Non-standard experimental tests of sandstone and its pre-cracking for fracture testing

M Šperl and M Drdácký

1 Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, rosecká 809/76, 190 00 Prague 9, Czech Republic
Email: sperl@itam.cas.cz

Abstract. The paper presents a methodology for investigating fracture phenomena in sandstone. It shows the preparation of test specimens with a cyclic loading generated crack, control of the test specimen preparation and verification by means of x-ray microCT and digital image correlation (DIC) techniques. There are also presented tests studying tensile and fatigue characteristics of arkose sandstone used i. a. for the construction of the medieval Charles Bridge in Prague where weather induced tensile damage and failure occurred. Finally, the new methodology for pre-cracking of the specimens was verified experimentally and fracture toughness was computed.

1. Introduction
The presence of cracks in many historical structures indicates the action of external forces accompanied by internal strain gradients. This is usually a repetitive process, and damage cumulation may occur in porous brittle or quasi-brittle materials. The authors have performed a study of environmental fatigue effects for which they developed a suitable methodology for testing historical stone subjected to repeated tension strains [1].

Cumulative tensile damage may occur in stone monuments due to mainly two reasons. The stone objects are subjected to repeated change of temperature from solar irradiation when the heat is transferred unevenly inside the material. The accompanied different thermal dilation may cause dangerous stress and cause cumulative crack propagation, typically initiated in usually present interior defects. Similarly, negative effect has been observed in composed materials, namely masonry made of stone and mortar with different thermal dilation characteristics. Recent examples are presented in Figure 1 (detritic limestone sculpture in Eisgarn - Austria) and Figure 2 (sandstone masonry block of the Charles bridge parapet wall). In the second case, a very strong mortar has been used for repair of the bridge and the block cracked across the whole profile during a very severe winter when temperatures dropped under -20°C. Such adverse effects called for studies of behaviour of similar stone structures under extreme climate effects.

This paper takes advantage of the experimental assessment of changes in the mechanical characteristics of sandstone from Božanov (one of the typical medieval rock materials used in Charles Bridge) due to the accumulation of damage. The Young modulus and the Poisson number were investigated, using a verified methodology for testing stone in simple tension and in cycling simple tension/compression loading. The results have shown that the first tension load-displacement can be approximated very satisfactorily by a power function, and the optical DIC method again demonstrated its capacity and suitability for measuring the complex deformation field on porous surfaces and on
naturally well-structured surfaces. Nevertheless, the methodology that had been adopted required painstaking specimen preparation and highly-skilled staff and can be recommended only for special small-series tests.

![Figure 1. Ruptured limestone sculpture.](image1)

![Figure 2. Ruptured bridge rail stone.](image2)

This paper also needed a special methodology for the preparation of test specimens with defined cracks for a series of tests to study the effects of consolidation on fracture behaviour, crack propagation and ultimate loads. Experimental investigations on specimens with cracks have rarely been published. Two such studies were published in [2] and [3] but they were focused a bit differently.

2. **Experimental works**

Božanov stone is a greyish beige gross grain strong arkose sandstone without marked layering, Figure 3 (medium grained arkose sandstone by geologists). The material used for two types of tests was extracted from the eleventh arch of the Charles Bridge parapet wall, which had to be replaced during recent repairs. The material can be characterized as a quasi-brittle inelastic silicate composite.

![Figure 3. Composition of the Božanov sandstone.](image3)

2.1. **Tensile, compression and fatigue tests**

Testing specimens (cut out from the stone block) of dimension of 50 mm × 50 mm × 200 mm were fixed into steel rectangular tubes with axially welded flat steel hangers which served to fix the set into hydraulic grips (by the help of the special-self procedure with safety loop) of the loading frame Instron 1343 – Figure 4. For gluing a two component Sikadur-31 CF RAP resin was used. The fixtures had to
be prepared with careful precision in order to ensure perfect alignment and perpendicular arrangement for tension and combined loading. The specimens in prismatic form were cut without geometrical imperfections.

Figure 4. Test specimens and test arrangement.

Four pilot experiments were completed on the specimens from Figure 4. The tests involved i) compression, ii) very low cycle fatigue (altering unsymmetrical cycle), iii) tension, iv) fatigue (altering unsymmetrical cycle). Compression force was applied in three steps: -1.5 MPa, -26 MPa and -37 MPa. During the test the deformation was measured in order to study change of Young modulus and Poisson number in relation to the applied load – Figure 5. Hysteresis and irreversible deformation was observed (measured by DIC) and the Poisson number reached a value of 0.23.

The tension tests were performed with a very low velocity of the crosshead movement at about 5 μm/min. A crack initiated at one interior defect and due to very low loading velocity it was possible to evaluate the overall energy absorbed during the crack origin and propagation - Figure 6. The load-displacement diagram shows the overall amount of energy absorbed during the test (0.4 J) and for the crack growth (0.16 J) which corresponds to a very brittle material behaviour even though the strength was decreased by a defect inside the material. The course of stress and deformation can be well described up to the fracture by means of a suitable power function.

Figure 5. Load-deformation diagram – compression.  Figure 6. Load-displacement - tension test.
Sinusoidal altering non-symmetrical loading cycle with the stress limits of +1.5 MPa and -2 MPa was applied during the very low fatigue test. The stress mean value was -0.25 MPa, the stress double amplitude of 3.5 MPa and frequency of loading of 0.2 Hz, Figure 7.

Fatigue tests used the same sinusoidal altering non-symmetrical loading cycle, here with the stress limits of +0.265 MPa and -0.354 MPa. Two modes of cycling velocity were used - a frequency of 0.25 Hz for the main loading sequences and at certain stages 0.01 Hz for a group of three cycles with the measurement of deformations from which the second cycle was evaluated, and the E modulus calculated. Such a detailed measurement was accomplished up to 2000 cycles. Then the specimen was loaded up to failure. The overall lifespan reached 224 908 loading cycles. The modulus of elasticity E changed during the cycling. Its value dropped from the initial figure of 11 214 MPa to 10 705 MPa after 82 loading cycles (about 5% decrease). Then its value stabilized around 10 865 MPa after 2002 cycles, see Figure 8.

2.2. Three point bending tests with cycling and fracture tests

Test specimens with dimensions of 20 mm × 20 mm × 100 mm were placed on one side in the center with an initiation notch 1 mm thick and 2 mm deep. Then the specimens were cyclically loaded in three-point bending generated by a resonance pulsating machine - Rumul Mikrotron. The initiation notch was placed on the side in tension and the load pulsed in a mode with the asymmetry of the cycle being R = 0.0385 – i.e., with a nearly vanishing load cycle. The resonance loading frame started cycling with an initial force impulse and then the loaded specimen acted as an elastic member in the system. The cycling at a given force was controlled by a resonance frequency which was dependent on the stiffness of the test specimen [4]. Then, a change in stiffness of the specimen was followed up during the loading, which signaled the crack initiation and propagation, and enabled control of the crack depth. To this end, a change in loading frequency was measured. In this way it was possible to prepare a series of test specimens with approximately the same damage in front of the initiation notch. However, a series of preliminary tests had to be carried out in order to identify a suitable level for the loading force. They included a static three-point bending test (3PB) and a series of fatigue tests on various low-force levels to determine the approximate fatigue behaviour of the test material.

Then, in order to ascertain the depth of the initiated cracks X-ray micro-tomography was applied. A special table-top loading device allowing simultaneous X-ray imaging of the test specimen during loading was employed. A specimen was loaded in a cylindrical chamber made of a high-strength composite which had a low attenuation for X-rays and allowed observation from all directions. Both simple 2D transmission images and CT acquisitions could be acquired in individual loading steps. The focal spot of the X-ray source was approximately 50 μm with this setting, which was sufficient with respect to the desired resolution. A scintillation flat panel detector of 2048 × 2048 px resolution and 200 μm single pixel size was used. The resulting imaging geometry allowed 4× magnification, which entailed the resolution of 50 μm at one pixel. The standard three-point bending test was performed with
the specimen. The load was applied only until the moment when the crack was observable by simple transmission radiography. In this position CT data (1200 projections per 360°) was acquired. The acquisition time of one projection was 2 s. The images obtained were corrected with regard to beam hardening effect by a set of alumina filters and subsequently a final CT reconstruction was carried out. A 3D visualization of the reconstruction obtained was performed in a VG studio.

Now these specimens with the same damage are consolidated using the most typical agents: elastified Steinfejster 300 (cca 30% concentration of the active substance), Paraloid (2% concentration), Funcosil 100 (10% concentration of the active substance), and will be tested by standard three-point bending. The specimens without consolidation were already tested in 3PB. By comparing the acquired characteristics it will be possible to determine the consolidation effects.

The acquired ultimate loads were used to calculate $K_{Ic}$ toughness [5], which attained the value of 0.331 for the notched beam, 0.349 for the notched beam with the crack in MPam$^{0.5}$. The toughness values are approximate estimates based on an engineering approach to the crack depth assessment from the above mentioned X-ray CT scans and the DIC reconstructions and analytical equation (1).

\[ K_I = \sigma \sqrt{\pi a} \cdot F(a/b) \]  
\[ \sigma = \frac{6M}{b^2} \Rightarrow M = \frac{F \cdot s}{4} \]

\[ F(a/b) = 1,090 - 1,735(a/b) + 8,20(a/b)^2 - 14,18(a/b)^3 + 14,57(a/b)^4 \]

where:
- $a$......total depth of crack (mm),
- $b$......specimen height (mm),
- $s$......span length (mm),
- $\sigma$......stress per unit thickness of the specimen (N/mm$^2$).

3. Results and Discussion

Cycling the specimens in the high frequency resonance loading frame helped to understand fatigue behaviour of the Božanov sandstone. At a given force level (3PB arrangement under point load cycling from -10 N to -260 N) the majority of specimens exhibited fatigue life in a range between 90 000 and 140 000 cycles. However, there were specimens with one order lower or higher fatigue life due to the heterogeneity of the sandstone. To prepare the test specimens, a lower number of loading cycles was applied (between 32 000 and 40 000), and only specimens exhibiting behaviour similar to those of the above mentioned majority were accepted for further experiments.

A typical record of the change of resonance frequency is presented in Figure 9. Visible steps are the results of the regulation loop reaction which keeps the mean loading value within an interval of +/- 2 N.
Figure 9. Decrease of loading frequency during cycling of the specimen bo_10 (for 134 N).

The character of the damage after cycling was determined by means of X-ray CT. It was not possible to identify the crack originating in the granular structure of the sandstone without applying a slight 3PB loading to the specimen and opening the crack. Thus, the specimen under investigation (BO_5 after 140 300 cycles) was loaded with 200 N and under such loading scanned with the X-ray CT. Then the DIC method was used to identify similar situations within the sections in the specimen depth. DIC proved to be a useful tool for crack propagation studies, e.g. [6] and [7]. A comparison of crack visualization for loaded and unloaded specimens is shown in Figure 10.

Figure 10. X-ray pictures of unloaded (left) and loaded (right) sandstone specimen BO_5.

The results of uniaxial tests (Figure 7) also shows that the first loading course can be well approximated by a power function. However, the parameters in the constant differ from the previous case. This may have been influenced by the interior defect in the first case, or just by the natural dispersion of the characteristics of the material. The change in the tension branch of the fatigue loop in the second cycle should be noted. Compared with the first cycle, it is remarkably flatter and straighter. It can even be approximated by a linear function. It signals major damage to the material developed in the first loading cycle, which corresponds to the applied stress. This specimen exhibits rather high
hysteresis. The compression component is steeper than the tension component. Some results were in good agreement with a previous work [8].

4. Conclusions
The methodology of tension tests using specimens inserted and glued in tubular fixtures is functional and has been verified. However, it is very demanding from the point of view of specimen preparation, and it requires very skilled staff. It can be recommended mainly for special small-series tests. However, the pilot tests were successfully completed, and the energies for crack initiation and propagation in the given sandstone have been determined.

The optical DIC method again proved its capacity and its suitability for measurements of a complex deformation field on porous and naturally well-structured surfaces.

The described methodology involving the use of the resonance loading frame to generate cycled cracks in stone was demonstrated. It enables the successful creation of well-defined and controlled crack damage in stone.

The computer X-ray micro-tomography is a useful tool for visualizing and measuring generated cracks in combination with the digital image correlation technique. The crack is usually close and to identify its depth the specimen must be loaded slightly in order to open the crack and make it more visible.

The fracture toughness of untreated notched and cracked specimens reached almost same values, which means that with such heterogeneous material we cannot expect stress concentration factors similar to those of metals. This magnitude will be good indicator for research on consolidation effects.

Acknowledgement
The authors acknowledge kind support from Czech Science Foundation Project GAČR P105/12/G059.

References
[1] Beran P and Drdácký M 2007 Influence of Temperature Changes on Stresses in the Triforium Tracery of St Vitus’ Cathedral in Prague” Proc. Computational Methods for Coupled Problems in Science and Engineering II Coupled Problems 2007 ed E Oñate, M Papadrakakis and B Schrefler pp 433-436
[2] Feng X, Zhang N, Zheng X and Pan D 2015 Strength restoration of cracked sandstone and coal under a uniaxial compression test and correlated damage source location based on acoustic emission PLOS ONE 10 (12): e0145757 (doi: 10.1371/journal.pone.0145757) p 20
[3] Ferestade I, Hosseini P and Heidary R 2017 Fracture toughness estimation of ballast stone used in Iranian railway J. of Rock Mech. And Geotech. Eng. 9/2017 pp 892-899
[4] Vavřík D, Jandejsek I, Fila T and Veselý V 2013 Radiographic observation and semi-analytical reconstruction of fracture process zone silicate composite specimen Acta Technica CSAV vol 58 No 3 pp 315–326
[5] Gross 1965 Stress-Intensity Factors for 3PB Specimens by Boundary Collocation NASA TN D- 3092
[6] Lin Q and Labuz J F 2013 Fracture of sandstone characteristics by digital image correlation Int. J. of Rock Mechanics & Mining Sci. 60 pp 235–245
[7] Nath F, Salvati P, Mokhtari M, Seibi A and Hayatdavoudi A 2017, doi.org/10.2118/187515-MS SPE Eastern Regional Meeting (USA: Society of Petroleum Engineers) ID: SPE-187515-MS
[8] Čechová E, Drdácký M, Frankeová D, Lesák J, Slížková Z, Valach J, Vála O, Zeman A and Zíma P 2010 Research report of ITAM AS CR (in Czech) Technology guidelines for restoration of the XIth arch of the Charles Bridge in Prague (Prague: ITAM) p 139