STATE ASSESSMENT OF SANDSTONE BY ULTRASONIC MEASUREMENTS

ZUSTANDSBEURTEILUNG VON SANDSTEIN MIT HILFE VON ULTRASCHALL-MESSUNGEN

ESTIMATION DE L'ETAT DE GRES A L'AIDE DE MESURES ULTRASONIQUES

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SUMMARY

The ultrasonic resonance method ("impact-echo") was adapted for detection of cracks and delaminations in sandstone. However, additional to reflections from the cracks also flexural vibrations occur. This can be shown by the help of theoretical calculations as well as by laboratory tests. Although cracks cannot be detected there, this enables a state assessment of weathered sandstone in-situ.

ZUSAMMENFASSUNG

Das Ultraschall-Resonanzverfahren ("impact-echo") sollte zur Detektion von Rissen und Delaminationen in Sandstein angewandt werden. Jedoch treten dabei neben Reflexionen von den Rissen auch Flexuralschwingungen auf. Dies kann sowohl anhand von theoretischen Berechnungen als auch mit Hilfe von Labormessungen gezeigt werden. An verwitterten Sandsteinobjekten vor Ort ergibt sich aber gerade daraus eine Möglichkeit, den Zustand des Steines zu beurteilen, obwohl Risse hier nicht detektierbar sind.

RÉSUMÉ

La méthode de résonance ultrasonique ("impact-echo") a été appliquée à la détection de lézardes dans les roches grésenses. Cependant, en plus des réflexions dues à la présence des lézardes, apparaissent aussi des vibrations flexurales. Cela peut être démontré au moyen de calculs théoriques ainsi que par des mesures en laboratoire. Bien que les lézardes ne puissent pas être détectées, il est possible de faire une estimation de l'état d'effritement de grès.

KEYWORDS: sandstone, delaminations, resonance method, flexural vibrations

1. INTRODUCTION

The Ludwigsburg castle ranks among the largest and most important baroque castles in Europe. However, many facade details of its old main building that are carried out in sandstone (*Schilfsandstein*) like window-sills, mouldings, and the first floor of the facade itself are deteriorated. Extensive conservation was done applying a technique called "conserving filling". Therefore, ridged edges, cracks and delaminations are filled with stone replacement material basing on silicic acid ester, quartz sand and stone powders in a liquid form. This material is specially adapted to the hygric and mechanical properties of the stone. In the presence of salts, the acid esters tend to coagulate instead of transforming to a gel that strengthens the material. Another problem of this technique is that very fine fissures and brittle zones cannot be reached by the filling material.

Additional to geological investigations carried out by department 32 *preservation of historical buildings* of the FMPA, non-destructive tests should be carried out in order to judge the results of the conservation. This work was instructed by the *Staatliches Hochbauamt Ludwigsburg*. The resonance method, also called impact-echo method [CHENG and SANSALONE, 1993], which was developed for thickness measurements of concrete structures, was adapted to this matter.

2. PHYSICAL BASES

Starting with the theoretical background laid down in a previous paper [GROSSE and REINHARDT, 1992], we realized that it was insufficient for the explanation of the frequency spectra obtained from the first laboratory tests. First, the relation for the resonance frequency

$$f_{res} = \frac{v_p}{2 \cdot d}, \tag{1}$$

where v_p is the compression wave velocity and d the depth of the structure, is valid only for reflections from boundaries where the material through which the wave is propagating is stiffer than the material into which the wave is refracted. For example, this is true for boundaries between concrete or stone and air, water, or soil. The physical constant related with this phenomenon is the acoustic impedance, which is defined as a function of density ρ and compression wave velocity:

$$Z = \rho \cdot v_p$$

For cases where the material below the boundary that causes the reflections has a higher impedance, the following relation holds for true [CHENG and SANSALONE, 1993]:

$$f_{res} = \frac{v_p}{4 \cdot d} \tag{2}$$

Second, these formulas are strictly valid only for media where the lateral dimensions are unlimited. They can also be applied to reflections at defects whose lateral dimensions are small against their distance from the surface, such as deep delaminations. In our case, we deal with shallow delaminations. The cracks observed and simulated in the laboratory lie only very few centimetres below the surface to which the impact is subjected. The fundamental difference to the reflections described above is the additional excitation of flexural vibration modes of the section between the impact surface and the delamination. An idea of these vibrations gives the movement of a drumhead when excited by the drumstick.

Extensive finite element analyses [CHENG and SANSALONE, (1993)] were carried out to simulate these flexural vibrations. Within certain limits, the results of these numerical analyses are in accordance with a theoretical solution for a vibrating thick rectangular plate supported on all four edges [MINDLIN et al., (1956)]. For the fundamental flexural frequency holds

$$f_{flex} = \frac{v_s}{2 \cdot h} \sqrt{\frac{1 + 3{,}36\lambda - \Omega}{2}} , \qquad (3)$$

where

$$\lambda = \left(\frac{h}{a}\right)^2 + \left(\frac{h}{b}\right)^2 \text{ and } \Omega = \sqrt{(1 + 3{,}36\lambda)^2 - 8{,}6 \cdot \lambda^2} .$$

Although real cracks and delaminations do not have a well-defined shape, this formula provides a better understanding of the spectra that will be measured. First, the frequency is related directly to the elastic properties of the medium expressed in terms of its shear wave velocity v_s. The other parameters that affect this fundamental flexural frequency are the geometrical dimensions of the delamination (or plate, resp.), namely its depth (or height, resp.) h, and its lateral dimensions a and b. As these relations are not straight-forward, the flexural frequency is plotted as a function of depth and lateral dimensions in figure 1 for typical delaminations in sandstone.

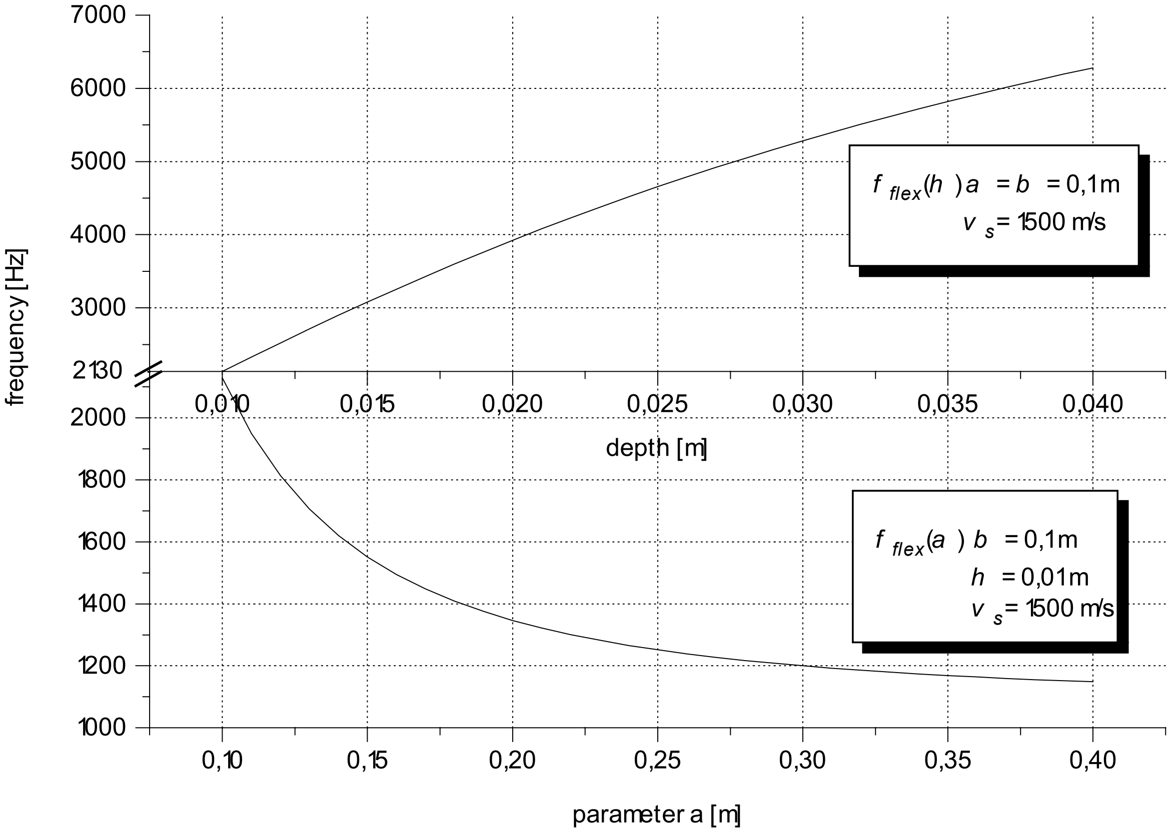

Fig. 1: *Fundamental flexural frequency as a function of depth (top) and lateral dimensions (bottom)*

The frequency of the vibration increases with the depth of the delamination. As the dimensions of the delamination increase, the frequency shifts to a lower value. However, as the aspect ratio of these dimensions exceeds a value of about 3, the frequency does not change significantly. Although both lateral parameters are equivalent, it must be considered that higher modes not only can be produced in the short, but also in the long dimension. Additionally, the mode that is excited depends on the position of the impact relative to the delamination. To summarize these studies, a wide spectrum of flexural frequencies in the area of up to 10 kHz has to be expected.

3. EXPERIMENTAL

For laboratory tests, a block of sandstone (*Schilfsandstein*) 100x150x200 mm was prepared to provide a means of studying spectra from structures where all the relevant parameters are known. A delamination was simulated sawing a cut horizontally at a distance of 36 mm from the surface and ending at 56 mm. Short ultrasonic pulses with a bandwidth of up to 100 kHz were excited by dropping a small steel ball. The response was detected using a broadband piezoelectric accelerometer. The signals were recorded by a personal computer with an ADC-plug-in board and transformed into the frequency domain using the Fast Fourier Transform technique. With this set-up shown in figure 2, profiles were obtained consisting of single spectra made at distances of 10 mm. For each spectrum of a profile, the signal energy was calculated. Thus, the spectra could be normalized with respect to the maximum energy and the displayed relative amplitudes are correct.

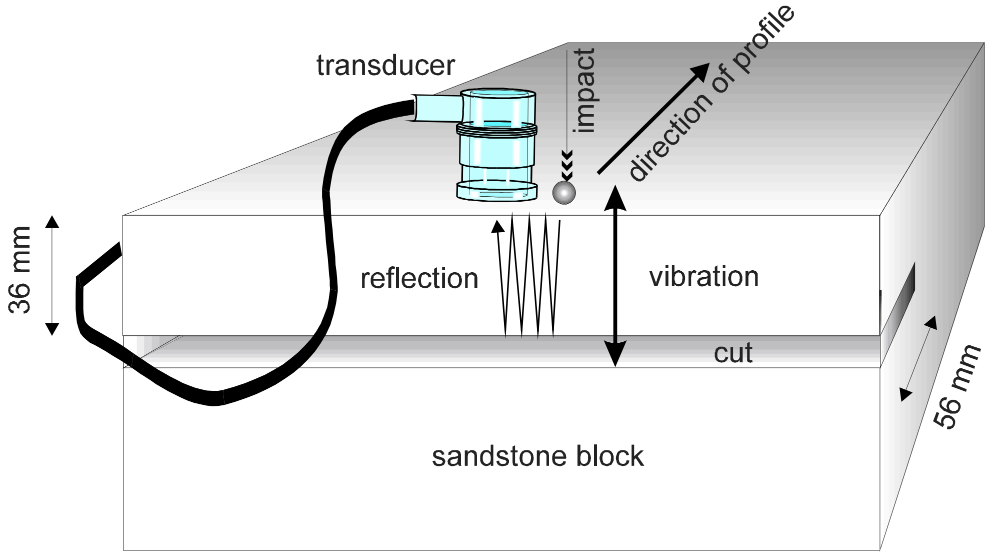

Fig. 2: *Test set-up for laboratory tests at a Schilfsandstein specimen 100x150x200 mm*

The same equipment and technique was used for the in-situ tests, where the distance of the single spectra for a profile was 5 cm.

4. RESULTS

4.1 Laboratory tests

As will be seen later, the crucial frequency range extends up to 60 kHz. No calibration certificate for the broadband transducer was available that could give information about the frequency response of the transducer at frequencies of below 30 kHz. For being able to distinguish the transducer's response from the response of the object, the steel ball was dropped directly to the transducer. The spectrum obtained this way shows a strong peak at 27 kHz (see figure 3). Due to the high amplitude of this resonance peak, no deconvolution of the signal was possible. Hence, this frequency had to be excluded from all future considerations about cracks' responses.

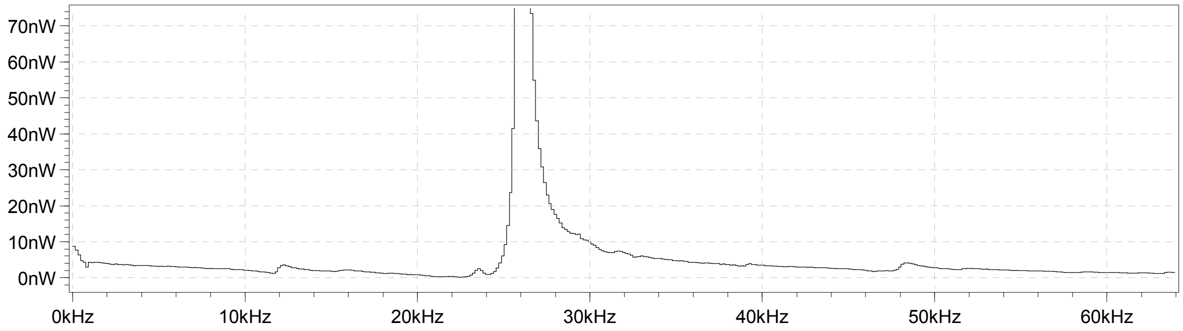

Fig. 3: *Amplitude spectrum of the transducer's impact response*

Prior to performing initial resonance tests on the specimen, the compression wave velocity v_p = 2140 m/s was determined by travel-time measurements. Subsequently, the frequencies corresponding to multiple reflections from the bottom of the specimen and from the top surface of the delamination could be calculated as 12 kHz and 34 kHz, respectively. These frequencies can be identified in the waterfall profile of figure 4. In the sawed section, the spectra are dominated by multiple low-frequency peaks below 10 kHz which are produced by fundamental and higher flexural modes of vibration. In the other area, the spectral response is dominated by the transducer peak.

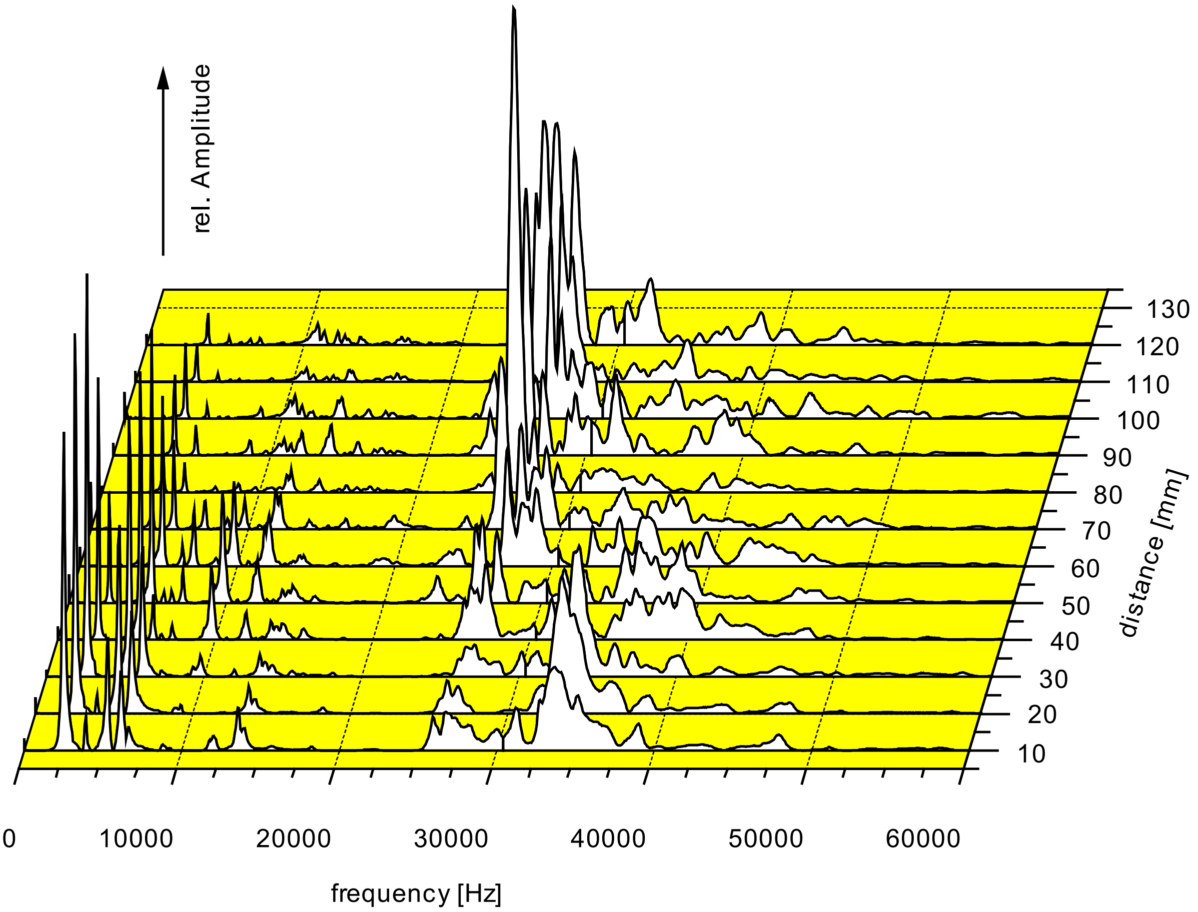

Fig. 4: *Profile (waterfall plot) of unfilled laboratory specimen*

The same profile is shown in figure 5a as contour plot, which is a more adequate form of representation. In figure 5b, an 80 mm part of a profile is shown that was recorded after filling the cut with plaster. Here, across the whole specimen, the spectra are dominated by the transducer peak. The delamination resonance peak has vanished, the multiple flexural modes are still present, but have shifted to higher frequencies, however still below 10 kHz.

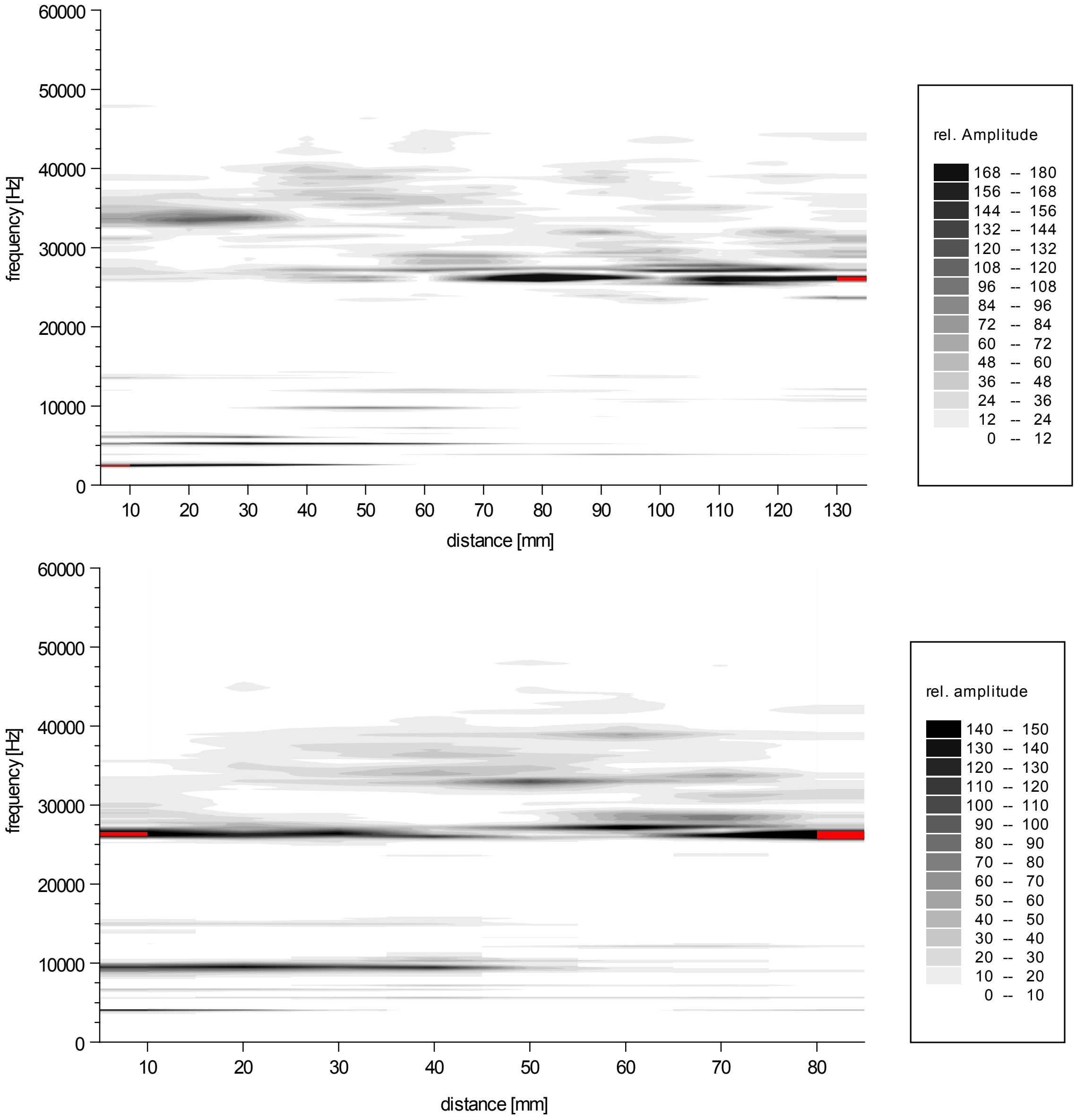

Fig. 5: *a) Profile of unfilled laboratory specimen (top)*
b) Profile of filled laboratory specimen (bottom)

4.1 In-situ tests

The most interesting profiles obtained in-situ are shown in figure 6. They were taken from a conserved window-sill at distances of 25 mm, 75 mm and 125 mm from the edge.

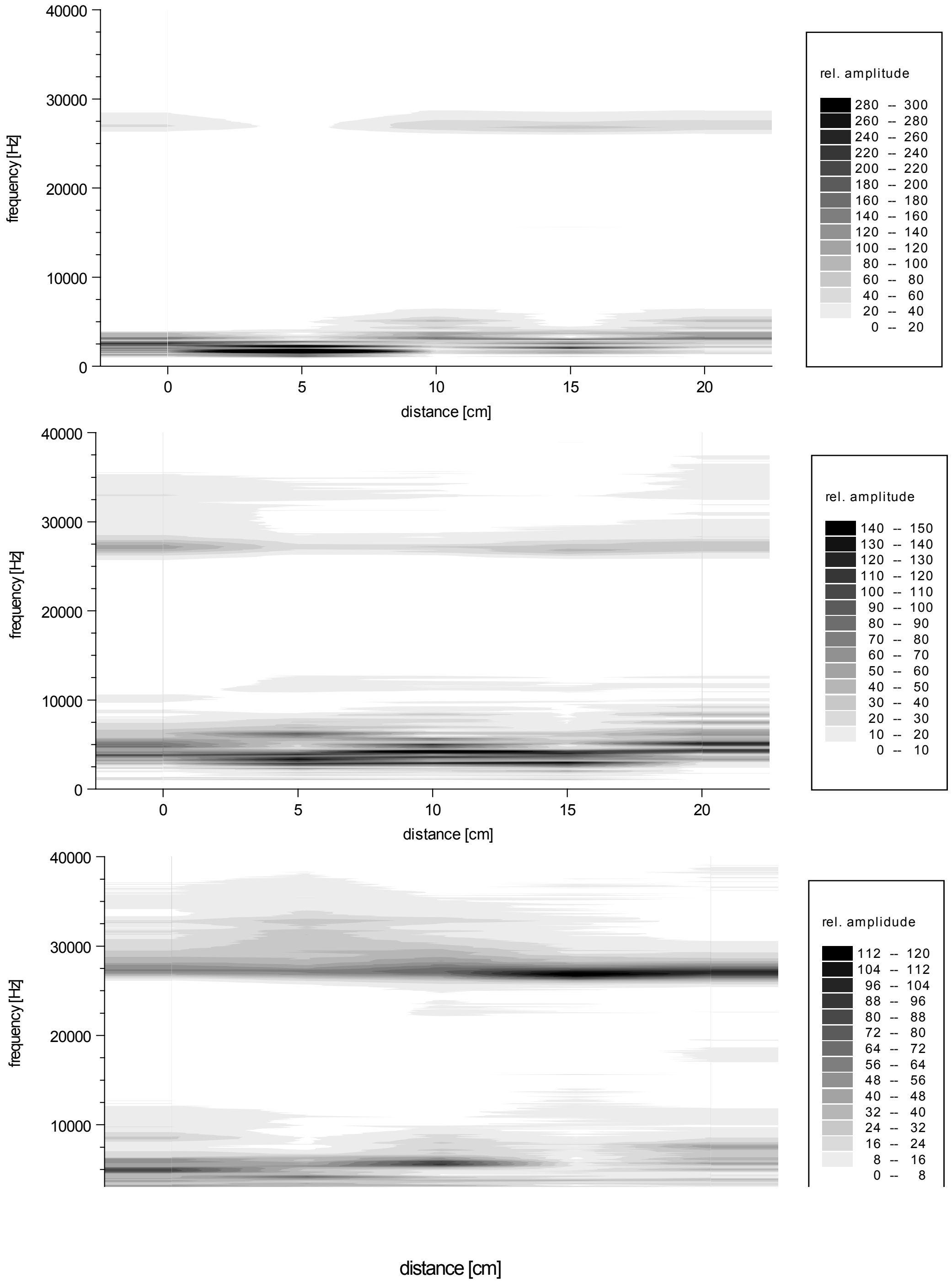

Fig. 6: *Profiles taken from a window-sill at different distances from the edge: a) 25 mm (top), b) 75 mm (middle), c) 125 mm (bottom)*

These profiles all exhibit a wide spectrum of flexural modes as well as the transducer resonance peak. Frequencies corresponding to resonances from the bottom of the window-sill or to reflections from cracks or delaminations do not occur.

5. DISCUSSION AND CONCLUSIONS

Impact responses of sandstone structures containing shallow delaminations were analysed. The laboratory tests show, that the flexural vibrations are rather large relative to reflections from the bottom of the structures or from the top of the delaminations. The deeper the horizon of a reflection, the lower its amplitude. As the difference in the acoustical impedance between sandstone and delamination is reduced by filling the delamination with plaster, no peaks due to waves reflected at this interface can be measured any more, but the flexural vibrations are still excited. The higher stiffness caused by filling the delamination shift the flexural modes to higher frequencies. When no flexural or high-amplitude reflections are excited, the transducer resonance peak becomes dominant.

There are difficulties in transferring these laboratory results to an object in situ. These problems arise as a result of weathering. The compression wave velocity is reduced, in the present case to approximately 1300 m/s. No single delaminations are formed, but arrays of several cracks in different depths. As could be shown by coring, brittle zones occur, where the strength of the stone is considerably reduced. During all in-situ tests, no reflections from cracks could be detected. Nevertheless, a state assessment of the stone could be made. The profiles displayed in figure 6a)-c) show, that the transducer resonance gets more and more dominant as the distance from the edge becomes larger. It can be assumed, that away from the edge the stone is less influenced by weathering effects. This is accompanied by lower-amplitude, higher-frequency flexural peaks. Obviously, the stone gains a better ability to transfer high frequencies.

All these arguments can be used to assess the state of stone structures, although no detailed statements can be made.

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