

# Determination of load-bearing capacity on the roof arches of the Bremen Ratskeller

by Walter Ropers and Klaus Steffens

Substantial sections of the basement facilities of Bremen town hall are situated underneath public traffic areas. In order to be able to allow occasional entry of this overlying pedestrian zone to fire-fighting and delivery vehicles, large parts of the basement vault were reinforced. This was not possible in some sections due to the lack of available height and local conditions were not suitable for computerized safety calculations. Therefore fail-safe loading equipment and modern on-line measurement techniques were used to experimentally determine the load-bearing capacity. The load was measured with a force transducer and the deformation of the arches with inductive displacement transducers. A multipoint measuring system, coupled to a computer, was used to process the transducer signals.

The Ratskeller (lit. *townhall basement*) in Bremen is a famous basement area underneath the town hall and a large part of it extends under public traffic surfaces outside of the town hall. For example, the Bacchuskeller - the remains of the Bremen stock exchange which was destroyed by fire in 1888 - is situated under the paved Liebfrauenkirchhof. This area is connected with the historical Ratskeller by an irregularly arched connecting wing. Figure 1 shows part of the plan of the Bremen Ratskeller. The edged area is located outside of the town hall under the paved traffic surfaces.

Due to damage caused by damp conditions, the ceilings and walls in the basement area underneath the Liebfrauenkirchhof were resealed. On opening up the ceilings during the work doubts were raised regarding the load-bearing capacity of the ceiling structure. The ceilings of the Bacchuskeller and the restaurant rooms were therefore structurally reassessed and partially reinforced. In the region of the connecting wing between the Bacchuskeller and the town hall reinforcement of the ceiling was not possible due to the lack of

overlying ground. **Figure 2** shows the refurbished vault construction in which the lightly reinforced-steel concrete slabs only provide a protective, load-distributing layer.

The total roof area is a pedestrian zone and designed for an evenly distributed traffic load of  $p = 5.0 \text{ kN/m}^2$  ( $105 \text{ lbf/ft}^2$ ). In order to enable occasional use by fire-fighting and delivery vehicles up to a total mass of 16 t (15.75 tons), proof of stability was required under vehicle loading conditions. An analytical investigation would have been unsuitable, because all the important variables were unknown:

- material properties, dimensions and the quality of workmanship in the vault walls varied significantly and could not be determined without substantial effort,
- the boundary conditions could not be stated with sufficient reliability, because there were no accurate cross-sectional drawings available,
- with the irregular geometry in all coordinates a simple static system could not be derived and a solution in three-dimensional finite elements would have been very complex.

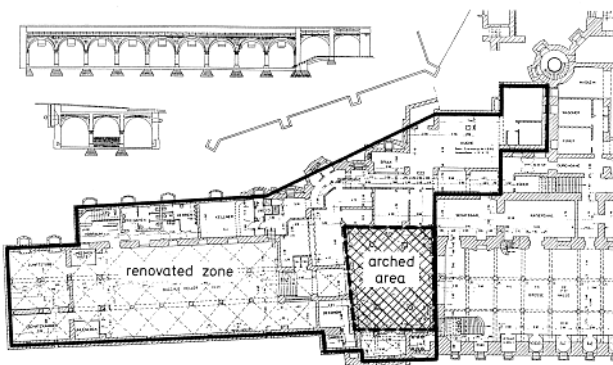


Fig. 1: Sectional outline of the Bremen Ratskeller. The edged area lies outside of the town hall underneath public traffic areas

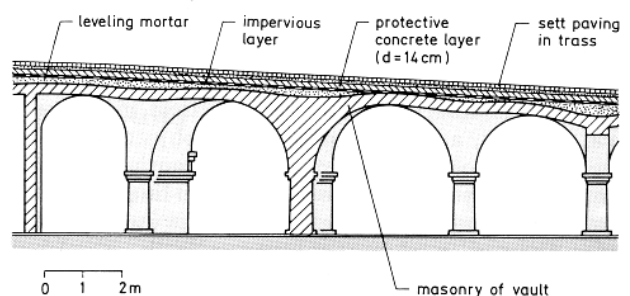
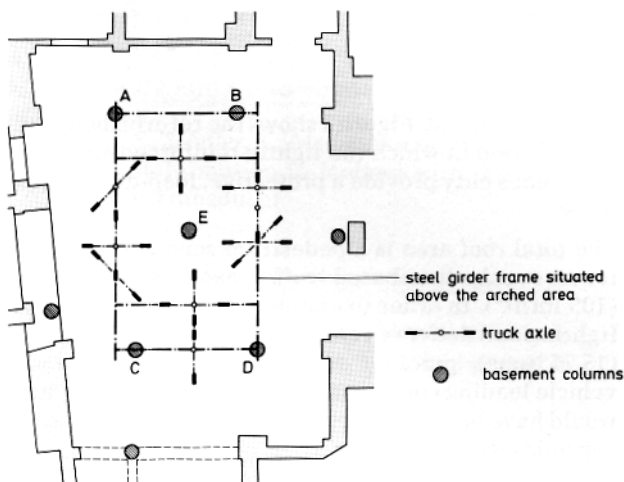


Fig. 2: Roof construction of the renovated basement arches

## Experimental principles

In this case an experimental method of proving stability seemed appropriate and the authors of this article were given the task of planning, implementing and supervising the tests. The experimental investigation on the actual structure or building has a distinct advantage over the analytical method in that principally a large number of unknown factors are bypassed. Therefore with a reduction in the safety margins (but not the safety! ) for the remaining unknown quantities which arise due to the applied loads, the material characteristics and the computational model, substantial reserves of strength can be explored.

In experimental strength determinations the component's own weight also has a tangible effect, which can be obtained even if deviations from the designed construction occur. The unknown quantities of the external loads, i.e. the applied loads, are the same as with



**Fig. 3: Plan for the experimental determination of stability for the arches, showing the position of the loads which simulate a rear truck axle**

the analytical method. Also material defects of a general nature can be detected by the experimental method and faults in construction, even when hidden, also become apparent. Unknowns which are produced by changes in the material characteristics, e.g. by continual loading or corrosion, are the same as in the analytical method.

A further advantage of the experimental method is that the forming of a physical model, which may be quite unreliable, together with a practical, mathematical solution, are not required. The object under investigation solves its descriptive differential equation, including physical and geometrical non-linearities and boundary conditions, completely on its own! In addition, the statistical uncertainty can be directly determined from the number of samples and the distribution of the results. With proper application of modern measurement methods the uncertainty in the readings is only slight and can usually be neglected.

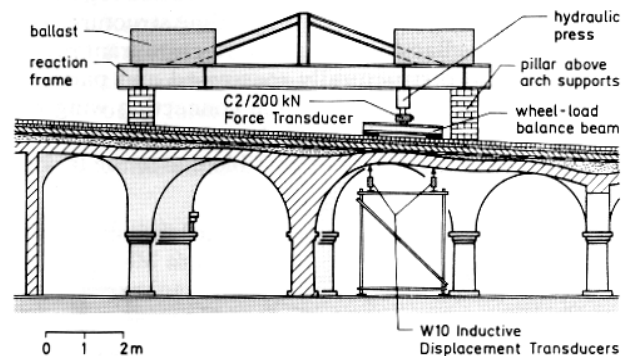
Based on the differentiable known and unknown quantities, the test load can be found according to German regulations [1] for the determination of safety requirements in structural systems, taking into account the safety aspects of materials and methods. With regard to safety, partial safety coefficients were assumed which include the effects of random deviations from the characteristic values.

## Loads used during the test

In this case study of the occasional entry of a fireengine or delivery vehicle onto the roof area under investigation, the actual applied load could be represented accurately enough by a vehicle with two axles. For the existing distribution of the arches and their load-bearing properties the simulation of the heavier rear axle of a truck was sufficient. This load was set at  $F = 150$  kN (33,750 lbf) which included the partial safety coefficients for the experimental determination of stability. The loading locations and the corresponding direction of the vehicle's axle was selected such that the weakest points of the arches could be almost fully loaded. A plan of the loads applied in the tests is given in Fig. 3.

## Test arrangement

In the test arrangement a method of loading was selected that was inherently safe. With a larger deformation of the loaded arches, i.e. the beginning of failure, the test load would automatically decrease. Also, in order to avoid taking up too much room in the basement and to minimize the effect on the restaurant facilities, the measurement rig and test time were reduced as much as possible. The steep, evenly sloped road surface was also taken into consideration.

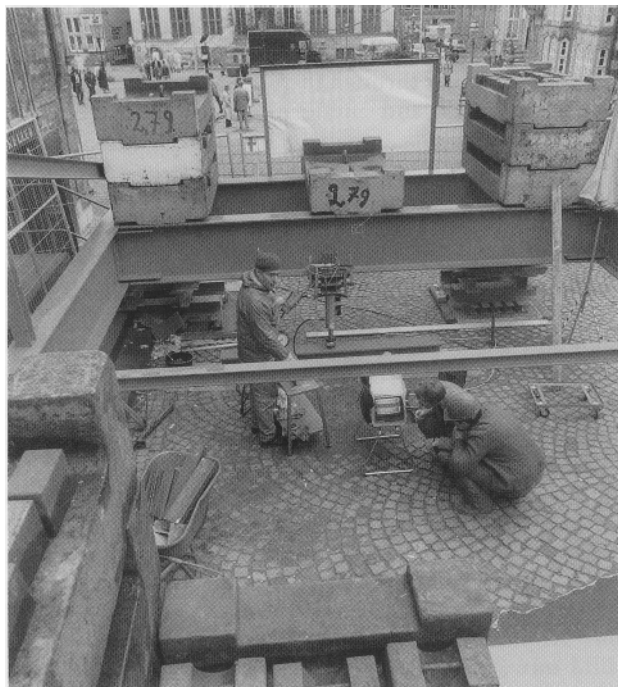


**Fig. 4: Diagram showing the inherently safe test loading equipment**

For these reasons a horizontal framework of steel girders was erected on the road surface at about 1 m (3.28 ft) height to transfer loads through four pillars of cross-stacked beams directly into the arch supports A, B, C and D. The positions of the supports can be seen in Fig. 3. The frame was preloaded with weights to a total mass of 36 t (35.4 tons). A hydraulic cylinder was ap-

plied between the frame and the road surface. Under the action of oil pressure this cylinder pressed against the frame downwards onto the arched roof. The load transfer into the roof was carried out using a balance beam supported by two footplates, the dimensions of which corresponded to the contact area of a truck tire, thus simulating the burden of a truck's rear axle. The test rig is shown diagrammatically in Fig. 4. Figure 5 shows a view of the loading arrangement.

On account of the extraordinarily difficult nature of the problem presented by the rigidity of the arches, the risk of larger cracks occurring during measurements in the region of the arches' maximum test load had to be eliminated. The start of any failure would be reliably detected using a modern on-line measurement system, thus preventing any damage. In order to minimize hysteresis of the burden when carrying out the test, the stacks of beams were set in mortar and preloaded; the main girders were also preloaded at a supporting width of 8 m (26.25 ft).

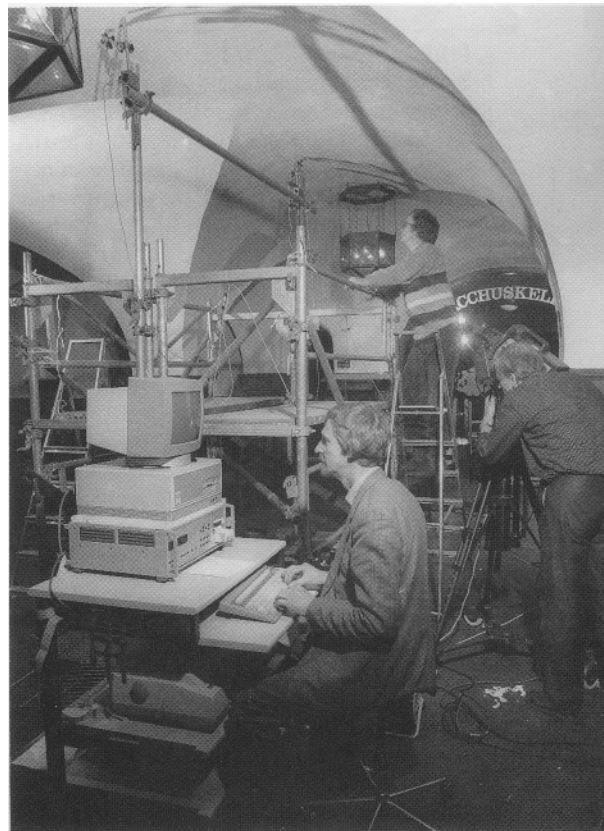


**Fig. 5: View of loading equipment consisting of the reaction frame, hydraulic cylinder, HBM-C2/200 kN Force Transducer and balance beam for the wheel load**

The load transferred to the arched roof was measured with an HBM-C2/200 kN (4500 lbf) Force Transducer, which was located between the head of the piston bar on the hydraulic cylinder and the balance beam providing the load transfer. The arch displacements in the vertical direction were measured from below with HBM-WT 10 Inductive Displacement Transducers. These displacement transducers were fixed to a steel scaffold structure which was situated in the basement and which also provided the measurement base. Figure 6 shows the scaffolding with the displacement transducers under the arched ceiling, together with the measurement and evaluation equipment.

The measuring points for the displacement transducers were re-positioned by traversing the measurement base in the basement according to the position of the load transfer on the road surface.

The signals from the force measurement and the deformation measurements were passed to a computer-controlled HBM-UPM 60 Multipoint Measuring Unit that was coupled to an Olivetti M 24 PC. The processing of the measurement data was carried out on-line by this computer. The results were shown graphically on the



**Fig. 6: View of the scaffold structure under the arches, showing the displacement transducers and the measurement and evaluation system**

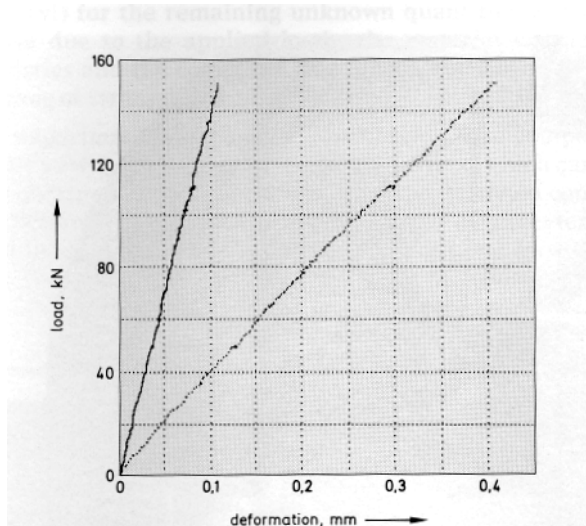
monitor as load-deformation curves or column diagrams and could be recorded on a plotter as hard copy. The measurement and evaluation equipment used can be seen in Fig. 6, showing from top to bottom, the monitor, Olivetti M 24 PC, HBM-UPM 60 Multipoint Measuring Unit, keyboard and plotter.

## Test results

Depending on the position of the load the deformation characteristics of the arches were measured with two inductive displacement transducers beneath the ceiling. The deformation measurements were taken as a check on the static characteristics of the arches, rather than for determination of the absolute bending values. In all cases an almost linear characteristic was

found from the start of loading through to the application of the final load. The maximum deformation was 0.5 mm (20 mils). After relief of the load the deformation returned approximately to zero. The maximum permanent deformation was 0.05 mm (2 mils). It can therefore be deduced that the arches behave almost elastically under the applied load. **Figure 7** shows typical force-deformation curves as they appeared on the monitor during the gradual increase in load.

- Regular entry onto the arched roof area by trucks cannot be permitted due to the lack of investigatory results regarding long-term stability and because the vibration characteristics have not been considered.



**Fig. 7:** Typical force-deformation curves as they appeared on the monitor during the loading tests

Monitoring of the linear shape of the force-deformation curves during the test was necessary in order to avoid damage to the arches by the test load. Since the design of the loading system was inherently safe, any deviation of the curve from a linear characteristic would have resulted in the immediate relief of the arched structure.

From the results of a total of 18 measurements it could be generally stated that the load-bearing capacity lay clearly above the maximum test load of 150 kN (33,750 lbf). However, no statement could be made regarding the actual reserves in the load-bearing capacity. In order to cover the uncertainty of this sample type of test loading, it was recommended that the maximum test load was made equal to the calculated load-bearing capacity.

The determination of load-bearing capacity is based on once-only, short-term loads (quasi-static). From these results and taking into account safety calculations during the determination of the load used for the test (see above), the following conclusions could be drawn:

- An evenly distributed traffic load of  $p = 5 \text{ kN/m}^2$  (105 lbf/ft<sup>2</sup>) is generally acceptable even in the most unfavorable point of loading.
- Entry into the arched roof area under investigation by a truck conforming to the German standard DIN 1072, bridge loading class 16/16, can be permitted in exceptional cases.

## Summary

A substantial part of the Bremen Ratskeller lies underneath public traffic areas outside of the historical town hall. Occasional entry to this pedestrian zone by trucks (fire-brigade, supply vehicles, "strays") could only be prevented by closing off the area in question and this was not acceptable to the town planning authorities. Therefore, during renovation work the opportunity was taken of reinforcing the basement arched area. Due to the low height this was not possible in some parts. Also it was not possible to provide calculated proof of stability due to the complex local conditions. For this reason an experimental determination of load-bearing capacity was undertaken, which led to successful results through the use of an inherently safe loading system and modern on-line measurement methods.

Adequate load-bearing capacity was found for occasional truck traffic at thirteen load points within an arched roof area of about 150m<sup>2</sup> (1614 ft<sup>2</sup>). The measurements took place during two working days without causing any structural damage. The costs of this investigation were only a fraction of the costs that would have been incurred for improving the structure's static characteristics. The result corresponds to the results of measurements on other structures [2] which have been carried out with the mobile measurement facility of the Laboratory for Experimental Statics at Bremen University.

## References

- [1] DIN Deutsches Institut für Normen e.V.: "Grundlagen zur Festlegung von Sicherheitsanforderungen für bauliche Anlagen." 1981 edition; Beuth Verlag GmbH Berlin
- [2] Steffens, K. (publisher): "Experimentelle Traglastermittlung an Bauwerken - Grundlagen, Technik, Anwendungen"; Abridged versions of 10 papers by the authors; Series of publications from the Faculty of Civil Engineering at Bremen University, private publisher, Bremen 1988

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