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Investigation of Historic Masonry by Means of Radar

Investigation de constructions anciennes en maçonnerie au moyen du radar

Erkundung historischen Mauerwerks mit Radar

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SUMMARY

A radar method has been tested, improved and then employed on a number of buildings for the non-destructive investigation of the texture and condition of historic masonry. It has been used for the detection of vertical leaf boundaries, or leaf separations, voids and discontinuities as well as for the assessment of moisture contents.

RÉSUMÉ

Le procédé du radar a été testé afin d'examiner la structure et l'état de constructions anciennes en maçonnerie de manière non-destructive. Il a été développé et utilisé sur de nombreux bâtiments. Le radar permet de repérer les épaisseurs et les séparations des parements, les vides, et de constater l'hétérogénéité des matériaux, ainsi que le degré d'humidité des murs.

ZUSAMMENFASSUNG

Zur zerstörungsfreien Untersuchung von Struktur und Zustand historischen Mauerwerks, wurde das Radarverfahren getestet, weiterentwickelt und an zahlreichen Bauten eingesetzt. Mit ihm lassen sich Schalengrenzen, Schalenablösungen, Hohlräume und Materialeinlagerungen orten, sowie der Feuchtegehalt bestimmen.

1. INTRODUCTION

Unsatisfactory inspection and diagnosis of historical buildings often leads to inappropriate restoration measures, which cause excessive damage, a delay of time and additional costs.

By thorough investigations of the structure these mistakes can be avoided. However, in many cases it will not be sufficient to inspect surfaces, but to obtain data from the inside of a structural member. For this purpose, non-destructive methods are required, since data acquisition should be made on a very dense grid without causing damage.

2. THE RADAR METHOD

The main components of the equipment used are the control unit, a microcomputer containing specific software, a transmitter and a receiver. In the reflection arrangement both antennas are connected in one box which is moved along vertical or horizontal lines with scans every 2 cm approximately, fig. 1, 2, 3.

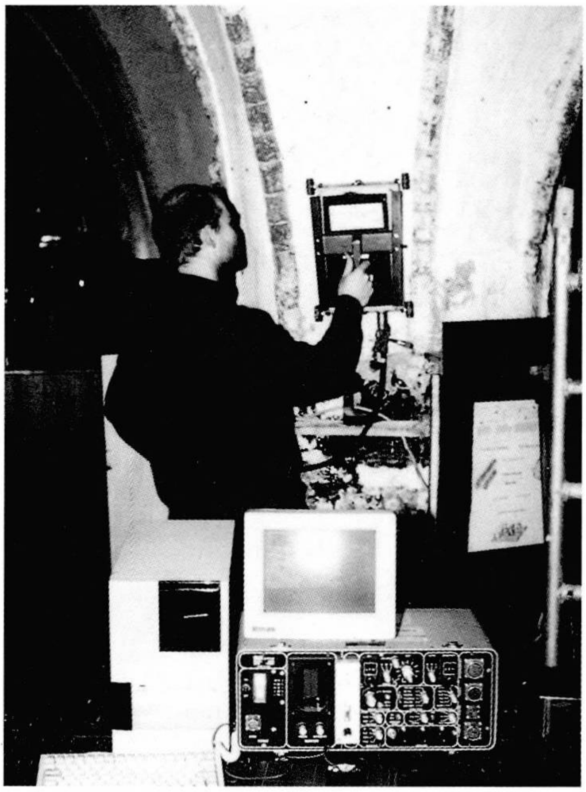

Fig. 1: The radar equipment

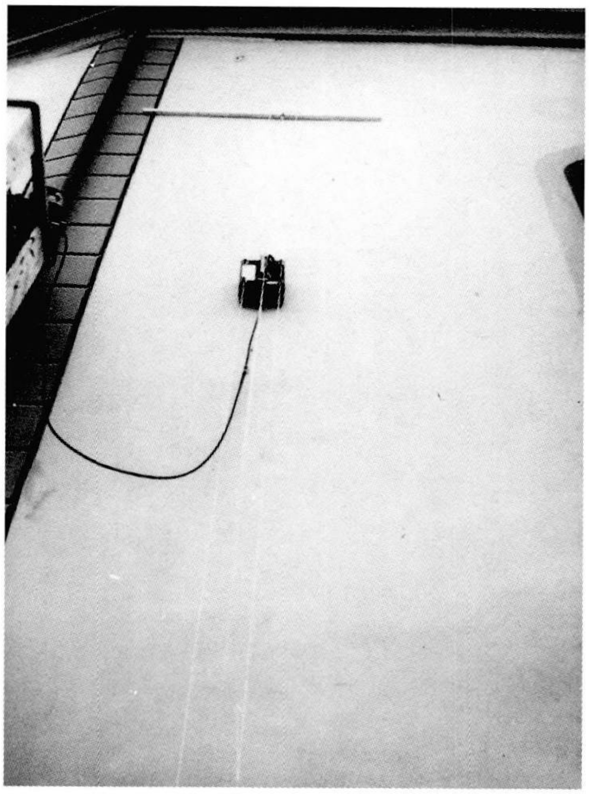

Fig. 2: The 500 MHz-antennas in the reflection arrangement

The transmitter directs pulses of low power electromagnetic waves of one and a half wavelength duration at frequencies of 100 to 1000 MHz into the structure. The waves propagate through the material with the specific velocity of

$$v = \frac{c}{\sqrt{\varepsilon_r}} \qquad \text{with: } c = 3 \cdot 10^8 \text{ m/s} = \text{speed of light}, \quad \varepsilon_r = \text{relative permittivity} \tag{1}$$

At an interface separating materials of different electrical properties, a portion of the energy is reflected back to the surface, where it is picked up by the receiver. For vertical incidence the reflected field strength is given by the reflection coefficient

$$r = \frac{\sqrt{\varepsilon_{r,1}} - \sqrt{\varepsilon_{r,2}}}{\sqrt{\varepsilon_{r,1}} + \sqrt{\varepsilon_{r,2}}} \quad \text{with: } \varepsilon_{r,1}, \varepsilon_{r,2} = \text{relative permittivity of material 1 and 2 respectively} \qquad (2)$$

The received signals are amplified depending on the delay time, transmitted to the microcomputer and finally plotted in radargrams, fig. 3.

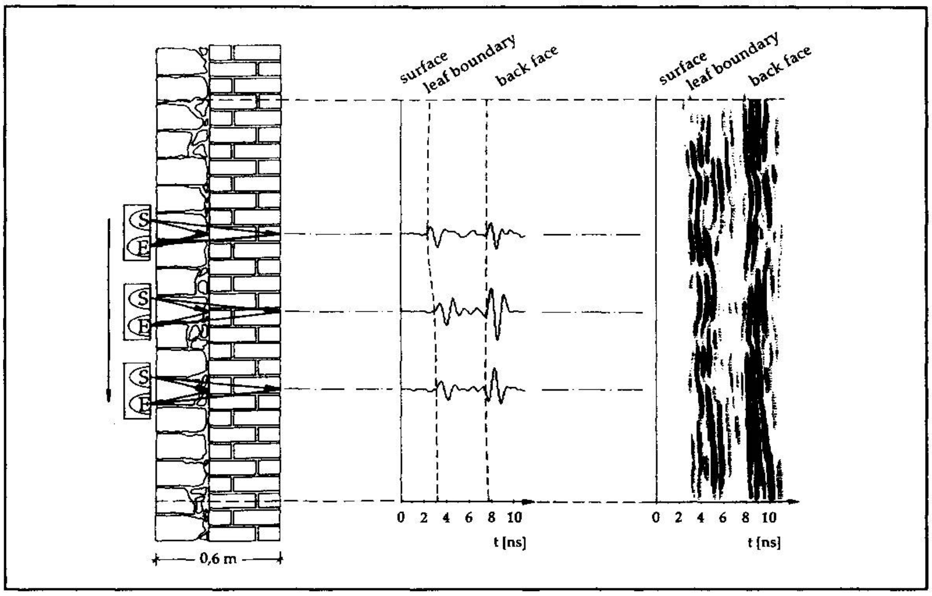

Fig. 3: The reflection arrangement on a multiple leaf wall; schematic cross section, received signals and radargram (S..transmitter, E..receiver, ↓.. direction of profiling)

The radargram provides a graphic profile presenting the amplitudes of the electromagnetic waves as a function of the delay time between the moment of entering and leaving the structural part. In order to condense the data display it is convenient to use dots, whereby the colour code or the colour density (in the case of grey as in the figures shown) is associated with the magnitude of the amplitude, fig. 3.

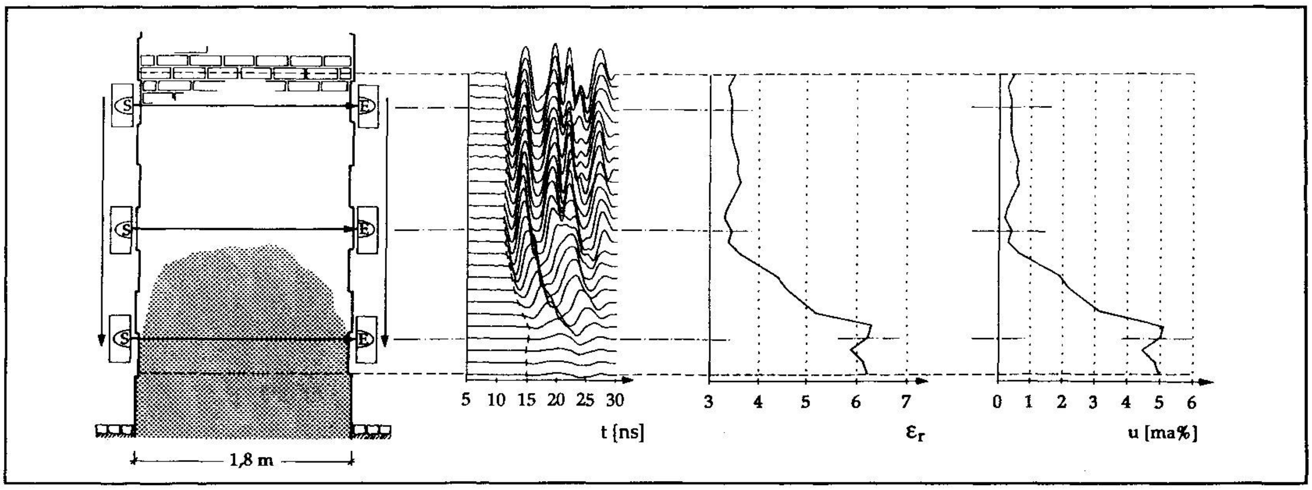

Fig. 4: The transmission arrangement on a column with rising moisture; schematic cross section, received signals, relative permittivity and moisture profile (S..transmitter, E..receiver, ↓..direction of profiling)

In the transmission arrangement, which is primarily employed for the assessment of moisture, transmitter and receiver are placed on opposing faces, fig. 4. Because of the difficult handling of the antennas, discrete scanning points at 5 or 10 cm spacing are chosen. The propagation time of the electromagnetic wave through the structural part is given by the location of the first deviation of the receiver signal, from which the velocity is calculated. Using equation 1 the relative permittivity is determined and from this value, the moisture content is derived (see §3 and §4.3).

3. ELECTRICAL MATERIAL PROPERTIES

The electric resistivity and the relative permittivity of the materials determine the velocity of the electromagnetic waves, the reflectivity at interfaces and the depth of penetration. Hence was examined the dependence of the electrical properties of materials commonly used in masonry from parameters such as: material matrix (chemical composition, texture and porosity), water content, concentration of dissolved salts, frequency of the waves, temperature and mechanical stress level. Since the literature provided unsufficient information, special laboratory tests had to be carried out.

The resistivity was determined on samples of different materials with the geoelectric direct current method. The resistivities for brick, given as a function of the moisture and salt content, are shown in fig. 5.

The relative permittivities were measured using the radar technique in the transmission mode. The dependence of the permittivity on the moisture content, as depicted in fig. 6, may be approximated by a linear relation. Dissolved salts cause a slight increase up to 10 % of the relative permittivity. The influence of temperature and pressure was found to be insignificant for the application of radar on historic masonry.

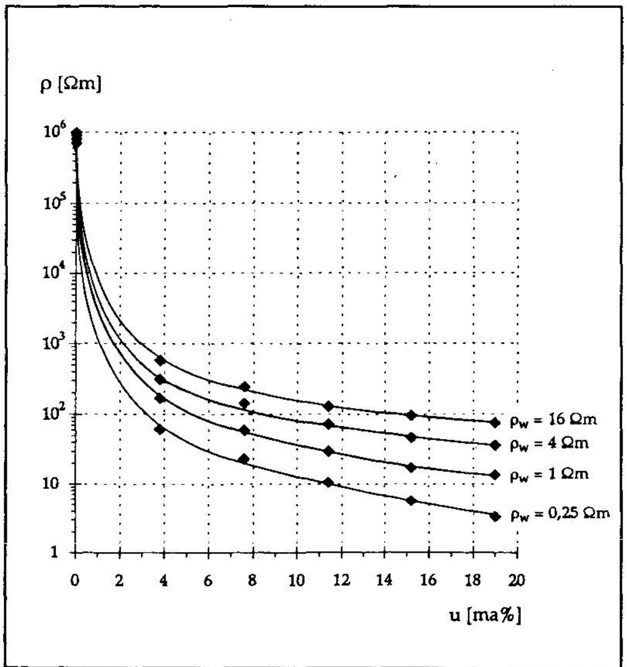

Fig. 5: Dependence of the electric resistivity ρ of brick on the gravimetric moisture content u; parameter ρ_w is the resistivity of the porous aqueous solution

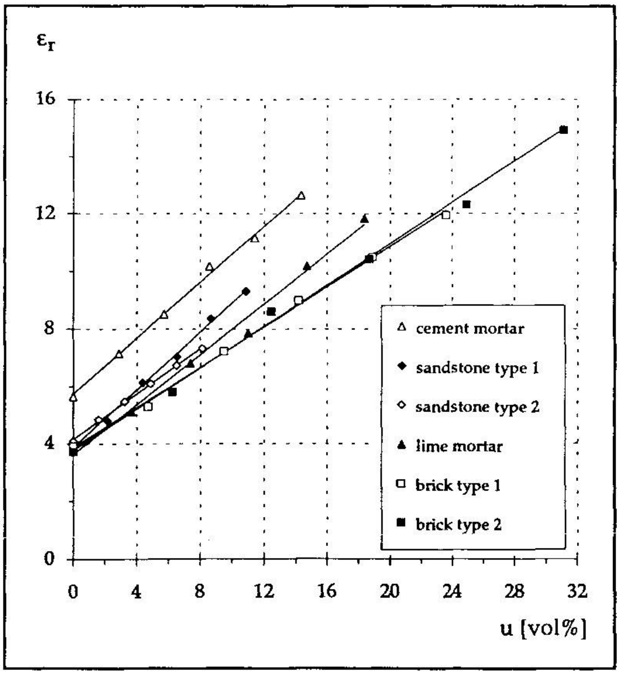

Fig. 6: Dependence of the relative permittivity ε_r of different materials on the volumetric moisture content u

4. BUILDING INVESTIGATIONS

4.1 Leaf Boundaries

The radar method is capable of detecting boundaries of multiple leaf masonry in the way depicted in fig. 3. The result of the investigation and the data quality is dependant on the nature of the boundary surface and the difference in the electrical material properties. Smooth boundaries yield clear and uniform reflection bands in the radargram. In this respect the example in fig. 3 is an ideal case.

Since the leafs are usually bonded and often consist of similar materials, the radargrams picked up from several multiple leaf stone walls looked like the one on fig. 7. The data is less distinct, but the leaf boundaries are imaged in short reflection bands and moreover, the leafs show different reflection patterns.

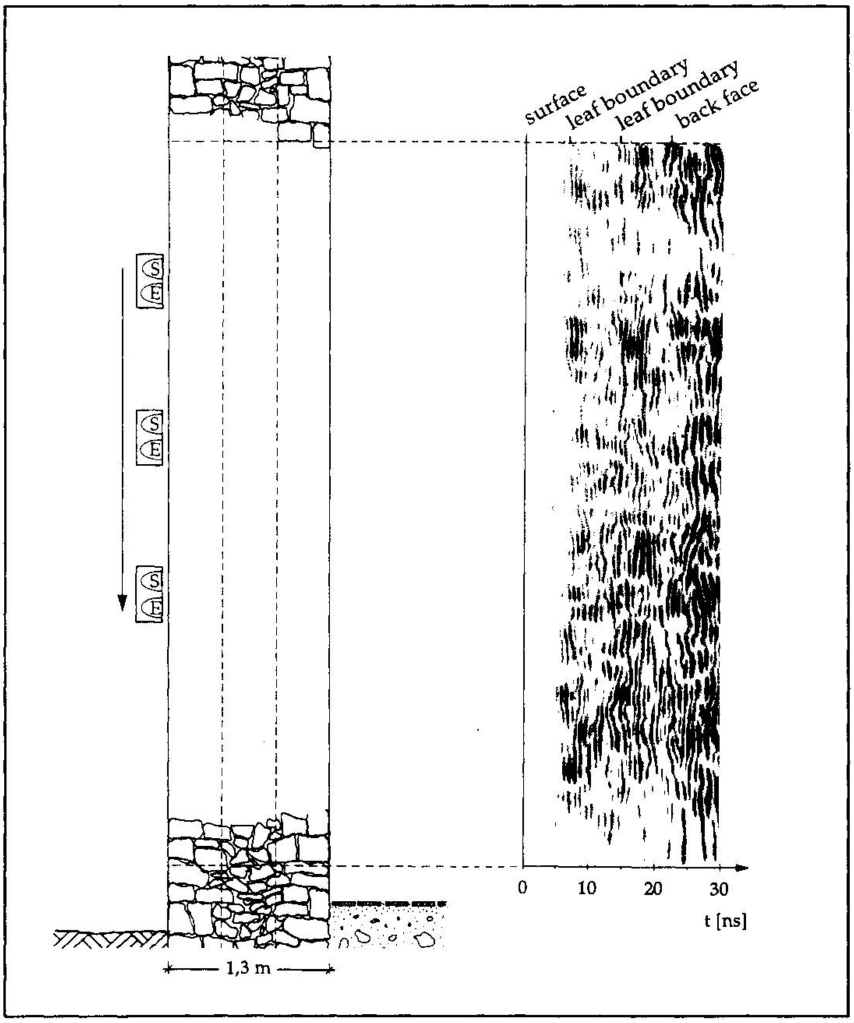

Fig. 7: Detection of leaf boundaries; wall cross section and radargram

Some investigations were carried out on walls with leafs which have separated, fig. 8. In these cases, because of the high reflection coefficient, the reflection from the interface stone/air was very strong with amplitudes in the order of 10 times as much as from comparable intact wall elements. If the gap was filled with debris the intensity was lower but still significant.

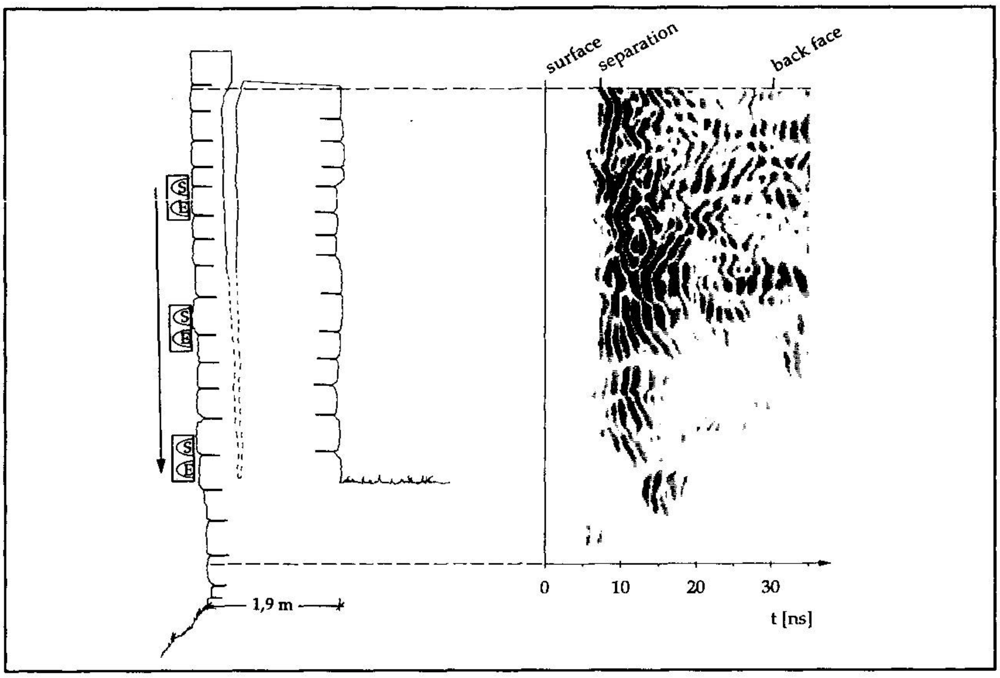

Fig. 8: Detection of leaf separations; wall cross section and radargram

4.2 Anomalies

Because of its high resolution the radar method is capable of detecting discontinuities due to voids or enclosed materials. The reflections from the boundary of the anomaly are imaged as diffractions in the radargrams, fig. 9. A charac-

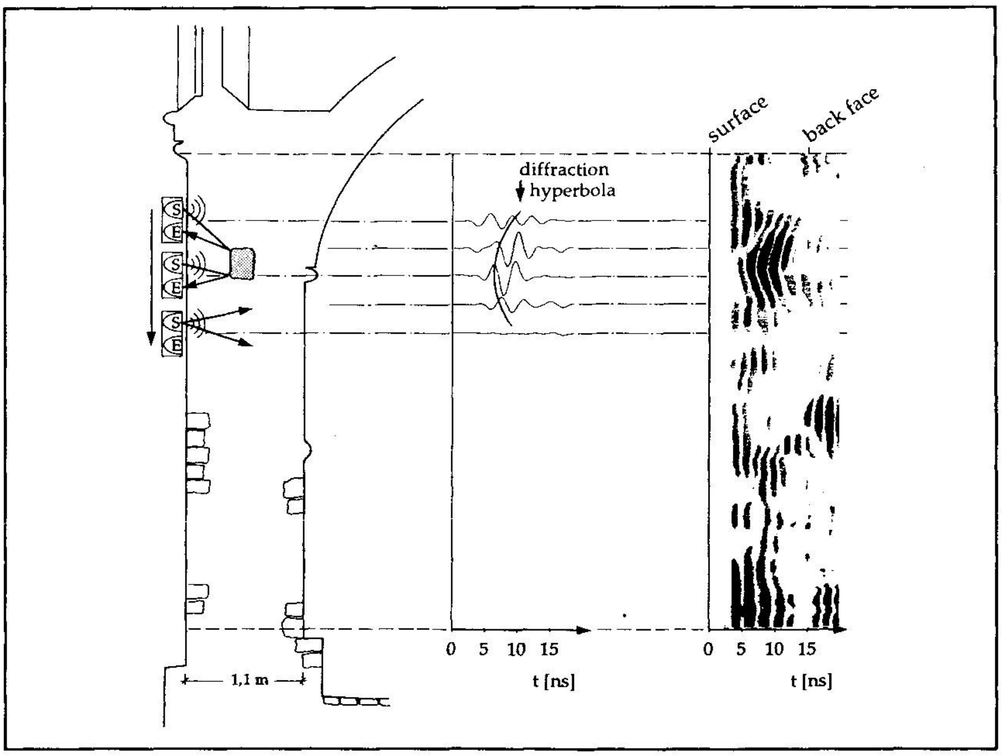

Fig. 9: The detection of anomalies with the reflection arrangement; wall cross section of the Matthiaskapelle in Kobern/Mosel, receiver signal and radargram

teristical hyperbolic shape is created because the anomaly is captured over a certain profile length while the distance between the anomaly and the antennas changes. At the Matthiaskapelle, shown in fig. 9, a long hole for a wooden tie beam was found by this means.

Several investigations on masonry containing voids or enclosed materials occupying 10 % of the wall width or less, served to show that the resolution is usually sufficient to detect all significant characteristics of historic masonry.

Radar measurements on the Jägertor in Potsdam were carried out in order to define its bearing structure which was not known and especially to reveal possible hidden metal ties or clamps. The radargrams, picked up from underneath the beam, showed distinct diffractions from singular metal bodies plus reflection bands from several joints. Thus the data was interpreted in the way presented in fig. 10.

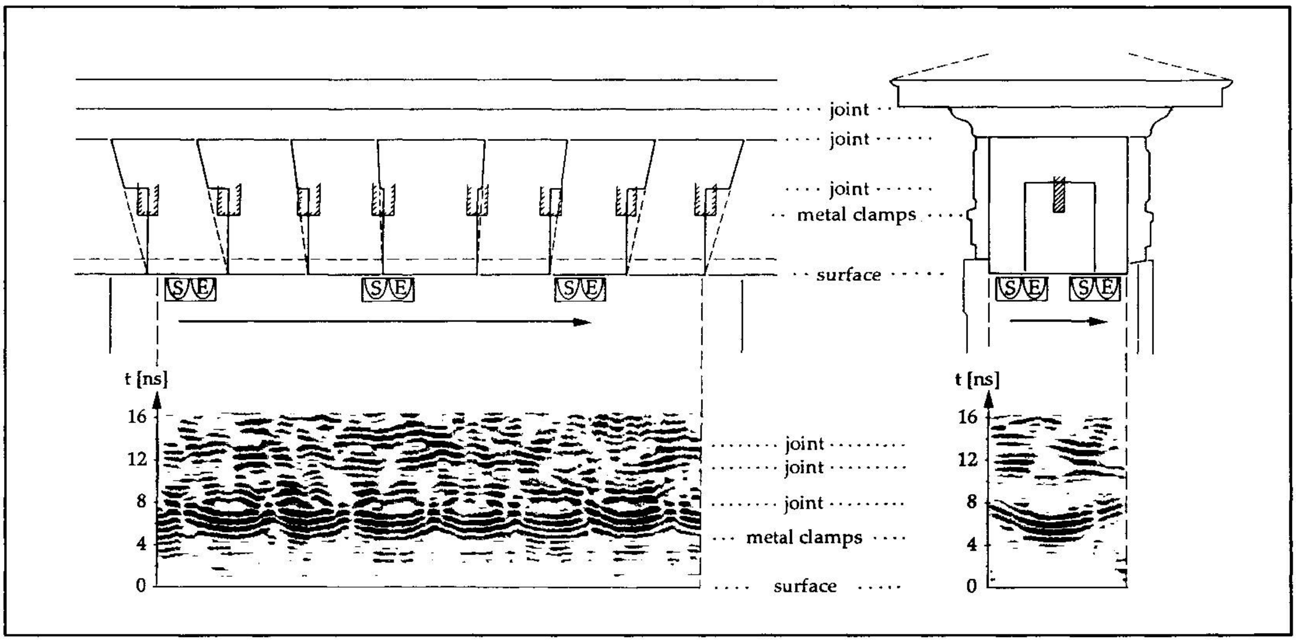

Fig. 10: Longitudinal and transversal cross section of the beam of the Jägertor in Potsdam and corresponding radargrams

4.3 Moisture

The possibility of measuring the moisture content of masonry with radar is derived from the dependence of the relative permittivity on the amount of water in the material matrix, fig. 6. The transmission arrangement usually yields the best data, but the reflection arrangement can be used on the condition that the reflection from the back surface is caught precisely and the width of the structural part is known.

The relative permittivities are calculated from the radar data using equation 1. From this values the moisture contents are determined by means of linear relations of calibration, which are either transferred from experience (S3) if applicable, or are derived from gravimetric moisture control on samples from the investigated member. In any case, a mean moisture content is measured from an averaged cross section and a lateral area according to the antenna size.

A comparison of the results from radar and the gravimetric moisture determination on drill debris from about 120 samples was made on a brick wall of a church. Fig. 11 shows 3 cross sections with the values from both methods, the profiles from radar being much smoother because of the larger measuring volume.

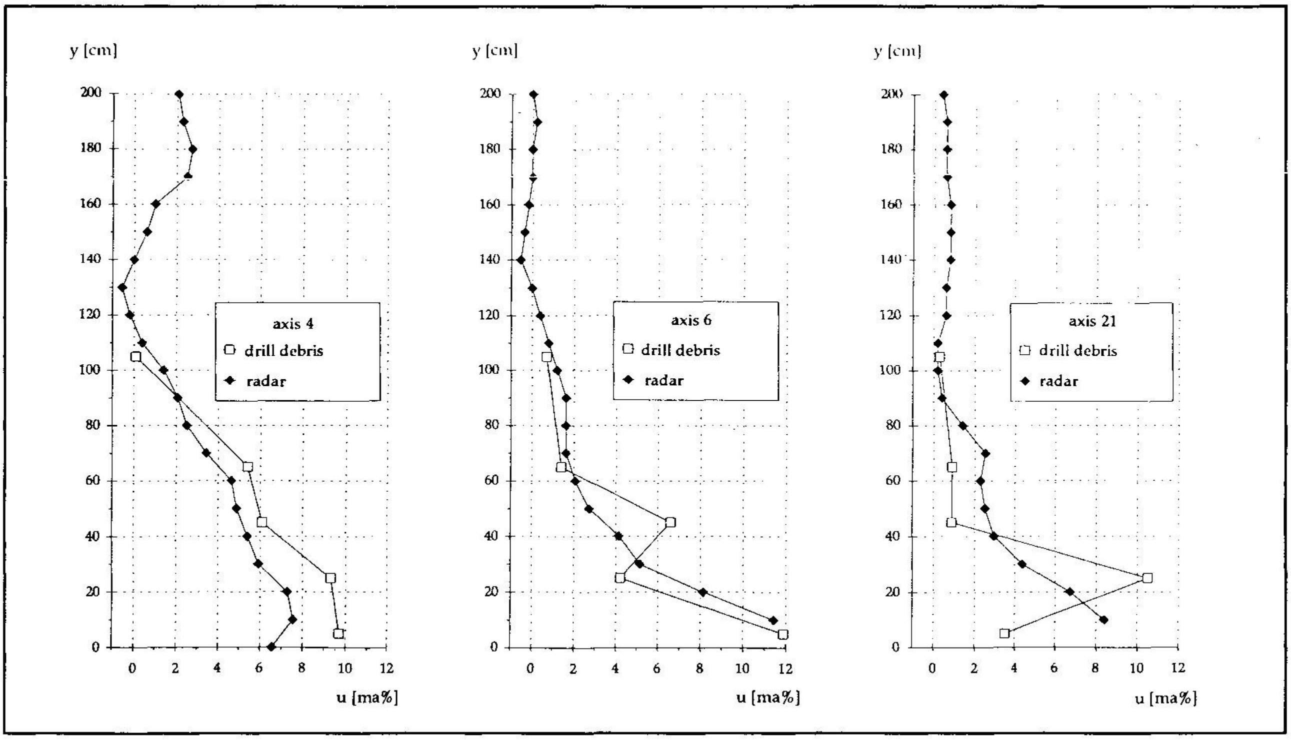

Fig. 11: Moisture content u of a brick wall at 3 cross sections, determined with radar or the gravimetric method on drill debris

5. CONCLUSIONS

Within the scope of the research program, concluded at the end of 1992, radar proved to be a versatile and efficient method for the investigation of texture and condition of historic masonry. It is expected and indeed hoped that the method will come to be used as a credible commercial tool, since this would be of benefit to the historic buildings and assist the engineers involved. The savings in the design and execution of restoration measures may easily surpass the costs of a radar investigation.

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