STRAIN RELATIONSHIP

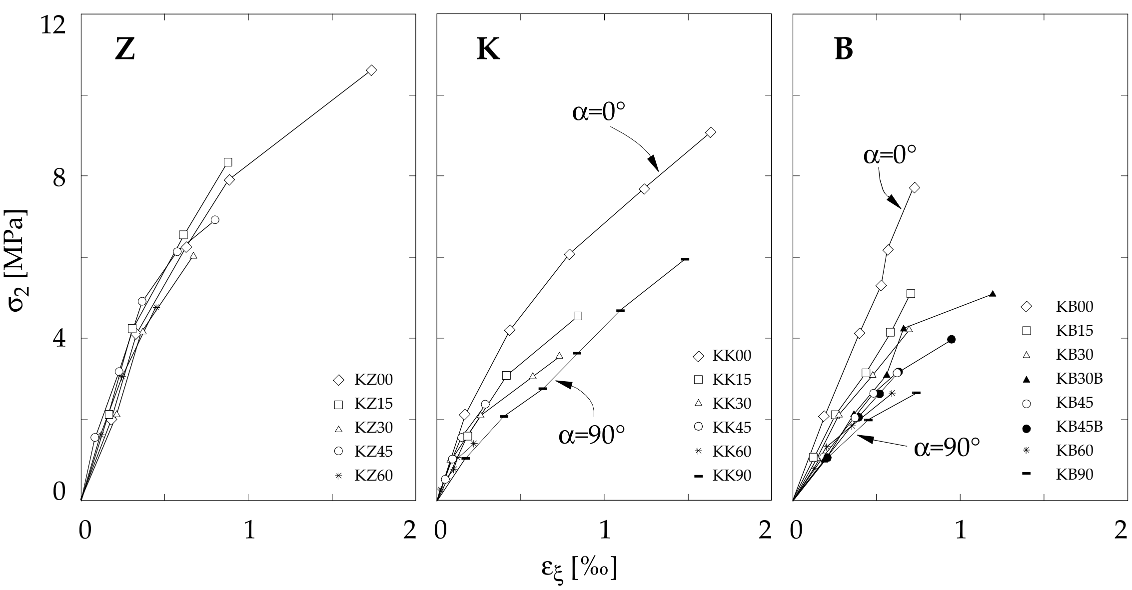

Figure 2 – Stress-strain relationship for concrete block (Z), calcium-silicate block (K) and clay brick (B) masonry

The stress-strain relationships for different masonry types were derived from the strain measurements [4] and are presented in Figure 2. They show the dependency of the strain in the vertical direction, ε_ξ, on the corresponding principal stress, σ_2. It can be seen that the behaviour of concrete block masonry is almost independent of the angle of inclination of the bed joints, α. In spite of a void ratio of 20% the concrete block masonry exhibits more or less isotropic behaviour. It is to be noted that there was no test at an angle α of 90 degrees, but a parabolic nonlinear isotropic idealisation for the σ_2-ε_ξ relationship is proposed similar to that for concrete. Such quasi-isotropic behaviour can be explained by the same origin of masonry components - blocks and mortar. The stress-strain relationships of calcium-silicate block and clay brick masonry show a greater dependency on the angle α. With increasing α the curves become steeper, i.e. the specimens become less stiff. Considering this, an anisotropic linear elastic approximation of the stress-strain relationship, in particular for working loads (loads up to 30% of the failure load) can be assumed. The clay brick masonry remains linear elastic also for higher loads; calcium-silicate masonry exhibits a nonlinear behaviour for higher loads (see Figure 2).

COMPARISON WITH THE THEORY OF ORTHOTROPIC ELASTICITY

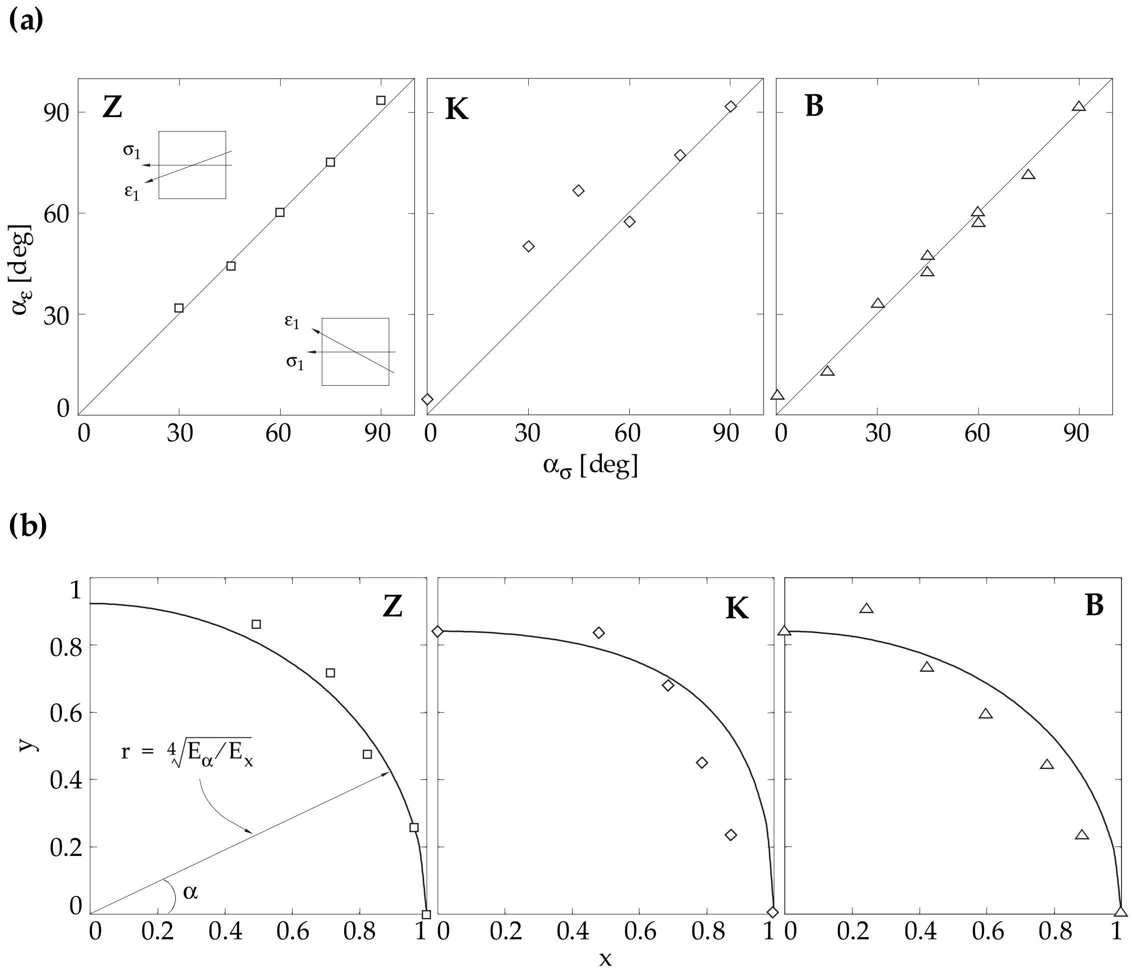

Figure 3 – Orthotropy of masonry: (a) Comparison of principle directions of stresses and strains; (b) Direction curves

Figure 1 (c) defines the angles of inclination of the principal stress and strain directions relative to the *x* axis, α_σ and α_ε. The angle α_σ is assumed to be given by the angle of bed joint inclination and thus equals $\pi/2-\alpha$. Figure 3 (a) shows the comparison of the principal directions of stress and strain, obtained later from the strain measurements [4]. The values of α_ε in the diagrams in Figure 3 (a) correspond to the average value of the measurements taken from all load cases up to the failure of the specimen. In the case of an isotropic material the angles α_σ and α_ε are equal and the corresponding points on the diagram in Figure 3 (a) lie on its diagonal. It can be seen that almost all points for concrete block masonry lie on the diagonal. This confirms the quasi-isotropic behaviour already found for this masonry type. The calcium-silicate block and clay brick masonry behave anisotropically. The anisotropic behaviour is more pronounced for the former material.

Generally speaking, masonry exhibits two irregularities: firstly, it has weak planes along the bed and head joints, and secondly it is characterised by openings in blocks or bricks. The question arises as to whether masonry can be modelled as an elastic orthotropic material. In order to answer this question a simple procedure, based on direction curves (Appendix), see also [6, 7], was applied to test results obtained from [4].

In Table 2 the masonry strengths in the x and y directions, f_x and f_y, together with the elastic characteristics of masonry obtained from tests are given. Both moduli of elasticity E_x and E_y and the shear modulus G_{xy} are represented by their secant values calculated at a load equal to 30% of the corresponding failure load. Table 2 shows also the values of the parameters β and γ defined in Equation 12 in the Appendix as well as Poisson‘s ratios ν_x and ν_y. The direction curves shown in Figure 3 (b) are constructed using these parameters. Figure 3 (b) shows also the values of the elastic moduli, E_α, found from tests. As already mentioned, no test was performed on concrete block masonry specimen with $\alpha = 90°$. To be able to compare the test results with the theoretical values, it will be assumed that the elastic modulus of the specimen with $\alpha = 15°$, E_{15}, satisfies Equation 11. Furthermore, it will be assumed that concrete block masonry also satisfies Equation 9. In this way the modulus E_y and Poisson's ratio ν_y given in Table 2 were derived.

Table 2 – Masonry strengths and elastic characteristics

	f_x[MPa]	f_y[MPa]	E_x[GPa]	E_y[GPa]	G_{xy}[GPa]	ν_x	ν_y	γ	β
Z	12.7	9.0	12.4	9.0	4.5	0.26	0.19	0.73	0.81
K	10.6	7.5	10.8	5.4	4.3	0.20	0.32	0.50	0.31
B	9.4	3.5	10.6	5.3	3.3	0.26	0.17	0.50	0.63

From the comparison shown in Figure 3 (b) it can be concluded that concrete block masonry satisfies the (partially assumed) conditions for a Green material but with small deviations. From Table 2 and Figure 3 (b) one can see that calcium-silicate block and clay brick masonry approximately satisfy the conditions for an orthotropic material. It should be noted that the deviations are greater than for concrete block masonry and, in particular, the condition given in Equation 9 for a Green material is not satisfied.

SOME SIMPLIFIED RELATIONSHIPS BETWEEN MASONRY CHARACTERISTICS

For uniaxial compression in the y direction ($\alpha = 90°$), setting $E_y \approx 1000 f_y$ one may assume that

$$\sigma_2 = E_y \varepsilon_\xi \qquad \text{Equation 1}$$

For uniaxial compression in the x direction ($\alpha = 0°$), using $E_x \approx 1000 f_x$, the linear-elastic relation

$$\sigma_2 = E_x \varepsilon_\xi \qquad \text{Equation 2}$$

may be assumed for clay brick masonry. The stress-strain-relationship for concrete and calcium-silicate block masonry may be represented by a parabola of second degree again using $E_x \approx 1000 f_x$

$$\sigma_2 = E_x \varepsilon_\xi \left(1 + 250 \varepsilon_\xi\right) \qquad \text{Equation 3}$$

Finally, using the relations

$$\upsilon_x = \upsilon_y = \upsilon \approx 0.25 \qquad \text{Equation 4}$$

$$G_{xy} \approx \frac{E_x + E_y}{3.5(1+\upsilon)} \qquad \text{Equation 5}$$

it is possible to calculate approximate values for coefficients of the matrix of elasticity in the case of plane stress (Equation 8). Thus, knowing only the masonry strengths, f_x and f_y, one can perform all elastic calculations.

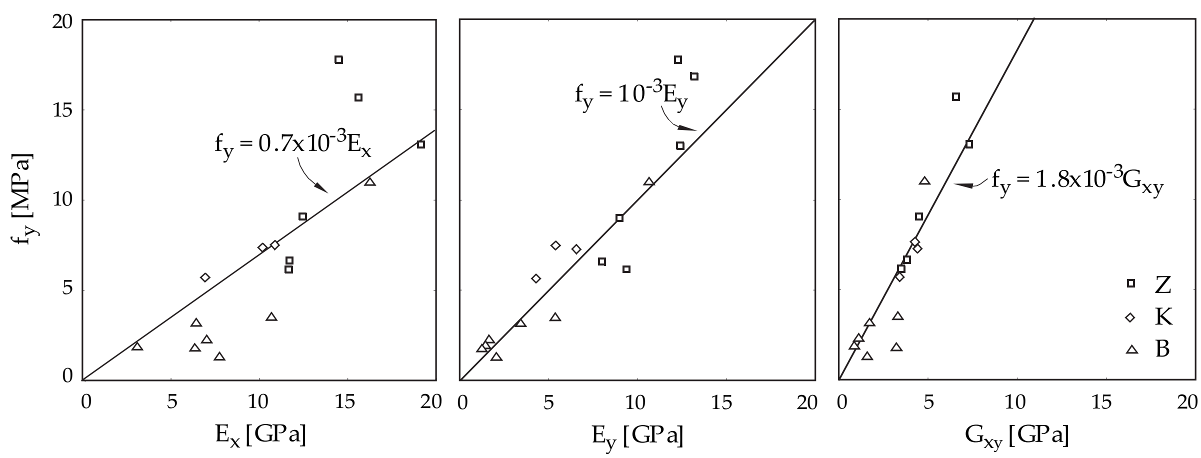

Figure 4 – Relationships between masonry strength and elastic moduli

If only one of the strength values is known, one may assume that

$$f_x \approx c f_y \qquad \text{Equation 6}$$

The average values of coefficient c are: 1.2 for concrete block masonry, 1.6 for calcium-silicate block masonry and 2.2 for clay brick masonry. A further simplification leads to only one value of c for all three masonry types – 1.4.

All approximations shown in this section are based on a comprehensive review of test data [6] derived from the abovementioned 130 tests on wall elements performed at ETH in Zurich. Figure 4 shows the comparison of these relationships with the test results. As can be seen, a reasonable approximation of the selected material parameters is achieved.

CONCLUSIONS

Considering the results of compression tests [4], it was possible to conclude that masonry behaves more or less as a linear-elastic material, in particular for working loads (loads up to 30% of the failure load). For higher loads, concrete and calcium-silicate block masonry exhibit nonlinear behaviour, while clay brick masonry remains linear-elastic up to failure. At the same time, concrete block masonry may be assumed to be isotropic, and calcium-silicate block and clay brick masonry to be orthotropic materials. Based on the test results of 130 compression tests performed over the last 30 years at ETH in Zurich, a set of simple linear relationships between masonry characteristics is proposed for practical use.

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APPENDIX: DIRECTION CURVES

The relationship between the stress and strain tensors for an elastic material is governed by Hooke's Law

$$\sigma_{ij} = D_{ijkl}\varepsilon_{kl} \qquad \text{Equation 7}$$

where the tensor of elasticity D has 81 independent components. Taking into account the symmetry of stress and strain tensors the number of independent components is reduced to 36 (Cauchy material). If an elastic potential is assumed to exist, then $D_{ijkl} = D_{klij}$, which reduces the number of independent components of D to 21 (Green material). Further reduction is only possible through the symmetry of material properties. If symmetry related to three orthogonal planes exists, the number of independent components is then further reduced to twelve for a Cauchy material and to nine for a Green material. Such a material is described as orthotropic. If one assumes a plane state of stress with principal material axes x and y, one obtains for Hooke's Law

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \frac{1}{1-\upsilon_x\upsilon_y} \begin{bmatrix} E_x & \upsilon_y E_x & \\ \upsilon_x E_y & E_y & \\ & & (1-\upsilon_x\upsilon_y)G_{xy} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \qquad \text{Equation 8}$$

with five independent material characteristics. The existence of an elastic potential leads to the relation

$$E_x\upsilon_y = E_y\upsilon_x \qquad \text{Equation 9}$$

reducing the number of independent elastic material parameters to four.

With known material parameters along the principal material axes it is possible, using coordinate transformations, to derive the material characteristics related to any coordinate system. These relations are generally polynomials of the fourth degree of coordinates. For a modulus of elasticity E_α in the direction $\alpha = \tan^{-1}(y/x)$ one obtains

$$E_\alpha = E_x\left(x^2 + y^2\right) = E_x\sqrt{\frac{\gamma\left(1 + 2\tan^2\alpha + \tan^4\alpha\right)}{\gamma + 2\beta\tan^2\alpha + \tan^4\alpha}} \qquad \text{Equation 10}$$

with x and y satisfying the relation

$$x^4 + \frac{2\beta}{\gamma}x^2y^2 + \frac{y^4}{\gamma} = 1 \qquad \text{Equation 11}$$

where the parameters β and γ are given by

$$\gamma = \frac{E_y}{E_x} \text{ and } \beta = \frac{E_y}{2G_{xy}} - \upsilon_y \qquad \text{Equation 12}$$

Equation 11 describes a direction curve. Setting

$$r = \sqrt[4]{x^2 + y^2} \qquad \text{Equation 13}$$

one obtains according to Equation 10

$$r = \sqrt[4]{E_\alpha / E_x} \qquad \text{Equation 14}$$

i.e., the length r for the chosen direction α, see also Figure 3 (b), is proportional to the 4^{th} root of the ratio between the modulus of elasticity in the direction α to the modulus of elasticity in the x direction.