

ram reports in applied measurement

Experimental determination of the stress in a plaster column dating from the 11th century and listed as a protected historic monument

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Introduction

The use of experimental investigative methods in building and civil engineering, particularly for assessing the safe load-bearing capacity of an existing building material, has received a significant boost in recent years due to the successful conclusion of cooperative research projects EXTRA I and EXTRA II [Lit. 1 and 2]. Experimental methods usefully complement tried and tested computational procedures. The usual computational proof assumes knowledge of a number of important characteristic values which are an absolutely indispensable basis for the computation. The procedure requires knowledge not only of the geometry, the support and the loading, but also of all the essential characteristics of materials and states. In reality, however, cases occur in which at least one of the assumptions for computational proof of safe load-bearing capacity is either unknown or cannot be defined with certainty. An experimental assessment of safe load-bearing capacity on the basis of the actual load state has the advantage that the result includes all states of the materials and components concerned that can affect load-carrying capacity, even when hidden and not revealed by preliminary investigations [Lit. 3].

It is impossible to prove safe load-bearing capacity experimentally unless some important conceptual conditions are met. These include preliminary computations and initial investigations into materials as well as a carefully



Fig. 1: St. Ulrich's church in Rastede

planned investigation programme taking into account the technology to be used and appropriate safety measures [Lit. 4]. Basic prerequisites for practical implementation of the experimental methodology are the availability of an easily controlled mechanism for applying a load, together with online measurement technology that includes a monitor giving an instantaneous graphical display of loading quantities and the reactions of the structure. By no means least, investigations of this kind must be undertaken only by experienced personnel trained in a number of disciplines (civil engineering, measurement technology, data processing).

This paper describes an investigation based on experimental techniques developed in the above-mentioned research projects and on the experience gained from them [Lit. 5]. In view

of the readership of the Reports in Applied Measurement, the paper will lay emphasis on the measurement technology used.

Definition of the task

St. Ulrich's church in Rastede, illustrated in Fig.1, has a history which can be traced all the way back to the 11th century. Beneath the raised choir of this church is a crypt with cross vaulting which is supported on four plaster columns with cubiform capitals. The four columns themselves most probably date back to the 11th century. Whereas the sandstone bases and capitals of the columns are in very good condition, the solid plaster columns themselves exhibit radial longitudinal cracks and in one case an extensive dish-shaped area of spalling. The observed cracks are giving cause for concern about their stability.

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Fig. 2: View of the crypt during preparations for the experiment

A feasible method of testing the stability was to use strain gages to determine experimentally the effective marginal strains occurring at the top and base of a column due to loading and to compare the results with characteristic quantities applicable to the material composing the columns. The view showing the crypt during preparations for the experiment (Fig. 2) gives an impression of the columns.

In practice this experimental method was performed by measuring strain relief, in the course of which hydraulic presses were used to lift the capital of the column being investigated, thereby relieving the load on the column, until the strain measured by strain gages located at each end of the column showed no further changes in strain values. The measurement information gathered in this way could be used in combination with the characteristic quantities determined for materials in preliminary investigations, in order to derive data about the amount and eccentricity of the support load as well as to evaluate existing strain in relation to critical strain limits and reach an opinion about renovation measures that might be necessary.

To minimise cost, only one column was subjected to investigation. The column chosen was the one in the south-west corner of the crypt

shown as column 2 in Fig. 3, which emerged from the preliminary ultra-sound investigations [Lit. 6] as the most severely damaged of the four.

Available characteristic quantities for the material and loads

Characteristic quantities for the material were determined in advance by means of laboratory experiments on samples of new gypsum plaster with a composition which resembled the original material of the columns as closely as possible. This was achieved as shown in Fig. 4 by fitting strain gages to plaster prisms which were then loaded to breaking point with compressive force in a materials testing machine. The characteristic values for the column material determined as above and on which the planning is based are: mean Young's modulus $E = 16900 \text{ N/mm}^2$, lateral coefficient of expansion $\nu = 0.25$, compressive strength $f_{ck} > 18.8 \text{ N/mm}^2$ and breaking strain $\epsilon_{break} \approx 1500 \times 10^{-6}$.

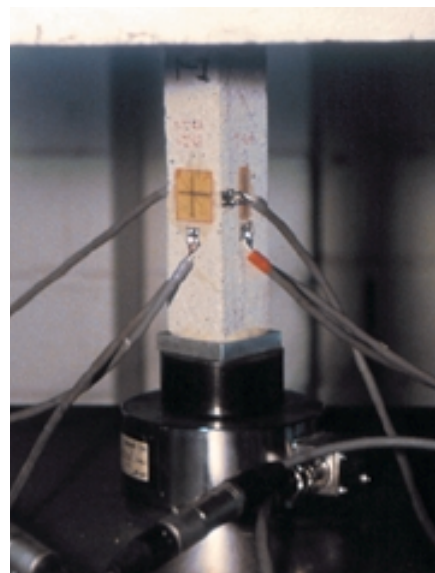


Fig. 4: Determining the characteristic quantities of a material from samples of plaster resembling the material of the columns as closely as possible

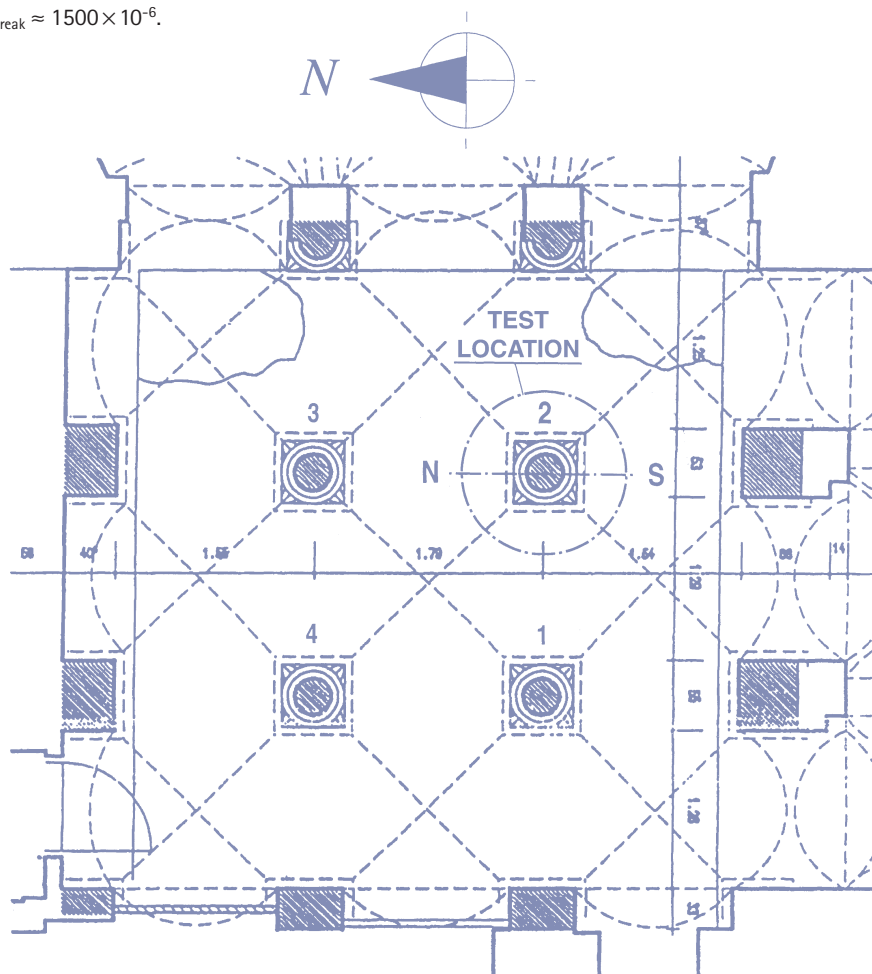


Fig. 3: Ground plan of the crypt showing the location of investigated column 2

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Based on the opinion of a consulting engineer [Lit. 7] derived from the continuous load, the support load for the column under consideration was assumed to be 66.5 kN. Upon adding a component amounting to 16.2 kN resulting from the superimposed load $p = 5.0 \text{ kN/m}^2$ the total load per column came to 82.7 kN.

Estimating the amounts of strain actually present

Prior to carrying out the strain measurement, a calculation was made in order to determine the compression existing in the column due to the applied load derived by calculation. Taking the support load as 66.5 kN and assuming idealised and uniform load distribution over the cross-sectional area $A = 50,300 \text{ mm}^2$ at the top of the column gave column compression $\sigma = 1.32 \text{ N/mm}^2$. On the basis of this compression and the Young's modulus of $16,900 \text{ N/mm}^2$ determined in the laboratory, a strain $\epsilon = 78 \cdot 10^{-6} = 78 \text{ } \mu\text{m/m}$ was to be expected at

the top of the column. This strain generates an electrical signal of 0.039 mV/V (since $2,000 \text{ } \mu\text{m/m} = 1 \text{ mV/V}$).

When installing full bridges, each with two strain gages in the lateral and transverse position per measuring point, the result for $n = 0.25$ is a bridge factor of 2.5 giving an increase in the signal of 2.5 times, which means that the strain of $78 \text{ } \mu\text{m/m}$ at the output from the full bridge generates a signal of 0.098 mV/V . A signal of this magnitude makes it possible to display the measurement results in usable form.

Configuration of the mechanism for applying load

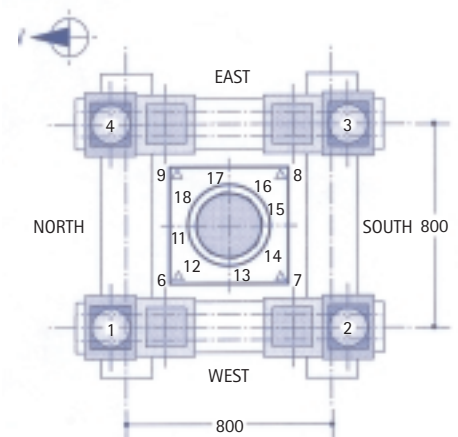
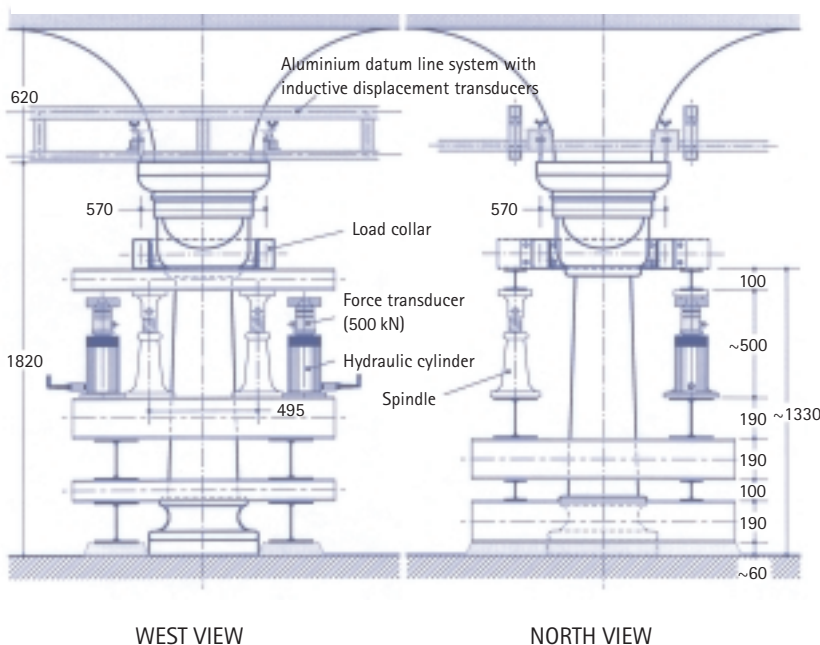
The column was to be relieved of its load by lifting the capital. For this purpose a load conducting collar was manufactured to fit the carefully measured dimensions of the capital. The gap between the collar and the capital was



Fig. 6: The column complete with loading mechanism

packed with cement grout without applying force. As a protective measure and to facilitate removal of the grout after the experiments, the surface of the capital was first covered with a textile membrane.

Fig. 5: Loading mechanism and test point plan



Measuring points:

- Force transducers 1 to 4
- Displacement transducers 6 to 9
- Strain gages 11 to 18 bottom 21 to 28

Fig. 7: Installing the strain gages



7a: Provisional space for preparatory work for installation



7b: Cleaning and pre-tinning the soldering terminals



7c: Installation work at the foot of the column

In order to shore up the downward load, two mortar beds were laid on membranes on the stone floor of the crypt. Steel bearers were placed on these mortar beds to act as a foundation for four hydraulic cylinders which would generate the upward force introduced into the load collar in order to lift the capital (Fig. 6). The force was generated with the aid of hand pumps. Fig. 5 shows plan and front views of the loading mechanism [Lit. 8].

To safeguard the capital from the possibility of a pressure loss in the hydraulic system and during a lengthy period of load relief, four continuously readjustable mechanical spindles were fitted parallel to the hydraulic cylinders to act as supports.

Measuring force and displacement at the loading mechanism

Each of the four hydraulic cylinders was fitted with a type C6 force transducer for nominal force 500 kN. Throughout the experiment the signals from these provided measurement data for the individual and total forces whenever needed.

To check that lifting was uniform, the travel was measured at all four corners of the capital by means of four W5TK inductive displacement

transducers against an independent datum line. This datum line was located clear of the column under investigation, on the masonry alongside. Individual and average displacement values were logged.

The lower part of Fig. 5 shows the positions of the force transducers at 1 to 4, the displacement transducers at 6 to 9, and the strain-gauge test points on the upper end of the column.

Installing the strain gages

Eight full bridge circuits with strain gages (type VY 11 6/120 manufactured by HBM) were installed on the upper and lower edges of the column, distributed uniformly around the circumference. Each of these strain gages held four lattices, two placed in the longitudinal direction and two transversely. These SGs cover a relatively large area and were chosen on account of the poor thermal conductivity of the material composing the measurement object. In preliminary tests using this type of SG on plaster it had been shown that no zero signal drift occurred due to possible internal heat within the strain gauge. Furthermore the full bridge circuit was easy to install in the case of each SG.

During installation the measurement places were optimised in relation to the cracks and surface defects on the column. When the measuring points were attached they had to be offset by 9° counter-clockwise in relation to the compass rose in order to avoid cracks and irregularities. With one exception this enabled the upper and lower measuring points to be located at the same point on the circumference. The centres of the upper measuring points were 40 mm from the upper end of the column and those of the lower measuring points were 60 mm from the lower end of the column. The distance at the upper end was dictated by the installation, whilst a greater distance was necessary at the lower end due to the presence of spalling.

Installing strain gages demands special care and even in unfavourable external circumstances it is essential to create a clean space for preparation work in the immediate surroundings of the measurement place. Fig. 7a shows a view of the improvised work table set up in the crypt when preparing the strain gages for installation. Fig. 7b shows preparations for installing essential soldering terminals by cleaning the contact surfaces with a glass fibre brush and then tinning. Fig. 7c conveys an impression of the uncomfortable installation work at the foot of the column.

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The strain gages and soldering terminals were attached using X 60 methyl acrylate adhesive, since it had been cleared for use on the material in the column following preliminary trials which the client carried out in view of the protected status of the column. The measuring points were protected with AK 22 plasticised mastic. With regard to this mastic covering it should be noted that it could not be permitted to overlap the edge of the adhesive layer in or-

der to prevent it coming into direct contact with the surface of this historic column. Fig. 8a shows measuring points on the upper edge of the column following installation without their mastic covering. In order to relieve the strain on cable connections, cables were attached to the column with the aid of a cord tied around the shaft. Fig. 8b shows the measuring points after they have been carefully masked with AK 22.



Fig. 8a: Measuring points on the upper edge of the column before masking, cord being used to relieve strain on cable connections

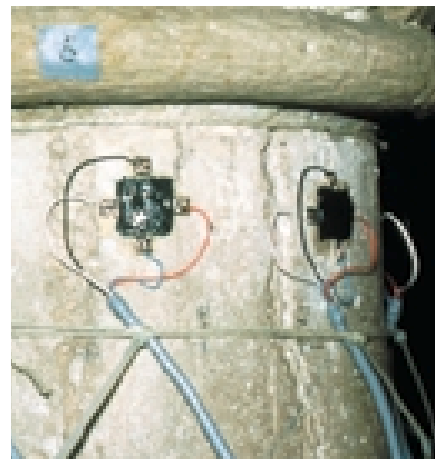


Fig. 8b: Measuring points after masking with AK22

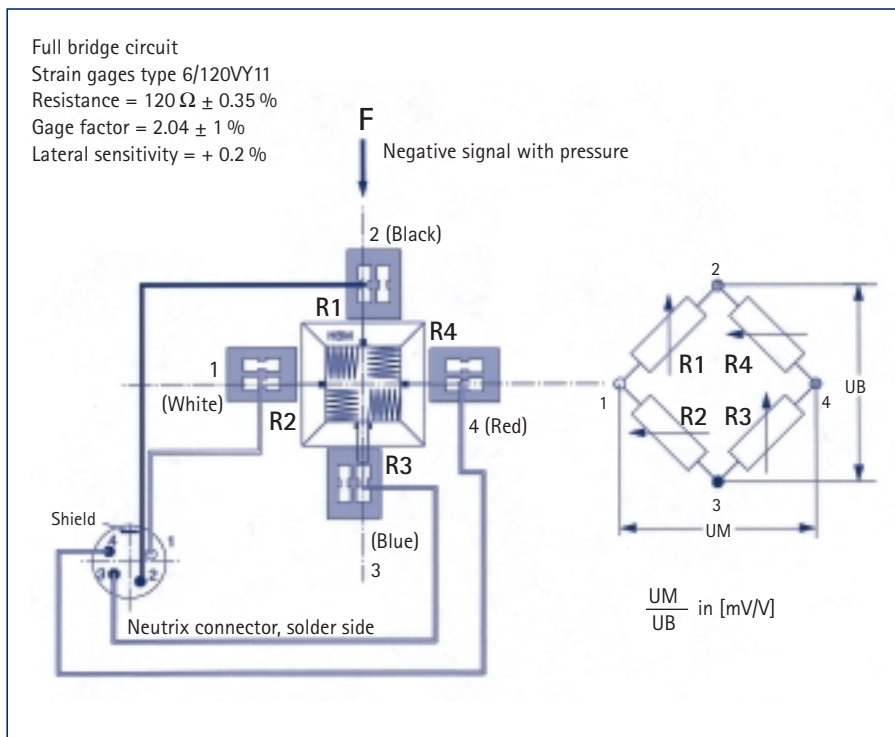


Fig. 9: Connection plan of an SG full bridge

Sensitivity and signal evaluation on installed full bridges

The k-factor of the SG used was $k = 2.04$. This meant that the sensitivity of the full bridge circuit used was increased by a factor of $2.04/2 = 1.02$ (some 2 %). Each measuring point used a 5-metre length of connection cable in four-wire technique with a copper cross-section of 0.14 mm^2 , assigned a sensitivity loss of some 1 % [Lit. 9]. This resulted in a net sensitivity increase of 1 %. This meant that the value established in the investigation programme needed a +1 % correction and from then on the relation between electrical signal and stress was taken as: 0.099 mV/V corresponds to $78 \mu\text{m/m}$.

This value meant that assuming an idealised and uniform load distribution over the column cross-section and using the preliminary calculated value for the column loading of 66.5 kN, a change in signal of 0.099 mV/V at the upper measuring points during lifting would show that the column had been relieved of its load.

Since the load-bearing point sloped, and due to the cracks in the column, uniform load distribution over the column cross-section was not to be expected. As a result, it was likely that the eight upper measuring points would show different changes in strain. Assuming a frictional bond between the column and the capital, the point at which the column was relieved of strain and at which further lifting would subject the column to a tensile loading could not be unambiguously determined from the SG displays. In a fully intact column this point would be reached when the average strain value for all eight measuring points at the upper edge, multiplied by the Young's modulus and related to the upper cross-section of the column, resulted in a calculated loading of 66.5 kN. The stress value would be $78 \mu\text{m/m}$. If no bond capable of transmitting a tensile force existed between the column and the capital, the column would have been relieved of its loading when no further change of strain occurred at the measuring points.



Fig. 10: View of the hand pump for generating pressure; in the background in the field of view of the operator is the monitor displaying measurement data online

Taking an average breaking strain $\epsilon_{\text{break}} \approx 1500 \mu\text{m/m}$, as determined in laboratory experiments on samples of new material, then on the basis of a safety factor of 2.5 the limiting strain for the column works out to $\epsilon_{\text{lim}} = 600 \mu\text{m/m}$.

For the column under consideration, the opinion derived from the ultra-sound investigations, assuming a fully intact zone, defines a residual safe load-bearing cross-section of at least a quarter of the initial cross-section and formulates on this basis a worst-case column pressure of 6.8 N/mm^2 [Lit. 6].

Assuming that the compressive loading on the column is supported by 25 % of the cross-section, and given uniform and constant stress distribution over the remaining cross-section, then a relieving strain of $\epsilon = 4 \times 78 \mu\text{m/m} = 312 \mu\text{m/m}$ would be expected in this area.

Measurement signal acquisition

All measurement signals were acquired online by a UPM 60 multipoint measuring unit and displayed in real time on the screen of the connected PC. With this method the measuring unit is specifically programmed for each measuring point and appropriate calibration values are entered, with the result that measurement data is automatically corrected for bridge fac-

tor, k-factor and cable attenuation, and then displayed in the unit appropriate to the actual measuring point (kN, mm or $\mu\text{m/m}$).

The sequence of investigations

After carrying out a zero balance on all measuring points, upward pressure was applied to the capital in 10 kN stages. Pressure was generated using the hand pump shown in Fig. 10. Measurement data could be observed online on the screen whilst the load was being increased so that application of the load could be halted at once in the event of anything untoward. The measurement results were printed out after each stage in increasing the load.

When the load had been relieved by a total of 69.8 kN a hairline crack appeared between the top of the column and the capital, leading to the conclusion that the load had been removed from the column. Lifting the capital by a further 10 kN brought about no further changes in the strain on the column edges. At a total load of 79.9 kN the column had been definitively relieved of its loading. When this state was reached the spindles were wound all the way up against the load collar at which point they took up the load in full.

Following this, as illustrated in Fig. 11, the STRABAG-Melsungen company made a manual saw cut between the top of the column and the capital in order to create a parallel contact surface between the column and the capital. The flat joint was injected with a plaster grout. A plastic sheet was placed around the column to protect the measuring points during this work at the top of the column. After waiting some 8 hours the load was returned to the column and the strain on the upper and lower parts of the column was logged. The load was transferred from the spindles to the cylinders when the total compressive force was 66.7 kN. This removed the load from the spindles, which

could then be removed. Before the capital was lowered onto the column a zero balance of the whole measurement chain was carried out. The load was then transferred to the column in 10 kN steps.

A review of the individual stages in the investigation sequence together with the associated measurement results is included in the report on the experiment [Lit. 8].

The loading force and displacement affecting the capital

Following a baseline test and zero balance of the measurement unit, the capital was lifted in stages of 10 kN. After eight stages, at a total force of 79.7 kN, the capital had been lifted off the column until a full clearance existed and there was no contact whatsoever. In this state the average vertical displacement amounted to 1.18 mm. The maximum movement was measured as 1.23 mm at measuring point 7 (south-west corner) and the smallest as 1.14 mm at measuring point 9 (north-east corner), although the greatest compressive force was exerted there (20.4 kN). The average vertical displacement of the capital as a function of the total compressive force is reproduced in Fig. 12.

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Fig. 11: Making a saw cut between the upper end of the column and the capital; a plastic sheet protects the measuring points during work at the top of the column

If the average strain on the upper column edge is represented as a function of the total load, as in Fig. 12, it can be seen that from about 64 kN upward there was no further change in the strain. This gives the total load imposed by the vaulting on the column under consideration as 64 kN to a close approximation. This is in close agreement with the value of 66.5 kN which was calculated in advance.

Strains at the top and bottom edges of the column

In general it should be noted that comparing the measured strains with those calculated from the force, cross-sectional surface and Young's modulus is only meaningful if the actual Young's modulus for the measurement object at the measuring point is known. Since the conical column was manufactured by casting,

it can be deduced that the Young's modulus is higher at its narrow upper end, which was the lower end during casting, because the material is denser there than at the wider lower end. This explains the fact that the strain values measured in the upper part with the smaller cross-section are lower on average than those measured in the lower part with the larger cross-section.

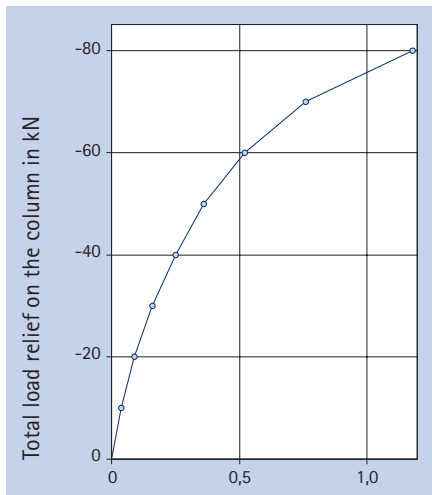


Fig. 12: Average vertical displacement of the capital as a function of the load relief on the column

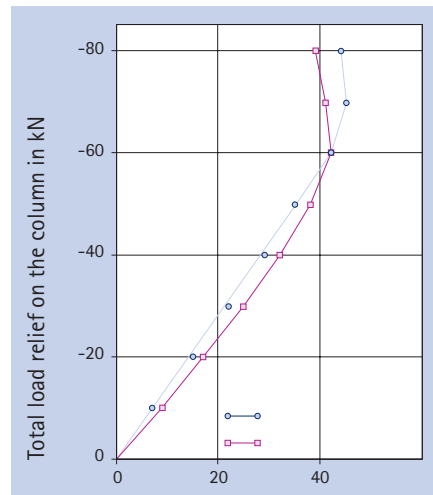


Fig. 13: Average strains at the upper and lower ends of the column as a function of the load relief on the column

Fig. 13 shows the average strain values measured for the load relief procedure at the upper and lower column edges as a function of the total force. The curve is linear until just before the point of load relief is fully reached. If these average strain values and the stress arising from the force per column cross-section are used to calculate the Young's modulus of the column material at the upper end, the calculated value of $E = 28,428 \text{ N/mm}^2$ is significantly higher than the value determined in the preliminary laboratory investigations where $E = 16,900 \text{ N/mm}^2$ on samples of new material. Doing the same for the lower end of the column, the average strain values in the linear section and the larger cross-section give a Young's modulus of $E = 15,181 \text{ N/mm}^2$.

On tracing the changes in the strain at the upper edge during the load relief procedure it can be seen throughout that there is a slight lag in the strains at south-western measuring points 13, 14 and 15 (Fig. 5). This leads to the conclusion that the north-eastern section of the upper end of the column is more heavily laden than its south-western counterpart. This correlates with the great rigidity of the north-eastern corner of the capital as revealed by the displacement measurements.

At the lower end of the column, the measurement results yielded by the load relief procedure do not show this tendency towards skewed load distribution. The strain distribution is indeed non-uniform, which can be

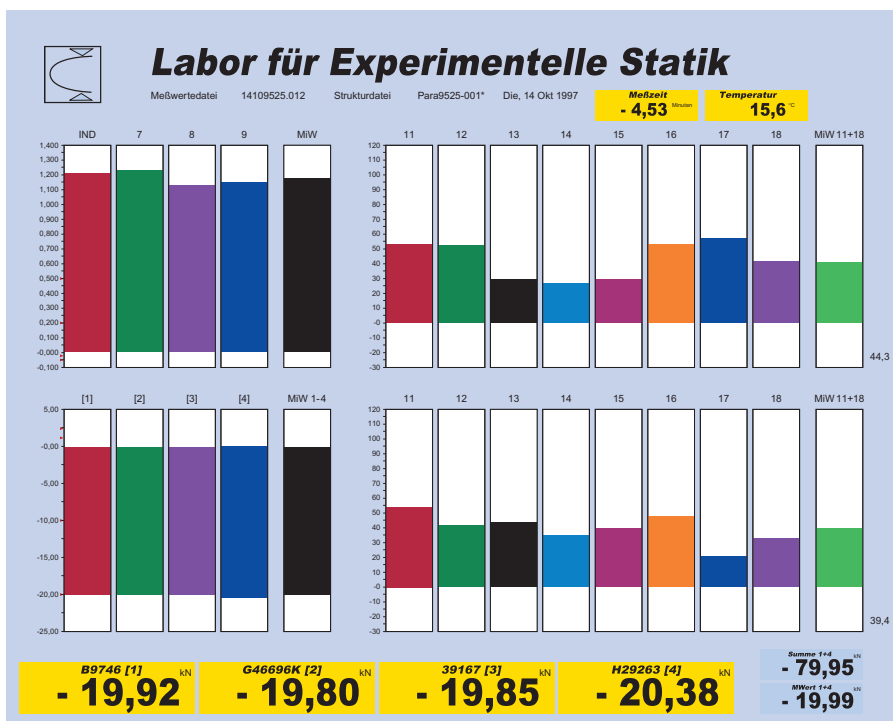


Fig. 14: Monitor screen with online display of the forces, displacements and strains measured at the moment the column was totally relieved of its loading

explained in part by the presence of the cracks and in part by uneven seating of the lower end of the column on its base. It is not beyond the realms of possibility that the lower bearing surface exhibits slight unevenness. A slight "tilting" of the unladen column lends support to this hypothesis.

All the measured strain values are low, however, compared with the final value of 600 $\mu\text{m}/\text{m}$ given as the limiting strain for the column material, a value derived from the average breaking strain determined in laboratory experiments with a safety factor of 2.5 times. The highest single strain value measured (measuring point 17) amounts to some 10 % of this limiting strain.

Measurement results for the strains that occurred during the return of the load to the column exhibit a slightly different pattern compared to the strain distribution during load relief. This suggests that after the pressure grouting of the saw cut, internal sections of the column were more involved in load transmission than before.

Displaying results

The measurement results were displayed online for the entire duration of the investigation. Fig. 14 shows a view of the screen at the moment the column was totally relieved of its loading. The details of the display are as follows: the lower line shows the digital values in kN for the four forces on the hydraulic cylinders together with their total and average values; top left is a bar diagram showing the displacement in mm at the four corner points of the capital and their average value; lower left is a bar diagram of the four forces acting on the hydraulic cylinders and their average value.

At upper and lower right the strains in $\mu\text{m}/\text{m}$ on the eight measuring points at the top of the column and at the foot of the column are displayed along with their respective average values. Finally the top line of the screen shows: the file name, the name of the structure file, the date, time and duration of the investigation, and the temperature in the crypt.

Conclusions

In the course of the load-relieving experiment, the load exerted on the column was determined as <64 kN. The strains measured at the upper and lower ends of the column are well below the value considered to be critical for the material of which the column is composed.

Despite the obvious cracks and skewed position affecting the column investigated, measurement of the present status of loading in the column appears to suggest no acute threat of danger.

The state of the column should therefore be regularly monitored. Changes in the loading status can be recognised from changes in the geometrical proportions, such as further displacement of the column foundation or a change in the skew affecting the column.

On these grounds it is recommended that the position of the column (height, skew, distance from the neighbouring columns and outer walls) should be accurately measured and checked periodically. The same approach is recommended with regard to the future progression of the cracks (number, length, width).

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the die cover as well as to the measuring pins in the drill holes. This type of installation proved to be robust and durable even under typical forging conditions (heat, dirt, dynamic loading).

The test die after an impact

Fig. 2 shows the die fitted in the hammer immediately after a forging stroke. It is impossible to fasten the wires with clips since the fastenings break after a few impacts on account of the high acceleration at the die (higher than 20000 m/s², Fig. 3).

Signal conditioning of all 39 SG channels was carried out in parallel over DC measurement bridges (DMCplus from HBM) up to a bandwidth of 4.8 kHz. Measurement time amounted to 100 ms per stroke, when the last two strokes of a series were recorded.

At the end of the series of impacts the deformation resulting from contact between the impact surfaces is close to that for die against die (duration of die-to-die impact approx. 2 ms). Fig. 4 shows the strain signal from a measuring pin in the impact surface. This signal can be used as input for the FE computation.

The other plots in Fig. 4 show the response signal, measured at the die cover in the direction of impact (axial), on two SGs attached at different heights. This signal can be used to adjust the FE model. Fig. 5 shows the stress distribution calculated with the aid of the measured force trends at the instant when the greatest reference stress according to Von Mises occurred. The greatest stresses occur in the radius of curvature of the die joint.

In addition to the strain measurements, acceleration was measured at the rammer and at the hammer frame. Rammer speeds prior to striking the die were measured with the aid of a dynamically modified cable displacement

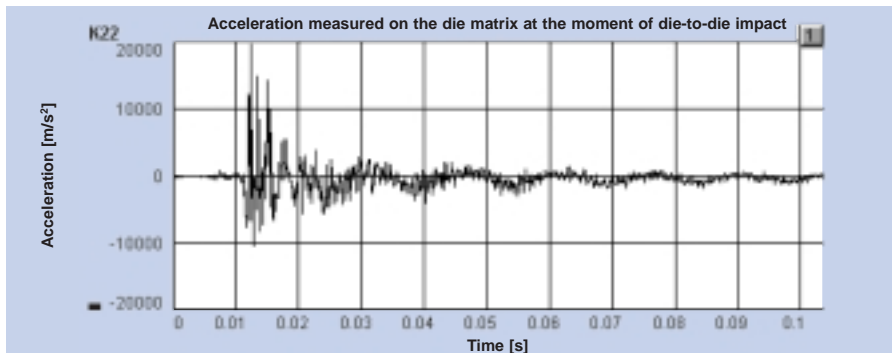


Fig. 3: Acceleration at the test die as a function of time

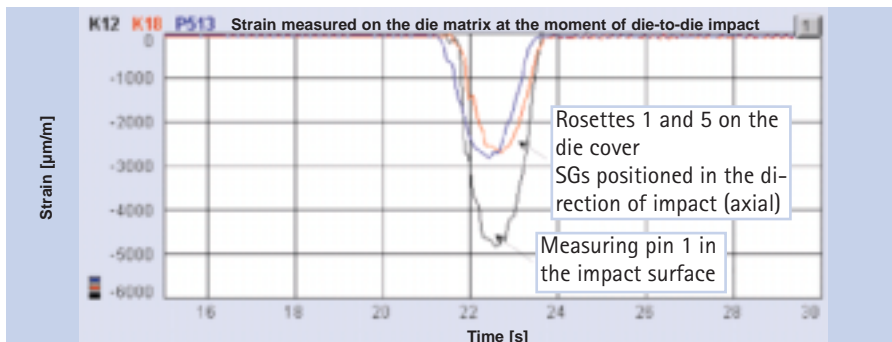


Fig. 4: Strain at the test die as a function of time

transducer. Comparisons with rammer speed measurements carried out in parallel using an optical correlation measurement system [Lit. 2] gave close agreement.

These experiments form part of a project sponsored by the AIF (Association of German Industrial Research Organisations) known as "Dynamic Loading and Design of Hammer Dies" (AIF 11171B).

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Fig. 2 The test die after an impact

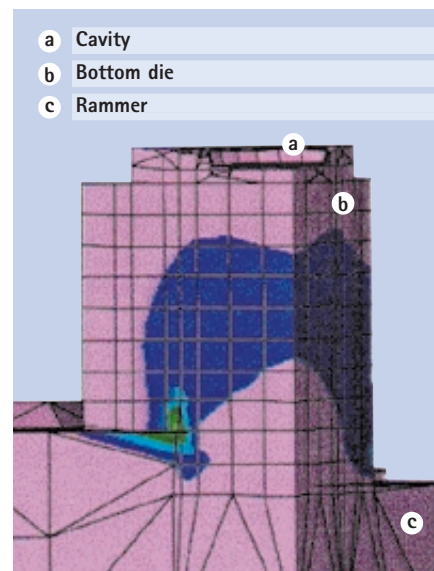


Fig. 5: Stress distribution at the bottom die and bottom rammer (quarter model, section)