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Portable Device for Indirect Assessment of Strength in Tension of Building Materials and Problem of Boundary Condition

Štěpán Major[1, a], Ivan Jandejsek[1,b], Jaroslav Valach[1,c] and Daniel Vavrik[1,d]

[1]Institut of Theoretical and Applied Mechanics/Academy of Science, Prosecká 809/76, 190 00 Prague 9, Czech republic

[a]major@itam.cas.cz, [b]jandejs@itam.cas.cz, [c]valach@itam.cas.cz, [d]vavrik@itam.cas.cz

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Abstract. A sensitive determination of mechanical properties of brittle building materials of existing buildings, requires gathering of samples by core drilling. Due to the fact, that the material samples may change their properties during transportion, it is preferred to test samples on site. Development of portable machine for Split test was therefore the first choice. The specimen is compressed with diametrically opposite symmetric line loads. The main goal of this paper is to document fine-tuning of experimental setup of the device to provide consistent and reproducible measurement. Therefore the paper concentrates on the biggest problem which is the boundary conditions of the test. For this reason, different types of contacts were studied. For boundary condition analysis was used photoelasticity. Set of experiments was performed in order to fulfill the condition of crack initiating in the middle of the specimen. Location of crack initiation was determined by the Digital Image Correlation - DIC. Various materials for contact were evaluated and it was found that the lead bar and grips with radius are best.

Introduction

A sensitive determination of mechanical properties of brittle building materials of existing structures, requires gathering of samples (stones) by core drilling. Due to the fact, that the material samples may change their properties (changes in humidity) during transport, it is preferred to test samples on site. Brittle materials are known for a high dispersion of measured parameters, especially in tension, due to present defects. This situation is usually overcome by large set of specimens and statistical evaluation, but this is not a case for materials from historical objects. Therefore method requiring less, ideally only one specimen is preferable. Development of portable machine for Split test was therefore the best choice. Split test is based on the Brazilian test, in which a disc specimen is compressed with diametrically opposite line loads, see Fig.1 (a). Contrary to Brazilian test is the diameter lower then length of specimen. The main goal of this paper is to document fine-tuning of experimental setup of the device to provide consistent and reproducible measurement. For this reason, different types of contacts were studied. Set of experiments was performed in order to fulfill the condition of crack initiating in the middle of the specimen. Location of crack initiation was determined by the DIC. Various materials for contact were evaluated and it was found that the lead bar or grips with radius are contact to the ideal situation.

Fairhurst [5] concluded that failure is expected to initiate at the center of disc, but actually the failure often initiates at the loading points. This conclusion was verified with experiments by Hudson [6].

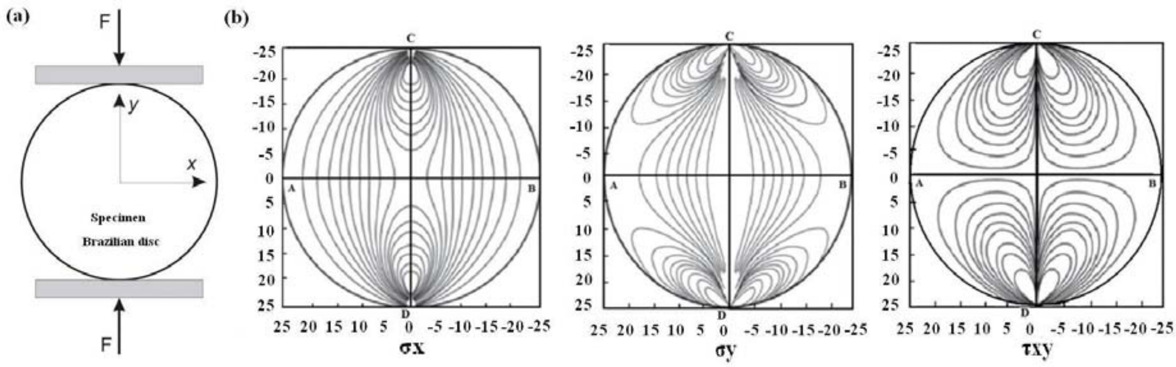


Figure 1 (a) Schema of the Split test; (b) analytic solution of the stress distribution within the disc (D = 50 mm).

The tensile strength R_T is calculated by equation [7]:

$$R_T = \frac{2F_{\max}}{\pi l D} \quad . \tag{1}$$

where F is maximum loading at failure, l is contact length and D is specimens diameter. According to ASTM, the basic assumption of this equation is loading with point like contact. Applicability of (1) is based on assumption, that stresses σ_x and σ_y are constant in the vertical central plane of the specimen in accordance with analytical equations for central plane. Stresses σ_x and σ_y can be expressed as:

$$\sigma_x = \frac{2F}{\pi l D}, \tag{2}$$

$$\sigma_y = \frac{2F}{\pi l}\left(\frac{D^2-1}{D^2}\right), \tag{3}$$

Under these conditions, effect of the contact between specimen and loading grip should be neglible. This assumption can be verified by non-contact (DIC) method.

Theoretical Analysis

The stress field of the isotropic Brazilian disc subjected to concentrated loads based on elasticity mechanics for isotropic rock materials has been described completely according to equations [8]:

$$\sigma_x = \frac{2P}{\pi l}\left\{\frac{(D/2-y)^3}{\left((D/2-y)^2+x^2\right)^2}+\frac{(D/2+y)^3}{\left((D/2+y)^2+x^2\right)^2}-\frac{1}{D}\right\}, \tag{4}$$

$$\sigma_y = \frac{2P}{\pi l}\left\{\frac{(D/2-y)x^2}{\left((D/2-y)^2+x^2\right)^2}+\frac{(D/2+y)x^2}{\left((D/2+y)^2+x^2\right)^2}-\frac{1}{D}\right\}, \tag{5}$$

$$\tau_{xy} = \frac{2P}{\pi l}\left\{\frac{(D/2-y)^2 x}{\left((D/2-y)^2+x^2\right)^2} + \frac{(D/2+y)^2 x}{\left((D/2+y)^2+x^2\right)^2} - \frac{1}{D}\right\}, \tag{6}$$

where P is the applied line-load, whose units are (N/m), l is the thickness of the disc, D is the diameter of the disc and x, y are the coordinates. Fig. 1(b) shows the distributions of σ_x, σ_y and τ_{xy} in the disc.

Portable Testing Device

Determination of mechanical properties of brittle building materials of existing structures, requires gathering of samples by core drilling. The mechanical characteristics of building materials are dependent on variations of the material composition and environmental influences like humidity or mortar-hardening. Due to the fact, that the material samples may change their properties during transport and storing (for example, due to changes on moisture content), it is preferred to test samples in situ. For such a purpose, a portable testing machine was developed, see Figure 2(a). Moreover it is possible to prepare other samples directly at work in situ, if it is necessary.

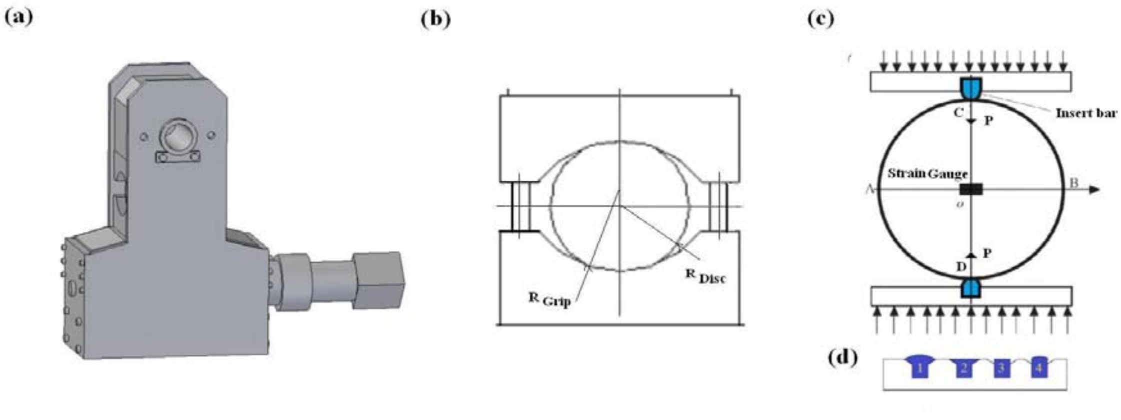


Fig. 2 (a) Testing device; (b) Grip geometry; (c) The configuration of the test adopted in this study;(d) Geometry of insertion bars: 1,2,3,4 –lead; 3,4-timber and rubber.

The testing device is primarily intended for split tests of core samples, but it can be also used for compression or bending testing. The length of specimen is not limited, but the distance between bearing pins is 100 mm.

The weight of testing device is approximately 30 kg, and its outside dimensions are 320x320x170 mm. Core sample should have diameter 50 mm (In fact, when using a drill with a diameter of 50 mm, the diameter of the cylindrical sample is between 47-50 mm) or 35 mm when removable grip is used. Maximal length of specimen is 100 mm.

The loading is performed by moving the lower grips upward. The lower grip is lifted by wedge mechanism. Linear movement of the wedge is implemented by screw rotation. Screw rotation is realized by stepper engine. Between screw revolution and moving grip this relationship exists: one screw revolution corresponds to 0.18 mm of grip displacement. Epicyclic- gear-box with transmission coefficient of 64 is inserted between stepper engine and loading screw in this case.

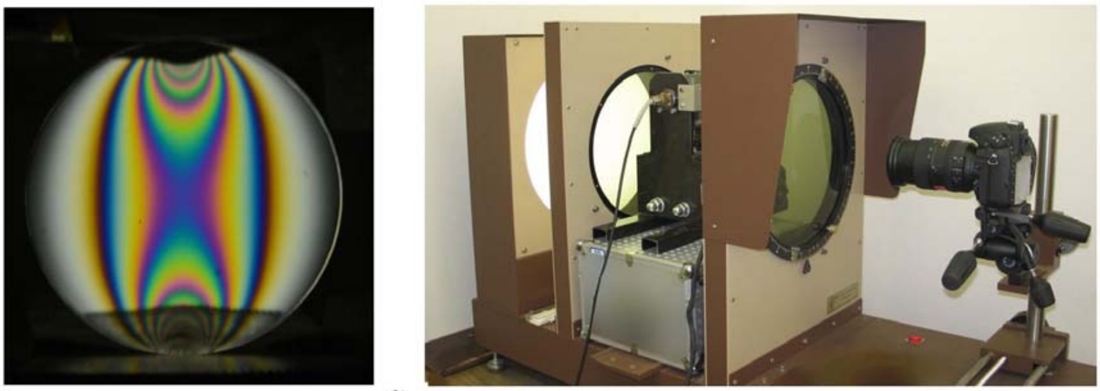
Maximal loading force is limited by 100 kN. Loading force is read by logger from measuring bolt. Force data are imaged by data-logger display and can be recorded by a computer in digital form. Loading displacement data are obtained directly by measuring instruments based on laser triangulation and by non-directly by counting of the loading screw revolutions, both types of data can be recorded by a computer in digital form.

Previous studies have shown that in the case of flat grip the Split test is often not valid [5,6,9] and the cracks initiates at the loading point. In this study, a simple method was proposed to achieve linear load, contact between grip and sample, is implemented by replaceable insertion bar, see Figure 2. The results of split test are strongly influenced by frictional stresses developed at the interface between grip and disc, this influence was studied by Kourkoulis [1,10,11]. Contrary to the theory, both specimen and jaws/grips are partly deformed and the contact problem is in reality "plane-to-plane", not "curve-to-curve". Between the jaw and the specimen exists considerable friction and the local deformation influenced displacement field. The displacement field can be described effectively if the grips have cylindrical shape with radius $R_G > R_{Disc}$, for shape of grips see Fig. 2(b). In this case, we consider parabolic radial pressure in contact region, and calculations can be adapted to this case. In this experimental study $R_G = 1.5R_{Disc}$. The insertion bars made from different materials and with different geometry were used, see Fig. 2(c) and (d).

Photoelasticity

Some materials become optically anisotropic when a mechanical stress is applied. This phenomenon is variously referred to as photoelasticity [12], stress birefringence, or mechanical birefringence. Birefringence is a property where a ray of light passing through a birefringent material experiences two refractive indices. The magnitude of the refractive indices at each point in the material is directly related to the state of stresses at that point. Information such as maximum shear stress and its orientation are available by analyzing the birefringence with an instrument. The colors are seen when the stressed materials are placed between crossed polarizers. It is useful for the visualization of mechanical stress in otherwise transparent materials.

The testing device was placed inside the polarizers. As the specimen was used clear transparent disc made of plastic. The measurement is in the correlation with theory, see Fig.3.



(a) (b)

Fig 3. (a) Photoelasticity – Stress distribution; (b) Experimental configuration

Digital Image Correlation

The DIC is an optical method to measure deformation on an object surface [13]. DIC tracks the position of the same physical points shown in a reference image and a deformed image. This pairing of corresponding points is carried out automatically utilizing method called image correlation. To achieve this, a square subset of pixels are identified on the speckle pattern around point of interest on a reference image and their corresponding location is determined on the deformed image. Fine structure of analyzed surface is presented in images for DIC applicability.

Experimental Procedure – Stone Testing

Core drill specimens were prepared from Maastricht limestone (it is soft bioclastic calcarenite). The specimens were conditioned in dry condition. Diameter of the specimens was 47-50 mm and length was about 50 mm. Specimens were loaded to final rupture by portable loading device. Influence of four contact surfaces were tested: flat grip made from steel was directly in contact with the specimen in first case, bar made from rubber was inserted between grips and the specimen in second case, bar made from timber was inserted between grips and the specimen in third case and bar made from lead was inserted between grips and the specimen in fourth case.

Experimental results

Front side of the Brazilian disc was monitored by Canon camera EOS 500 D equipped by the macro lens. Images were recorded directly into computer using appropriate Canon software for remote camera control. Set of acquired images was processed using our DIC software [13]. Figure 6 shows loading diagram of the test measured by the loading cell.

In the second case (contact between timber and specimen), timber bar was forced back into the groove with increasing pressure and the sample tested on the edge of the groove (contact between steel and specimen). This effect is caused by too low compressive strength of wood. The edge of the groove work as stress concentrator and assumption of point like contact was not met. The cracks initiates on the contact between edge of the groove and specimen. In the third case (contact between rubber and specimen), timber bar was forced back into the groove with increasing pressure and the sample rested on the edge of the groove (it is caused by too low modulus of elasticity). The final effect was the same as above.

In the fourth case (contact between lead and specimen), lead bar was deformed with increasing pressure, but the sample wasn't in contact with steel grip (during the whole experiment). It appeared that split test was processed in right conditions.

In the fourth case (contact between lead and specimen), lead bar was deformed with increasing pressure, but the sample wasn't in contact with steel grip (during the whole experiment). It appeared that split test was processed in right conditions. The analysis of the behavior of materials during tests shows clearly, that significantly best results (symmetry of the stress fields and agreement between calculated and measured stress/strain fields) were achieved in the case of lead insertion bar with geometry 1 and by grips with radius, see Fig. 4.

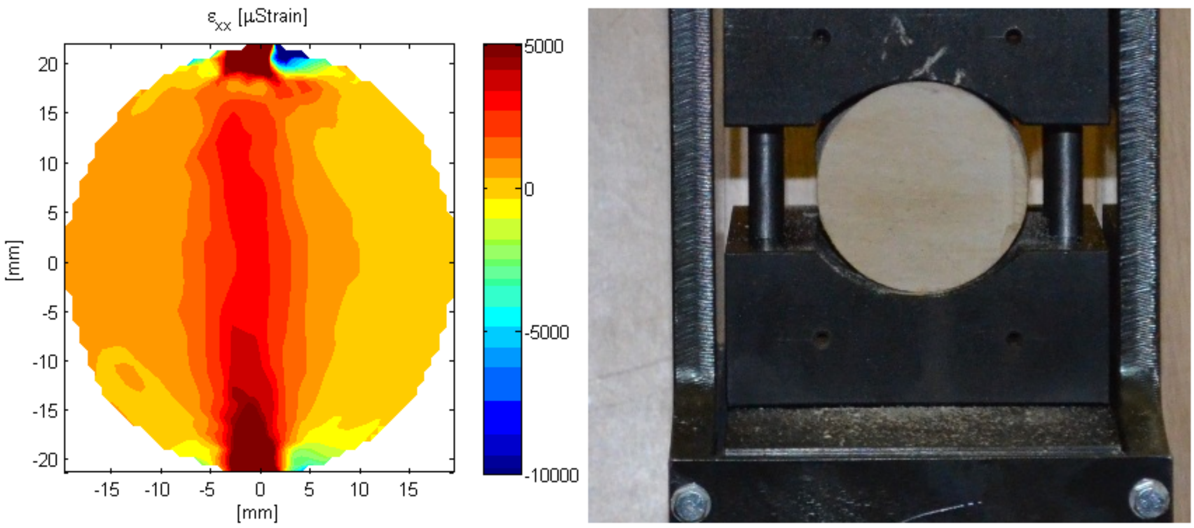


Fig. 4 Strain field ε_{xx} before rupture specimen, deformation is given in micro-strain and the specimen.

In the case of grips with radius, the crack initiate in the (most probably) middle of specimen. For
calculation of specimens strength was used parabolic distribution of load at the contact between specimen and jaw/grip. In this case was achieved most accurate results.

Summary

Experimental set-up was tested for different implementation of boundary condition by inserting contact bar from various materials. Although global behaviour of the specimen satisfied conditions of the split test, detailed study of the strain field on the specimen surface showed that strain distribution didn't satisfied theoretical assumptions, because strain reaches maximum values in the area of contact. Using maximal loading force for the tensile strength would resume in incorect estimation of the tensile strength R_T.

It was demonstrated that proper material for contact has to be in relation with mechanical properties of examined stone. First, it has to the modulus of the elasticity of the some order of magnitude as the tested stone (this is the rubber material failed). Second, its strength has to be less, but still comparable to the compressive strength of the stone.

Acknowledgements

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