DEVELOPMENT OF A MINIMALLY INVASIVE MOISTURE MEASUREMENT SYSTEM FOR CONTINUOUS MONITORING - MOISTURE DAMAGE TO THE ZEPPELIN TRIBUNE IN NUREMBERG

ENTWICKLUNG EINES MINIMALINVASIVEN FEUCHTEMESSSYSTEMS ZUR KONTINUIERLICHEN ÜBERWACHUNG - FEUCHTESCHÄDEN AN DER ZEPPELINTRIBÜNE IN NÜRNBERG

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SUMMARY

The Zeppelin Tribune in Nuremberg, built between 1933 and 1939, shows considerable structural defects. In addition to losses to the facades, there is also massive damage to the interior of the tribune. The city of Nuremberg has set itself the goal of preserving this building from the National Socialist era and ensuring safe accessibility to both the Zeppelin Tribune and the Zeppelin Field in order to preserve this historical-political learning site for future generations. As early as 2014, the city installed a climate monitoring system with the aim of developing a climate concept that would make it possible to reduce the very high relative indoor humidity levels that have a damaging effect on the historic building fabric [1]. The building climate concept provided for controlled ventilation to initiate drying of the building fabric and, in the medium to long term, to lead the moisture loads in the masonry to a lower moisture level that would not further endanger the building fabric. In order to verify the drying process in the masonry components, which are up to 2 meters thick, a measuring system was sought that consistently follows the principle of monument preservation of limiting the encroachment on the historic building substance to a minimum. Based on the measuring principle of Time Domain Reflectometry (TDR), moisture probes were developed and tested in the project that allow the moisture conditions in the complex masonry body to be recorded in a low-destructive manner and to be able to make statements about the location-dependent moisture condition with an appropriate evaluation algorithm. The development of such a measuring system was taken over by the companies TRUEBNER GmbH in Neustadt a. d. Weinstraße and TTI GmbH in Stuttgart, the TGZ MOCult, in order to be able to determine the material moisture conditions in the masonry with a largely non-destructive measuring method. For this purpose, a high-frequency method was used, which is characterized by a high measurement sensitivity. In addition to the electrical design for the probe, electronic circuits had to be developed, both for the measurement and for the interface to the data acquisition. Furthermore, a suitable mechanical design and installation technology for the probes had to be conceived and put into practice. In addition, measurement technology and sensors for laboratory tests had to be developed. Furthermore, laboratory tests were carried out on samples taken from the building in order to record and evaluate the moisture level prevailing in the masonry with laboratory comparisons.

ZUSAMMENFASSUNG

Die zwischen 1933 und 1939 erbaute Zeppelintribüne in Nürnberg weist erhebliche bauliche Mängel auf. Neben Verlusten an den Fassaden sind auch im Inneren der Tribüne massive Schäden zu verzeichnen. Die Stadt Nürnberg hat sich zum Ziel gesetzt, dieses Bauwerk aus der Zeit des Nationalsozialismus zu erhalten und eine sichere Begehbarkeit sowohl der Zeppelintribüne als auch des Zeppelinfeldes sicherzustellen, um diesen historisch-politischen Lernort für künftige Generationen zu bewahren. Bereits 2014 wurde seitens der Stadt ein Klimamonitoring installiert, mit dem Ziel ein, ein Klimakonzept zu entwickeln, mit dem es möglich ist, die sehr hohen relativen Raumluftfeuchten, die einen schädigenden Einfluss auf die historische Bausubstanz haben, zu reduzieren [1]. Das bauklimatische Konzept sah eine kontrolliert gesteuerte Lüftung vor, um eine Trocknung der Bausubstanz anzustoßen und mittel- bis langfristig die Feuchtelasten im Mauerwerk auf ein geringeres und die Bausubstanz nicht weiter gefährdendes Feuchteniveau zu führen. Um den Trocknungsprozess in dem bis zu 2 Metern mächtigen Mauer-

werksbauteilen nachzuweisen, wurde ein Messsystem gesucht, dass dem denkmalpflegerischen Grundsatz, den Eingriff in die historische Bausubstanz auf ein Minimum zu begrenzen, konsequent folgt. Auf Basis des Messprinzips der Time Domain Reflectometry (TDR) wurden im Projekt Feuchtesonden entwickelt und erprobt, die auf zerstörungsarme Weise erlauben, die Feuchteverhältnisse im komplexen Mauerwerkskörper zu erfassen und mit einem entsprechenden Bewertungsalgorithmus Aussagen zum ortsabhängigen Feuchtezustand treffen zu können. Die Entwicklung eines derartigen Messsystems wurde von den Firmen TRUEBNER GmbH in Neustadt a. d. Weinstraße und der TTI GmbH in Stuttgart, dem TGZ MOCult übernommen, um mit einer weitgehend zerstörungsfreien Messmethode die Materialfeuchtezustände im Mauerwerk bestimmen zu können. Hierbei wurde ein hochfrequentes Verfahren zur Anwendung gebracht, das sich durch eine hohe Messempfindlichkeit auszeichnet. Neben dem Elektrodenentwurf für die Sonde waren elektronische Schaltungen zu entwickeln, sowohl für die Messung als auch für die Schnittstelle zur Datenerfassung. Darüber hinaus musste eine geeignete mechanische Konstruktion und Einbautechnik für die Sonden konzipiert und in die Praxis umgesetzt werden. Zusätzlich galt es, Messtechnik und Sensorik für Laborversuche zu entwickeln. Des Weiteren wurden Laboruntersuchungen an am Bauwerk entnommenen Proben vorgenommen, um das im Mauerwerk vorherrschende Feuchteniveau mit Laborvergleichen erfassen und bewerten zu können.

1. PROBLEM DEFINITION AND OBJECTIVE

The Zeppelin Tribune is the only building in the Zeppelin Field in Nuremberg that was completed and used during the National Socialist era. It is therefore an important national cultural asset for remembrance, commemoration and education. Today, the Zeppelin Tribune has serious structural defects that can be traced back to damaging weather influences and require rapid and professional repair.

Extensive investigations were already carried out in 2013/2014 to assess the extent of the damage. The analyses and evaluations showed that the natural stone facades and staircases are considerably damaged or partly destroyed due to weather-related effects and the unhindered access of moisture. There are also high levels of moisture inside the tribune, which required rapid action to prevent further damage progression.

The structural engineering department of the City of Nuremberg therefore planned to achieve a safe condition and hazard-free accessibility of all areas of the Zeppelin Field and initiated a corresponding damage mapping and a repair planning based on this [1].

An essential task was to dehumidify the building mass. For this purpose, the relative humidity and thus the absolute moisture content inside the tribune building had to be lowered in order to prevent condensation from forming on the surfaces of the building components. The City of Nuremberg's Building Department developed and tested measures to protect the building fabric from further damage in an economical and sustainable manner that is compatible with the preservation of historic monuments. The most important goal was considered to be medium- to long-term drying, which was to be achieved with as little effort as possible and with careful intervention in the building fabric. In order to bring the thick masonry components close to the practical equilibrium moisture content of the individual building materials without causing further damage, it was therefore necessary to continuously assess the moisture distribution inside the masonry.

Thus, the masonry moisture should be observed and evaluated down to a depth of 200 cm in order to be able to bring about a controlled drying process that does not endanger the construction.

This requires the use of an innovative method for continuous moisture determination that requires only minimal intervention in the original masonry.

The Building Department of the City of Nuremberg implemented a long-term room climate monitoring system, which, in conjunction with a minimally invasive ventilation system, was to enable targeted dehumidification of the room air. With a control concept adapted to the problem, the successful dehumidification, i.e. a slow drying out of the masonry, was to be investigated and tested on a sample renovation section. At the same time, structural preconditions were created, such as sealing the roof surfaces and a functioning drainage system.

In order to be able to evaluate the drying success achieved, a continuous moisture measurement system was needed to record the time-varying moisture distribution over the cross-section of the building component. Continuous moisture measurement inside components is not yet possible with the systems available on the market.

For this reason, a DBU project was initiated by the building construction department of the city of Nuremberg together with TTI GmbH and Trübner GmbH, in which a minimally invasive moisture measurement system was to be developed, used and tested, with which the drying process occurring inside the masonry can be continuously recorded and evaluated.

The measuring method proposed for the realization of the project is based on a high-frequency measuring method using sensor electrodes that are inserted into a borehole and continuously measure the local moisture condition in segmented depth ranges [2]. Using multiplexer electronics, several sensor electrodes were to be interrogated and the data transmitted to a PC on site via a communication line. The calibration of the sensor electrodes was seen as a challenge. After all, each sensor signal must be assigned a material-related moisture content. For this purpose, comprehensive laboratory tests were carried out in advance on the cores already taken. In addition, the moisture and thermal properties of interest had to be determined in the laboratory, since hygrothermal component simulations were also carried out in the project, but these are not discussed in this article. Further information can be found in [1].

2. DEVELOPMENT OF PROBLEM-ADAPTED TDR PROBES

TRUEBNER GmbH develops, researches and tests TDR sensor systems that can be used in construction, forestry and agriculture as well as in many other fields of application [2, 3]. Validated systems are brought to the market by TRUEBNER GmbH in potential fields of application.

In the case of the novel TDR probe for use in the continuous detection of moisture distribution in masonry, microcontroller-controlled high-frequency measurement electronics were developed, which have a data interface for querying several measuring points. The TDR moisture probe can thus be used in thick walls, floors and ceilings to continuously measure moisture over the depth of the wall.

The physical measuring principle of the TDR probe is based on the interaction between moist material and the acting high-frequency electromagnetic field. With higher water content, the dielectric constant of the material increases. This increases the measurable electrical capacitance. For the electrode design, the geometrical boundary conditions (diameter of the borehole) of the installation situation had to be taken into account [1]. For example, the electric field emitted by the electrodes of the probes should penetrate as deeply as possible into the surrounding material. It must also be avoided that a possible air gap at the transition between electrode and masonry has a negative influence on the measurement result [2].

Therefore, numerical simulations using FEM were performed to optimize the electrode geometry in order to analyze the influences of the respective material properties of the masonry as well as the angular areas occupied by metal layers. With the final comparison of the calculation results, the most suitable probe geometry was selected. In the FE analyses, the material properties in the masonry as well as the angular areas occupied by metal layers had to be varied in order to achieve the best possible measurement effect.

Fig. 1 shows the arrangement of the probe, which is designed as a highly conductive copper electrode and is mounted on a plastic tube body. When selecting the probe materials, attention was paid to permanent flexibility and high moisture resistance.

Fig. 1: Close-up of the copper electrode on the plastic tube body

In order to be able to record a moisture condition distributed over the masonry depth, the probe was subdivided into 8 measuring ranges, in each of which an electrode group records the locally prevailing moisture condition (see Fig. 2). The distance between the individual electrode groups is selected in such a way that they influence each other only minimally.

Fig. 2: Segmented probe with 8 electrode groups

In order to be able to insert the probe into the prepared borehole and thus into the masonry without damaging the electrodes and, if possible, without an air gap, a full-surface insulating coating was applied (Fig. 3).

Fig 3: Probe with insulation covering the entire surface of the electrodes

The electrode supply lines to the switching and evaluation electronics (multiplexer) are bundled and led out over the end of the tube. The high-frequency measuring electronics components are located inside the tube. Consequently, only low-frequency signals are routed via the lines. This ensures low-interference transmission even over longer distances.

In September 2017, the measuring probes were installed together with the city of Nuremberg and integrated into the climate measurement system of the city of Nuremberg.

In addition, another TDR measuring system was set up by TRUEBNER, which was used by MOCult in the laboratory to carry out a comparison of the probe signal values with the moisture content prevailing in the material. The adjustment was carried out for all materials found in the Zeppelin Tribune.

In order for the electrodes to couple closely to the borehole wall, a suitable solution for installing the probes had to be worked out. Thus, attempts were made to achieve the desired contact pressure by means of spring mechanisms and pressure build-up (e.g. with expansion hoses and polyurethane foam to increase the pressure). In the end, an elegant and comparatively easy-to-manufacture solution was found. Here, the tube body is constructed with a slot. As a result of the internal stress in the slotted plastic tube, the plastic rolls in and the tube diameter is reduced slightly. This makes it easy to insert the probe into the borehole. The electrode groups are pressed evenly against the borehole wall by means of a clamping profile to be inserted into the tube.

The measurement signals acquired by the probe groups are transmitted from the high-frequency circuit in the probe to the multiplexer specially developed for the measurement system. An RS-485 interface was installed in the multiplexer, via which an MOD-Bus protocol of the software of the room ventilation system of the city of Nuremberg can be exchanged for humidity distribution in the probe. For this purpose, TRUEBNER developed a comprehensive microcontroller software, which enabled an integration of the measurement data of the TDR humidity probe in the data acquisition system of the building construction office of the city of Nuremberg.

3. PROBE INSTALLATION

With the availability of the probes, they could be installed in the boreholes previously drilled in the masonry of the Zeppelin Tribune with borehole depths of 1.0 m to 1.2 m. The boreholes themselves were drilled dry to a depth of 72 cm. The boreholes themselves were drilled dry to a depth of 72 cm. The further wall depth had to be drilled wet.

During installation, the boreholes were first inspected, cleaned out and blown out with compressed air (Fig. 4).

Fig. 4: left: Cleaning out the boreholes, right:Blow out with compressed air

Fig. 5: left: Driving in the clamping profile, right: Installation condition after clamping

The probe is then carefully inserted into the borehole (Fig. 5) so that the probe lies loosely in the borehole. Then the probe is pressed apart with the clamping profile. For this purpose, the profile coated with lubricant is driven in with a rubber mallet. Now the slotted tube and thus the electrode lie tightly against the borehole wall. In the next step, the probe cables are connected to the multiplexer and to the data acquisition system of the climate measurement system of the city of Nuremberg (Fig. 6).

Fig. 6: left: Wiring of the probe cables at the multiplexer, right:View of the measuring system on the masonry

4. LABORATORY TESTS

In order to be able to carry out a calibration of the TDR moisture probes in the laboratory on the part of MOCult, two additional multiplexers were manufactured by TRUEBNER, a sensor circuit was prepared and a software was created with which the measurement data of the materials examined in the laboratory could be recorded and evaluated. For the laboratory measuring system, with which the calibration was to take place, an electronic measuring system was created, which records four individual sensors and forwards them to a measuring computer via an RS-485 (MOD bus) interface (Fig. 7). The sensors themselves were created from electrode structures that correspond to those of the borehole probe, but which can be placed around a drill core.

The laboratory investigation initially focused on evaluating the TDR signals with respect to the moisture distribution inside the component. The long TDR probe was divided over its approx. 1 m length into 8 measuring sections, i.e. 8 individual probes. Thus, the 8 probe segments of the TDR probe give an integral value of the moisture of a depth section of 12.5 cm.

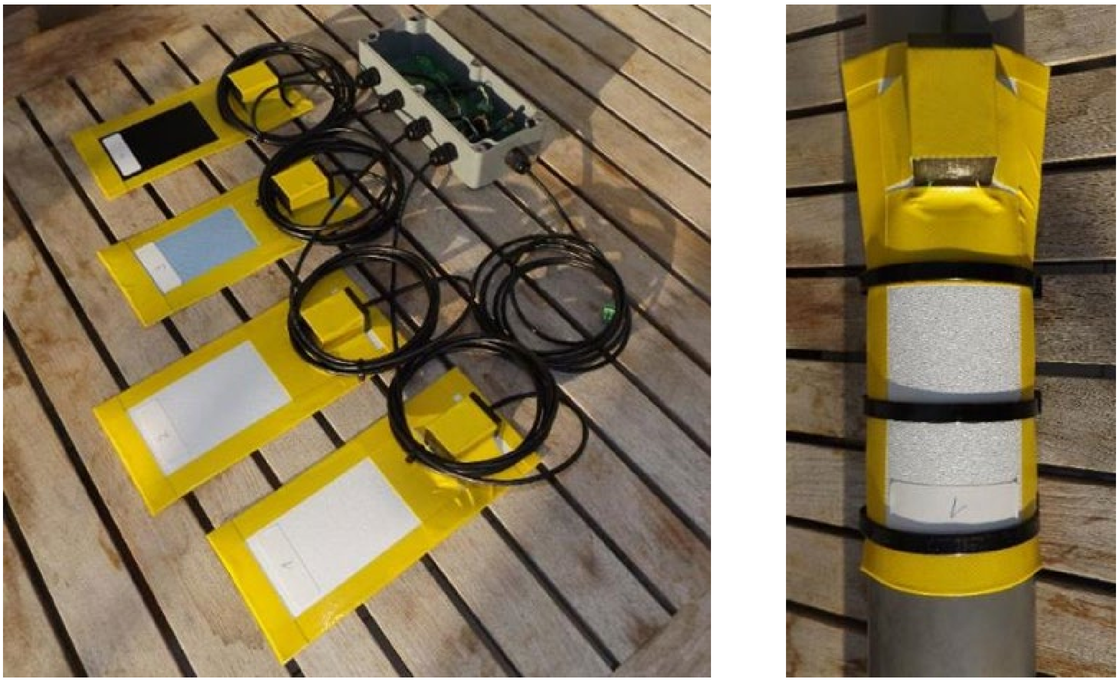

Fig. 7: left: Individual electrodes and measuring electronics of the laboratory measuring system, right: Fixation of the electrodes around a cylinder

Table 1 shows the water contents in mass- or volume-related form of the cores taken from the structure as well as the measured values obtained with the TDR probe during installation. An initial comparison of the gravimetrically determined water contents with the initial values of the TDR signals for the eight segments shows that a direct correlation of water content and TDR signal is not possible without further consideration. For example, the TDR readings show that in areas where gravimetric moisture determination results in values around saturation, the TDR probe does not show the signal value associated with a saturation moisture content.

Therefore, the TDR laboratory measurement system (cf. Fig. 7) was used to measure TDR signals on material samples preconditioned to different moisture contents [4]. Fig. 8, for example, shows the TDR measurement signals for a saturated brick as well as a saturated concrete. The test results show that for both saturated material samples there is a clear correlation between the amplitude of the signal and the moisture content in the measuring range of the probe. A high water content in the measuring range of the TDR probe leads to a smaller signal value than a lower water content, which results in a higher signal value, as evidenced by the two different saturated moisture contents of concrete (uv = 13.06 V.-%) and brick (uv = 21.12 V.-%).

Table 1: Measured values and mass- as well as volume-related water content of the TDR probe sections immediately after installation of the TDR probe in the brickwork

	TDR-Sensor	**Material type**	**Water content u (M.-%)**	**Water content u_V (V.-%)**	**TDR measured value Installation day**
Drill core I	1	Plaster/brick	2.36	4.60	18.300
	2	Brick	1.38	2.70	21.003
	3	Brick	6.80	13.26	22.550
	4	Brick	9.98	19.45	19.526
	5	Brick	9.25	18.04	24.368
	6	Brick	9.68	18.88	22.743
	7	Brick	10.83*	21.12	15.134
	8	Brick	10.83*	21.12	12.888
Drill core II	1	Plaster/brick	3.18	6.21	21.887
	2	Brick	2.43	4.74	22.586
	3	Brick	1.64	3.19	21.138
	4	Brick	3.50	6.82	18.698
	5	Brick	5.16	10.06	15.506
	6	Brick	6.21	12.10	21.706
	7	Brick	10.51	20.49	18.235
	8	Brick	10.83*	21.12	14.795
Drill core III	1	Plaster/concrete	3.39	7.45	21.702
	2	Concrete	3.49	7.68	22.634
	3	Concrete	3.61	7.93	22.639
	4	Concrete	5.37	11.81	21.811
	5	Concrete	5.82	12.81	22.515
	6	Concrete	5.94*	13.06	19.361
	7	Concrete	5.94*	13.06	17.896
	8	Concrete	5.94*	13.06	19.588
Drill core IV	1	Plaster/concrete	5.52	12.15	21.331
	2	Concrete	5.05	11.10	18.848
	3	Concrete	4.82	10.60	19.192
	4	Concrete	5.10	11.21	19.084
	5	Concrete	5.78	12.71	18.084
	6	Concrete	5.03	11.06	21.004
	7	Concrete	5.94*	13.06	19.489
	8	Concrete	5.94*	13.06	19.910

* no laboratory moisture content (only wet drilling possible) - samples soaked through

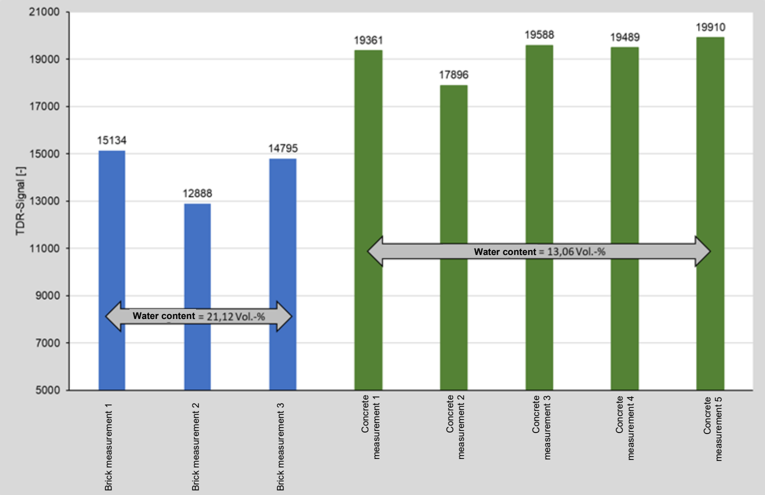

Fig. 8: TDR values at max. water content for a saturated brick and a saturated concrete of specimens taken from the Zeppelin stand

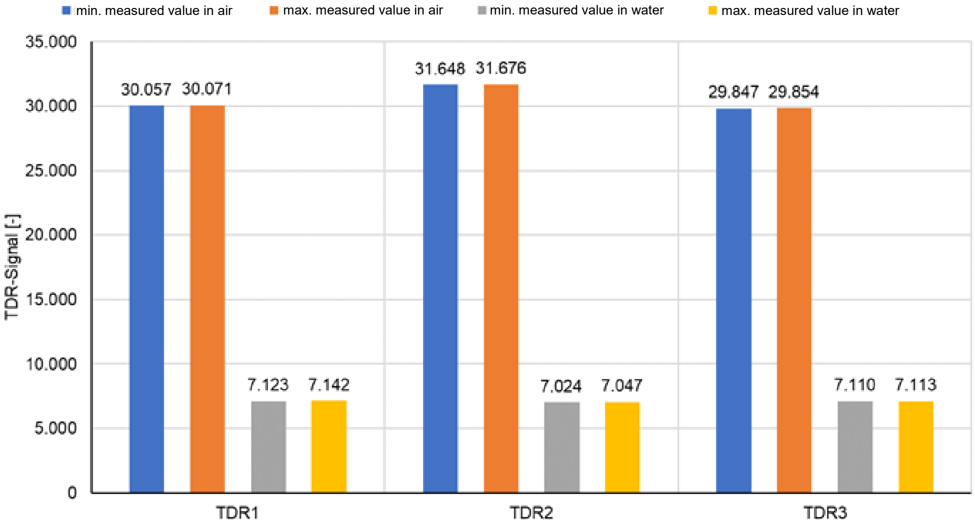

Fig. 9: TDR signal of the laboratory probes during pure storage in air and in water

Consequently, extensive laboratory investigations were carried out to analyze the measurement characteristics of the probes provided by TRUEBNER on the one hand and to determine the TDR measured values on dry and water-saturated sample material and to work out what influence the uniformity of the microstructure and the geometry of the sample has on the measurement signal. For this purpose, the probes were measured in air and under water without interference from sample material. Fig. 9 illustrates the small fluctuation range of the probe surrounded only by air or purely by water.

In order to work out the influence of the sample material, the material samples taken with the drill core sampling were examined with the TDR laboratory probes when stored in air and in water. Fig. 10 shows the results for concrete in a dry environment. Here, a large influence of the sample geometry can be seen, in that drill core pieces whose length is less than the length of the TDR electrode (12 cm) lead to very high measured values. This is also true for samples stored in water.

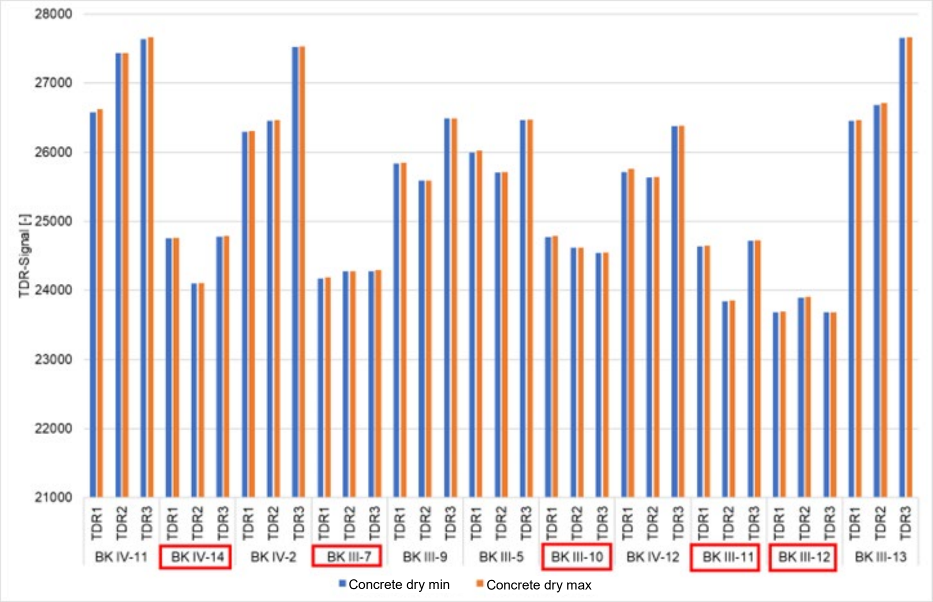

Fig. 10: Minimum and maximum measured values on dried concrete cores for each of the of the 3 TDR probes with individual characteristics

The tests showed the TDR signal values for the dry and water-saturated concrete specimens shown in Table 2.

Table 2: TDR signal values depending on the water content of the tested material samples

Concrete		Brick	
dry (0 M.-%)	water saturated (6 M.-%)	dry (0 M.-%)	water saturated (11 M.-%)
23.600–24800	19.800–23.000	25.300–28.400	18.150–23.800

In order to compare the signal values of the TDR probe for the two limit moisture states of the concrete with the signal values of the use of the TDR probe only in air or only in water, the measuring ranges shown in the table are graphically compared in Fig. 11. For concrete, a difference of only 6 wt.% in material moisture between dry and saturated can be represented by a TDR signal difference of 600 value units.

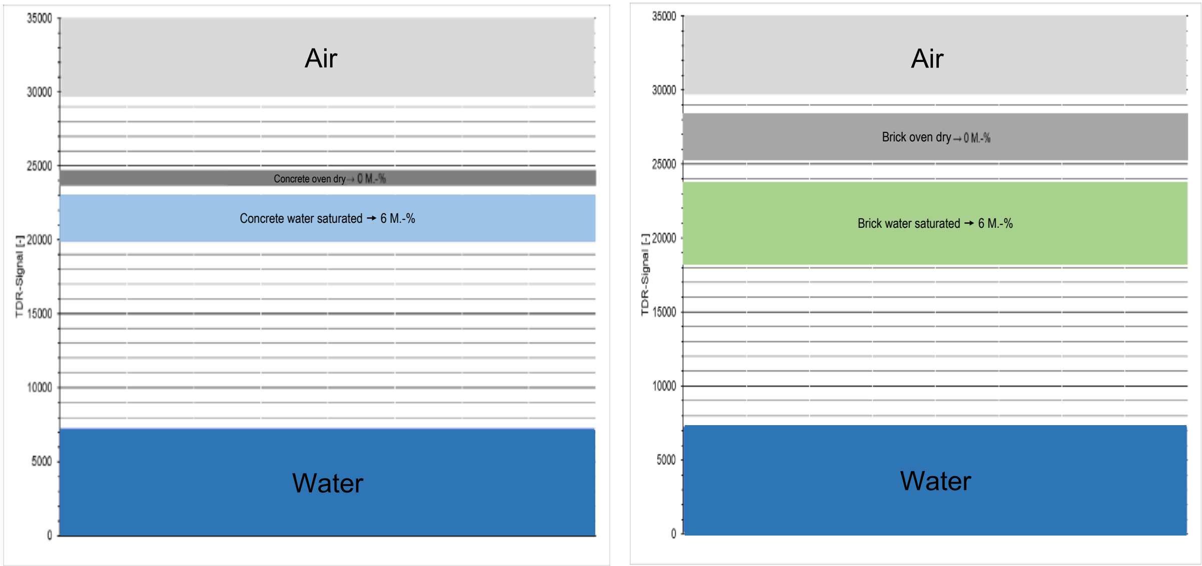

Fig. 11: TDR measurement signals of an oven-dried and water-saturated material in comparison compared to the signal values of probes only in air or in water (left concrete and right brick)

Since a TDR signal difference of 600 can be observed for the saturated concrete (6 wt.%) and a TDR signal difference of 1500 for the brick with 11 wt.%, further investigations and calibration taking into account the materiality must be carried out in order to be able to reliably determine the material moisture contents in the entire hygroscopic to the superhygroscopic moisture range on the basis of the TDR signal values.

It is expected that the TDR signal is influenced by the material, especially in the hygroscopic moisture range, since the capillary condensate that forms in the nanopores of the building materials at higher relative humidities (> 60 % RH) as a result of a reduction in saturation vapor pressure undergoes a different force interaction than free water in accordance with the Van der Waals forces. This effect affects the time response of the TDR signal. Especially for concrete, whose nanostructure is characterized by the gel pores, which remain water-filled as a consequence of hydration without drying at temperatures above 100 °C, such an effect is expected. These investigations are the subject of ongoing master's theses at the University of Stuttgart.

5. MOISTURE ANALYSES USING TDR PROBES ON THE STRUCTURE

Even if a specific material moisture content can in principle be assigned to the TDR signal value, the calibration tests showed that the determination of the probe values for air and water alone is not sufficient to draw a linear relationship between the value for the dry and the saturated material sample. Rather, further laboratory investigations are required in order to be able to take into account the material-specific features of the pore structure that have an influence on the TDR signal. Currently, corresponding investigations are being analyzed in more detail as part of student theses.

However, such a precise material moisture characterization is not necessary for the objective of the DBU project, which is to be able to carry out a targeted uniform drying of the massive building structures of the Zeppelin Tribune. After all, the only purpose of the TDR probes installed on site for the materials processed in the vicinity of the probe (primarily brick masonry on the upper floor and concrete fill on the ground floor) is to record the change in the moisture content of the building components over time in order to ensure uniform and slow drying of the building components through controlled and demand-oriented room ventilation. This relative comparison is easily possible with the TDR measurement method developed within the DBU project.

Thus, in the practical implementation, two measurements are carried out daily with each of the four installed TDR probes. In the following, only selected measurement sequences will be presented and discussed.

Fig. 12, for example, shows the measurement data of the installed TDR probes in the conditioned area, i.e. in the rooms on the upper floor that are ventilated in a controlled manner for optimum drying of the thick masonry. Here, some cores were taken from the brick masonry and TDR probes were installed. Fig. 12 shows the measurements of the TDR probe in position #2. The measuring points connected with straight lines show the TDR signals of the 8 electrode sections. The progressions of the TDR signal values connected in the measurement curves illustrate that the water content in the near-surface areas of the investigated masonry section decreases from September 2017 to March 2018. Consequently, the controlled ventilation of the conditioned rooms on the upper floor leads to the desired drying at least of the masonry areas close to the surface. However, the

TDR signals in the lower masonry areas decrease again in the following months until December 2019 and thus the material moisture prevailing here increases again.

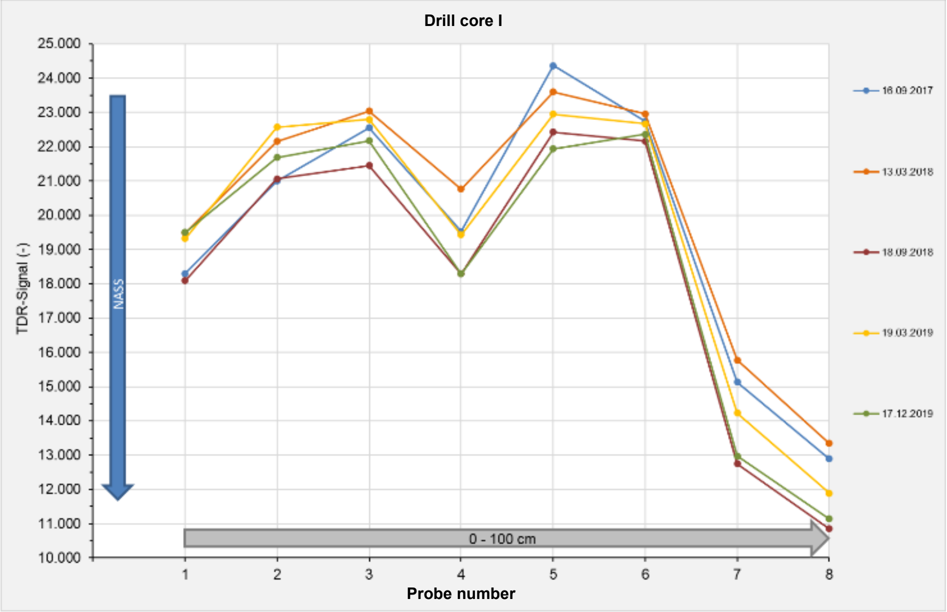

Fig. 12: TDR probe in position #2 (drill core I in the brick masonry of the upper floor). TDR signal values for the 8 probe segments in the period 09/2017 to 12/2019 in the conditioned area of the Zeppelin Tribune

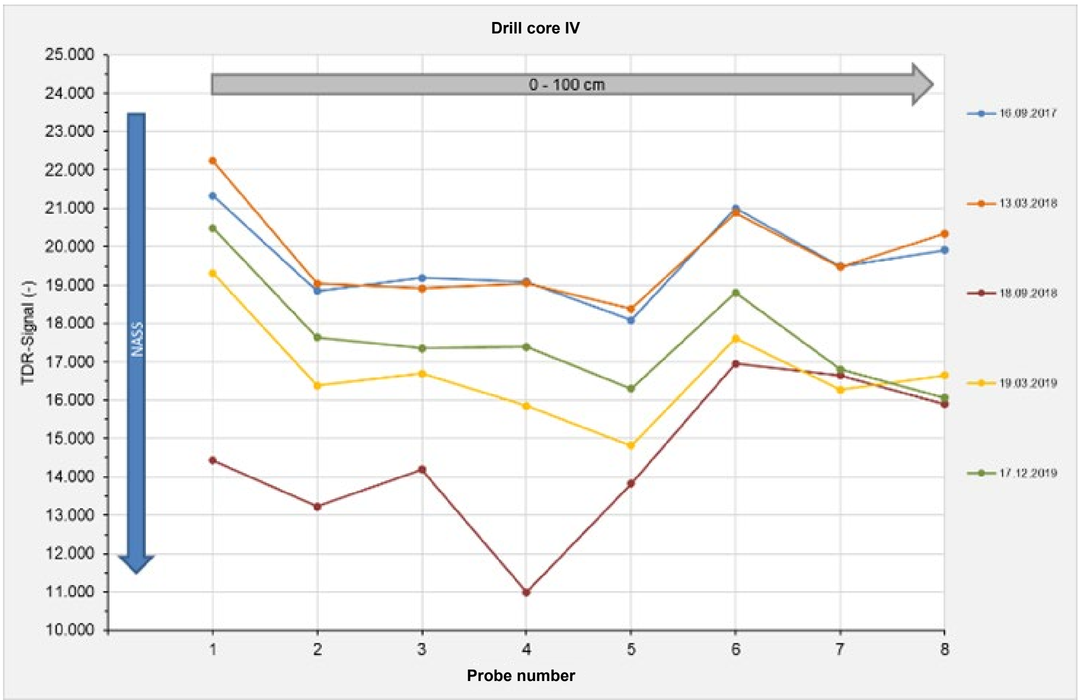

Fig. 13: TDR probe in position #4 (drill core IV in the concrete wall of the EG). TDR signal values for the 8 probe segments in the period 09/2017 to 12/2019 in the non-conditioned area of the Zeppelin Tribune

In the non-conditioned ground floor area, TDR probes were installed in the concrete wall.

Fig. 13 shows the TDR signal curves for drill core IV in the concrete wall of the ground floor. The measurement results for 2018 show an increase in the material moisture content down to a depth of 43 cm. In December 2019, however, the moisture content decreased again in a significant way. Basically, the unconditioned ground floor area shows an overall more favorable, i.e. drier, moisture situation across the component depth at the beginning of the measurements.

In contrast, the TDR signals of the near-surface probe segment show that the concrete edge zone is subject to strong changes depending on the prevailing room air situation, which can be attributed to the striving for sorption-related moisture adjustment.

Basically, the measurement curves of the probes in the brick masonry of the upper floor as well as the probes in the concrete walls on the ground floor, which were installed in both conditioned and unconditioned rooms, showed that with a targeted conditioning of the room, a stabilization of the humidity conditions in the concrete walls on the ground floor, at least the edge zone, can be brought to a stable, drier state in terms of humidity. In the brick masonry of the upper floor, the controlled room ventilation can even achieve uniformly favorable moisture conditions down to deeper masonry areas, depending on the moisture ingress from the stand, so that sufficient drying can be achieved.

The measurement data indicate that in late summer 2018, an increased moisture load and a corresponding increase in the moisture load led. Accordingly, the significant drop in TDR signal values is explained. However, the moisture load subsequently decreased again. Nevertheless, by December 2019, the moisture level observed at the start of measurement could no longer be established in the unconditioned area. Compared to brick masonry, concrete walls require longer drying processes due to the significantly denser structure of concrete.

6. CONCLUSION AND SUMMARY

In the DBU joint project [1], TDR probes were developed for minimally invasive installation in components in the form of masonry or concrete, which make it possible to continuously record TDR signals from all electrodes installed in a probe over longer periods of time and thus gather information about the current moisture distribution in the component cross-section. With the laboratory analyses, a clear correlation between the TDR measurement signal of the electrode and the material moisture could be derived, so that the long-term observation of the moisture distribution in massive wall, floor and ceiling constructions of buildings is possible with the new measurement technology by means of software adapted to the problem.

In the DBU joint project, a concept for controlled room ventilation was developed and implemented by the project partner, the building construction office of the city of Nuremberg, and tested on selected room areas on the ground floor and first floor as part of the project. TRUEBNER developed a TDR measuring system, which consists of a probe with 8 electrode segments and records the measured data of each probe installed in the system via a multiplexer and transfers it to the central data server of the City of Nuremberg. On the part of MOCult, the material-technological building analyses as well as the laboratory tests for the calibration of the TDR electrodes and the TDR probe were carried out. Ongoing research will be done at IWB to work out the influence of pore structural phenomenaof the material on the TDR signal. In addition, an FE simulation model was created with which hygrothermal component analyses could be carried out by calculation in order to be able to determine the temperature and humidity conditions inside the component by calculation, depending on the constantly changing climatic conditions recorded by monitoring. This procedure allows the moisture distributions measured on site with the TDR probes to be compared with the calculation results. The numerical investigations were not discussed in this paper, but they will be presented in a future publication.

Even though each TDR probe electrode has its own characteristics due to its individual geometric shape and electrical coupling to the borehole wall, the DBU joint project was able to prove that the probes developed and installed in the Zeppelin tribune can provide a very good relative comparison of the moisture conditions occurring in the investigated components over time as a result of changing boundary conditions (moisture loads and drying possibilities on the room side). However, the findings of the project to date have been used to optimize the manufacture of the TDR probes for future measurement applications and to develop and optimize methods for the necessary calibration of the TDR probes.

In further development steps, TRUEBNER plans to equip TDR probes with probe segments that differ only slightly from a metrological point of view. Furthermore, in future applications of the TDR probes, the TDR probe segments are to be calibrated in the laboratory on dry and water-saturated materials of the component before they are installed in the component. Such an "initial measurement" would ensure a sufficiently accurate characterization of the TDR probes in the hygroscopic measurement moisture range. Within the scope of further laboratory analyses, IWB will work out the influence of the pore-structural characteristics of the building materials with regard to their sorption characteristics with the TDR probes in order to be able to specifically record the material moisture contents associated with the compensation moisture. Within the scope of the joint project, initial but trend-setting findings were obtained, which are to be expanded in more detail in further investigations.

Using the Zeppelintribüne as an example, it was possible to prove that the conditioning of the rooms by means of controlled room ventilation, as developed and implemented by the building department of the City of Nuremberg, achieves a targeted drying of the wall components on the ground floor (concrete walls) and on the upper floor (brick walls) in a careful manner, thus allowing the future usability of the monument "Zeppelintribüne".

7. ACKNOWLEDGEMENT

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