Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Construction and Structural Behaviour of Lead Joints in Gothic Stone Structures

Rainer Barthel and Matthias Beckh
Technische Universität München, Faculty of architecture, Department of structural design, Munich, Germany

ABSTRACT: Lead was a frequently used material for the design of load bearing connections in historic stone structures. In many Gothic churches lead was employed to connect stone elements in ribbed vaults or tracery windows, particularly in places of high compressive stresses.

Although the traditional techniques of crafting lead joints are described by a few authors, very little is known yet about its structural behaviour. In the first part the authors discuss the application of lead joints, considering as example the restoration of a late Gothic hall church in Southern Germany. In the second part some preliminary testing results of sandstone elements with lead joints are presented.

1 HISTORY AND WORKMANSHIP OF LEAD JOINTS

Lead became particularly important in Gothic architecture to connect slender stone elements in vaults or tracery windows. Prominent examples are the cathedrals of Strasbourg and Cologne, among many others. Particularly in weathered structural components like stone bars of tracery windows lead joints are advantageous. Unlike mortar joints, they are quite durable and able to carry the load immediately after they have cooled down. In the case of tracery windows, the vertical stone bars are typically connected with pins made of wrought iron, which are afterwards encased with liquid lead and thus protected from corrosion.

Arnold Wolff, the former master builder of Cologne cathedral, describes the technical process of crafting this kind of joint in detail (Wolff 1989). Radial flutes or grooves, originating from the centre of area, are cut into the faces of the stone bars at the joint. The grooves not only facilitate the quick spreading of the lead, but also prevent differential rotation of the stone bars afterwards. The lead is brought into the joint through an inclined channel, which is drilled into the upper stone element. Small pieces of wood or lead are usually used as distance keepers. For the casting procedure the joint is sealed along its edges with a temporary collar of clay. As casting material thin fluid lead is used, sometimes with additional wax or tallow as a fluxing agent. The thickness of the joint typically varies between 3 and 6mm. Fig. 1 shows an open lead joint between the vertical stone bars of a tracery window, displaying the positive imprint of the grooves.

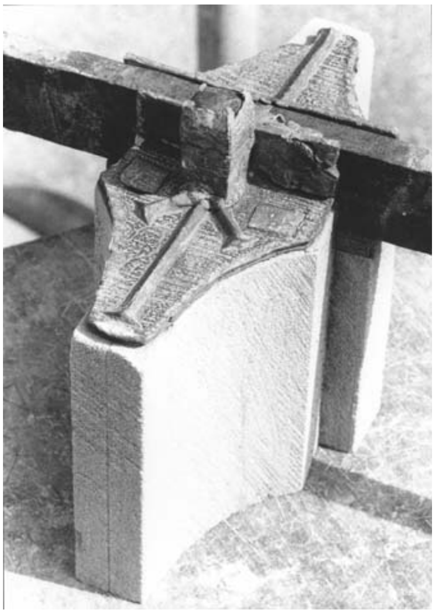

Figure 1: Mock-up of lead joint with horizontal wrought iron tie by M. Scherbaum, Nördlingen. The positive imprint of the grooves, distance keepers and iron pin are clearly visible

2 USE OF LEAD JOINTS AT THE EXAMPLE OF ST. GEORG IN NÖRDLINGEN

Within the last two years, the restoration of the late Gothic hall church of St. Georg in Nördlingen, Southern Germany, yielded vital insights. The assessment of the structural fabric unveiled that many of the stone connections had been carried out with lead. At various locations of high stresses, the master builder had wittingly favoured lead joints over mortar joints, disclosing an acute understanding of structural demands. In the following, two examples of lead joints within this church will be outlined.

2.1 The reticulated gallery vault

The reticulated vault above the Western entrance of the church was examined and analyzed to assess its capacity for additional loading. The sophisticated rib pattern showed some local damages at its Western edge, where diverging abutments had lowered the arch by about 5cm, causing the opening of some joints and local spalling of the sandstone bars. (See Fig. 2).

Figure 2 : Deformed arch of the gallery vault with the resulting thrust line. Seen from below, looking West

For restoration, the arch was lifted up by hydraulic jacks in its original position. During this process, the joints opened and missing stone parts were carefully inserted. The joints were then closed with “leaden wool”. (See Fig.s 3 and 4).

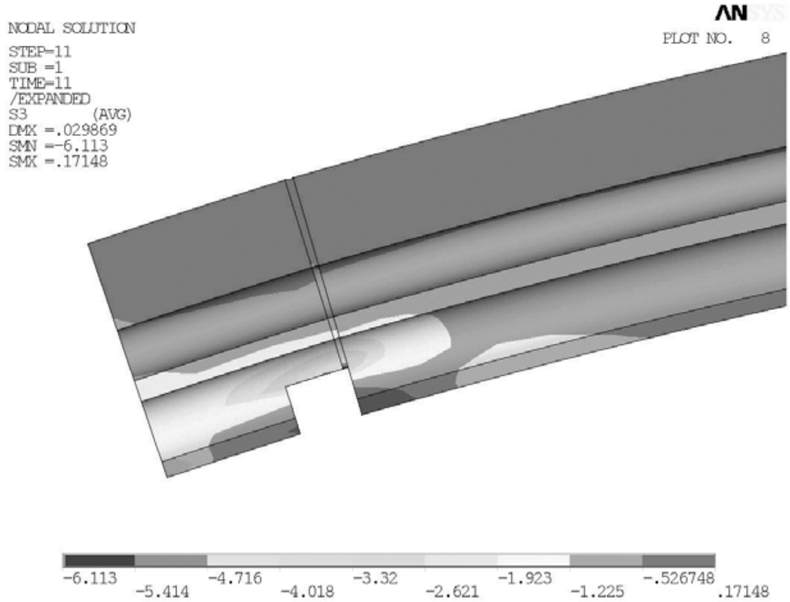

Figure 3 : ANSYS FEM model, detail at Southern support, showing principal compression stresses

Figure 4 : repaired historic lead joint in a reticulated vault. Here, the lead stops before the lower fillet to prevent excessive edge pressure.

2.2 The tracery window at the choir

The understanding of lead joints became particularly crucial in the examination and restoration of the large tracery window at the choir, made of very slender stone bars connected with lead joints. The window is 12.30 m tall and 3.70 m wide. The materials of the structure consist of stone elements made of local sandstone and horizontal wrought iron ties (See Fig. 5). The structure can be divided into four areas: The vertical stone bars below the horizontal beam, the ones above, the horizontal beam itself and the tracery.

Figure 5 : Main tracery window of St. Georg with scaffolding

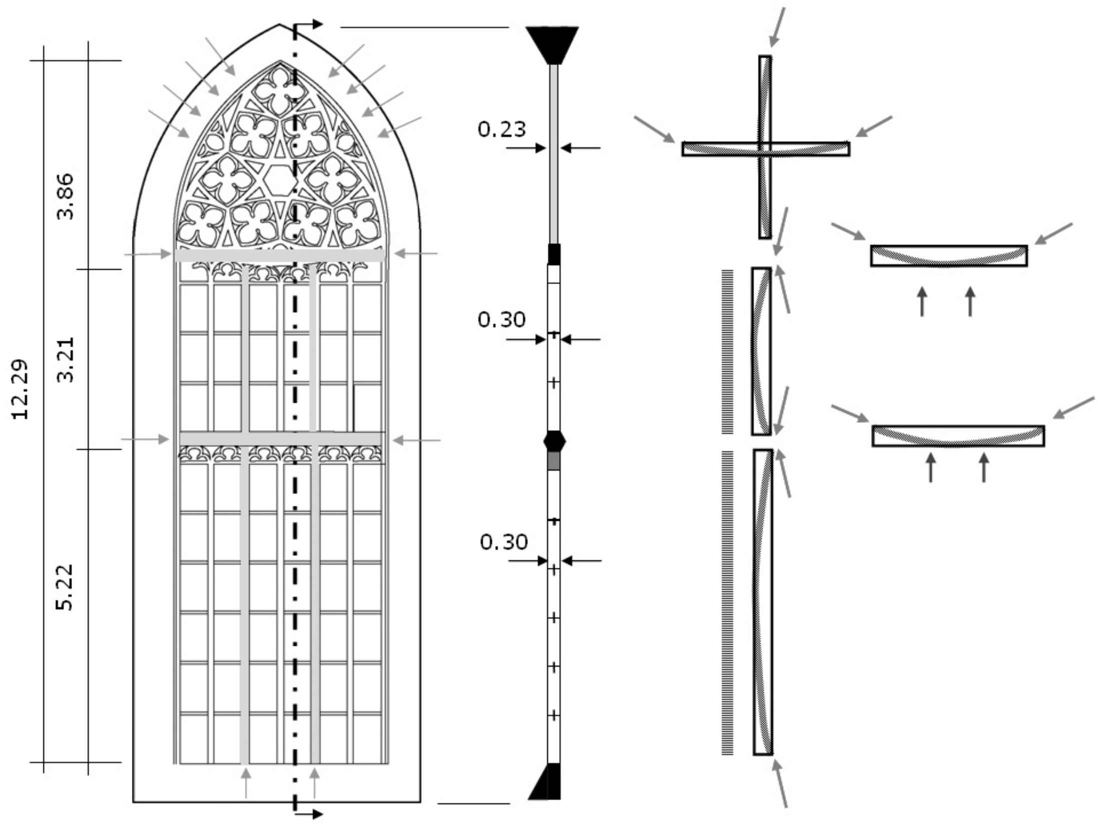

Figure 6 : Diagrammatic load bearing behaviour under horizontal wind load

The vertical stone bars are between 87 and 89 cm tall and spliced at every horizontal tie rod. The rods are evenly inserted into the lower and upper stone bar. The joints of the vertical bars are leaded, yet crafted without an iron pin. The stone elements of the tracery are much larger, sometimes measuring more than two meters. At the tracery, which is separated from the vertical bars by a “hanging arch”, the joints are leaded as well and secured with an iron pin.

Because of severe cracks in the choir walls next to the tracery window and damages of various parts of the window, the structure of the window was documented and analyzed in 2002. A closer structural examination came to the following conclusion: The horizontal shear of the main naves vaults in combination with a deficient roof structure had pushed the upper wall portions outwards and caused a gradual inclination of the walls of the choir. At the abutments of the pointed arch, the horizontal thrust had widened the width of the window by 50 mm. At the same time, the top of the arch had lowered by 20 mm. The pointed arch had developed the typical hinges that indicate diverging abutments. The imposed deformations had caused an intricate deformation mechanism within the structure of the window. At the tracery, the forced new boundaries had caused the opening of joints and some cracks.

To understand the load bearing behaviour of the window, the structure was first conceived in its original state. It was assumed that all the supports of the bars at the reveals were rigid. If sliding can be precluded, the stone structure will clamp between the rigid supports under horizontal loads. This requires a very stiff structure (including stiff joints!), so that a flat arch can form between the supports. If the supports are slackening or the structure is too elastic, the joints begin to open and the rise of the arch decreases. As a consequence, edge pressures increase drastically, often leading to spalling of the stone. Fig. 6 illustrates the flow of forces in the flat arches under wind load.

For the structural analysis of the window a Finite Element model using the program *Ansys* was created. The stone bars of the vertical bars and the horizontal beams were modelled as 3-dimensional volume elements, while contact elements were used to model the joints. The contact elements only allow compression and shear forces but exclude tension forces. Linear elastic material behaviour was used for the sandstone with lower and upper limits for the modulus of elasticity to evaluate its influence. In a similar fashion, a lower and upper limit was established for the superimposed dead load of the tracery on the vertical bars. Precisely because it is impossible to determine to which extent the tracery is supported by the vertical bars, or whether most its self weight is transferred by friction into the reveals. The calculations were based on the undamaged structure but included all the relevant deformations. The analysis, allowing large displacements and rotations, is geometrically nonlinear and iterative. By means of numerous parameter studies, the stability of the structure was calculated. In Fig. 7, thrust lines and edge pressures are shown for a rigid and elastic support conditions. A span increase of a few millimetres already results in a major increase of edge pressure.

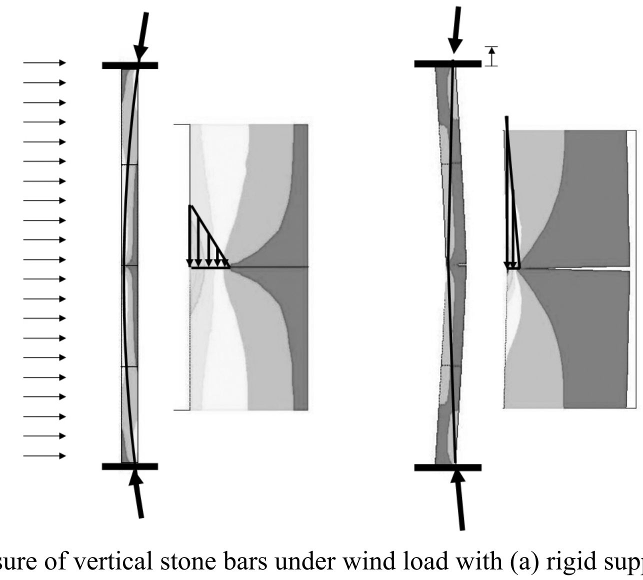

Figure 7 : Edge pressure of vertical stone bars under wind load with (a) rigid supports and (b) elastic supports

It should be noted that a thrust line analyses alone would not be sufficient to assess the ultimate bearing capacity of the window. Although a thrust line can indicate the global load bearing behaviour of such structures, it will ignore the formation of hinges, local overstressing, as well as questions of stability like snap through buckling. These questions can only be answered if the structure is modelled with discreet volume and contact elements that consider the deformation behaviour.

The two most important criteria of the undertaken "flat arch" analysis are the rigidity of the supports and the stiffness of the materials. The absence of reliable mechanical properties for lead led the authors to perform some preliminary material tests as a start of a wider research project.

3 PRELIMINARY TESTING OF LEAD JOINTS

The authors undertook some preliminary material testing at the research and testing laboratory of the Technische Universität München to gain further insight into the mechanical behaviour of lead joints.

3.1 Testing of lead cubes

In 2004, a small sample of roughly 20mm wide lead cubes was tested to research into the stress-strain relations. Four specimens were examined; two of both historic and new lead. The average modulus of elasticity was found to be about 4000 N/mm^2, with the old lead being a little bit stiffer than the new one. The yield point was found to be 10 N/mm^2. Due to the small range of specimen and the high scatter, the results are only indicative. Fig. 8 shows a stress-strain diagram of a cube made of new lead with vertical and lateral strain. As a result of the inhibited transverse expansion of the small and compact specimens, the resultant Poisson's ratio appears to be underrated.

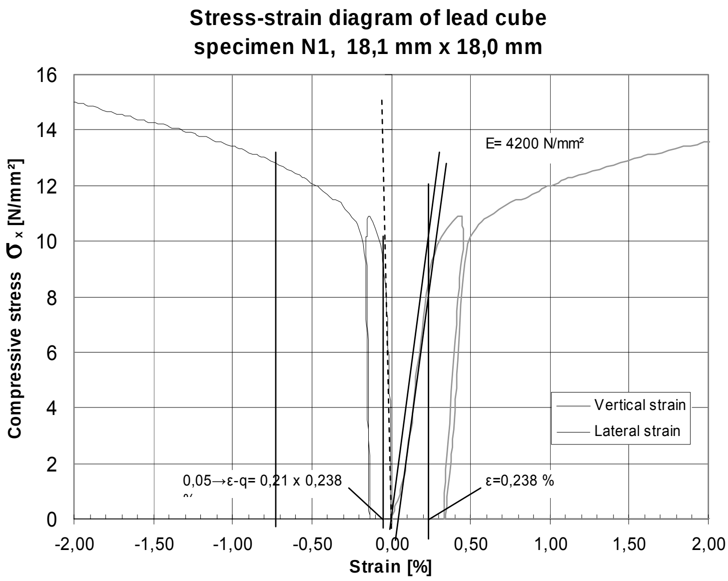

Figure 8: Stress-strain diagram of a small specimen of new lead

3.2 Testing of duplex units

In January 2006, the authors tested duplex sandstone elements with lead joints at the same facility. All sandstone elements measured 15x15x30cm. Four single units and four duplex units, consisting of two single units combined with a 3mm lead joint, were tested. Two different sandstone varieties – Schönbrunner and Udelfanger - were used for the tests. The sandstones were cut and installed with their bedding standing upright. Although the compressive strength of the anisotropic sandstone is lower if the load is parallel instead of perpendicular to the layers, this configuration was favoured because of its more realistic scenario. The long and slender stone elements used in ribs or tracery windows were typically quarried horizontally and their bedding therefore installed upright.

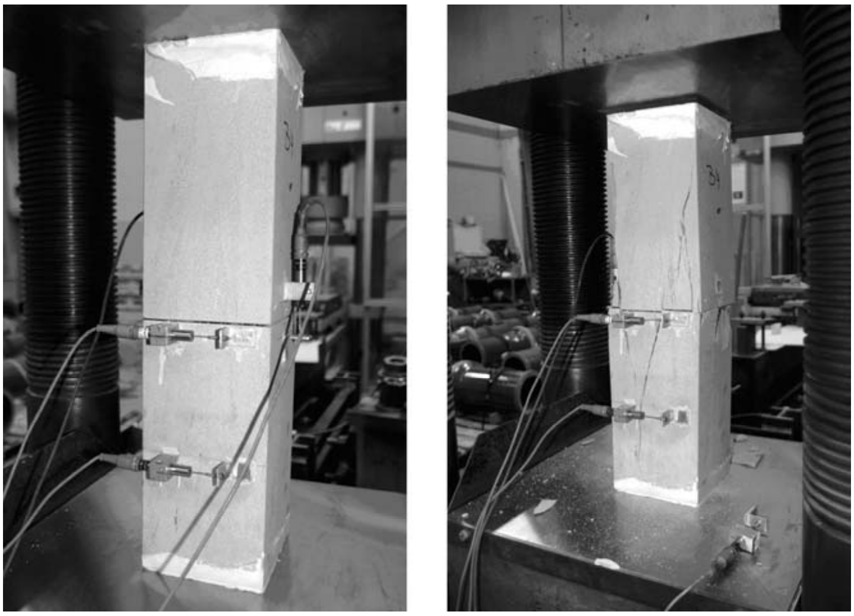

Figure 9a, 9b : Sandstone duplex with lead joint before and after the breaking test

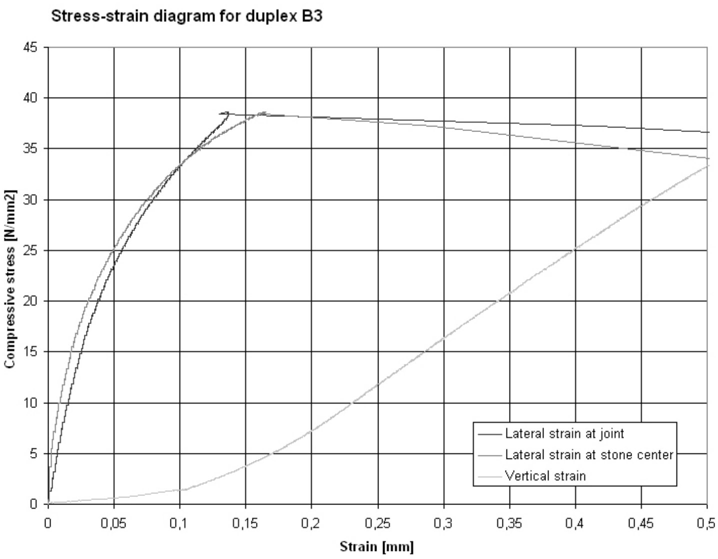

Figure 10 : Stress-strain diagram of duplex specimen B3 made of Schönbrunner sandstone

Displacement transducers were placed at three different locations: a vertical one at the joint and horizontal ones at top and mid height of the lower stone. Fig.s 9A and 9B show a duplex specimen with displacement transducers inside the testing machine before and after the breaking test. Both single and duplex sandstone units were tested for stress-strain relations and breaking load. The average breaking load of the single Schönbrunner sandstone unit was found to be 39,1 N/mm^2, of Udelfanger 51,3 N/mm^2.

The average breaking load of the duplex units resulted in 35,9 N/mm^2 with Schönbrunner sandstone, and 41,4 N/mm^2 with Udelfanger. Compared to the single units, the breaking load dips only 8% in the case of Schönbrunner sandstone, 19% in the case of Udelfanger sandstone. The drop in compressive strength is quite small, especially if one considers that the duplex units are double in height and no form factor was determined to adjust the results. Hence, the drop would further be decreased if form factors were established. The results are particularly salient if put into comparison with sandstone units with lime mortar joints: Material tests performed by Sabha and Weigert (1996) with a comparable testing configuration came to the following results. Using a similar sandstone ($f_{c,s}$ = 48 N/mm^2) and 6mm joints of lime mortar ($f_{c,m}$ = 0,68 N/mm^2), the breaking load was found to be 25,23 N/mm^2 – a decrease by 48% and a much bigger drop than in the case of lead joints.

The significant difference in breaking load becomes comprehensible if one compares the breaking behaviour of duplex units with lead joints to those with mortar joints. In natural stone masonry with mortar joints, the breakage is typically caused by the lateral expansion of the mortar, thereby inducing tension forces into the neighbouring stone faces. Breakage occurs when these lateral tension forces exceed the tensile strength of the stone (Sabha and Pöschel 1994, Warnecke and Rostasy 1995).

Lead joints, in contrast, seem to have an entirely different impact on the stone. The lateral expansions measured at the joint and at stone mid height are almost similar. Just before reaching the peak stress, the lateral expansion of the stone was actually even lower at the joint than at mid height. (See Fig. 10). This suggests that the Poisson's ratio of the lead is lower than the one of the tested sandstones. Therefore, lead would inhibit the free lateral strains of the adjacent stones.

4 CONCLUSIONS

The undertaken material tests of sandstone elements with lead joints indicate a remarkably high load bearing capacity under centric compression. The duplex elements reached almost the uniaxial breaking strength of the sandstone. Although, the preliminary tests still have to be verified in a wider ongoing testing program, the comparison to mortar joints is striking.

Interestingly, the old master builders must have been aware of the high bearing capacity of lead joints. It is surprising to see that these joints were not only used in weathered components where their advantages might have been obvious, but also in filigree stone structures subject to high forces like reticulated vaults. The decided application of these joints also reveals a deep understanding of structural design.

REFERENCES

Barthel, R., Schiemann, L., Jagfeld, M. 2003. Static analysis and evaluation of the construction system of a Gothic „choir window" consisting of a filigree tracery and stone ribs. In Huerta, S. (ed.), *Proceedings of the First International Congress on Construction History*. Madrid: Instituto Juan de Herrera

Barthel, R. 2005, Instandsetzung des Chorscheitelfensters von St. Georg in Nördlingen. In: *Denkmalpflege und Instandsetzung – Vorträge im WS 04/05 - Schriftenreihe des Lehrstuhl für Tragwerksplanung.* Band 14. München: Lehrstuhl für Tragwerksplanung - Technische Universität München

Sabha, A. and Pöschel, G. 1994, Ein theoretisches Modell zum Tragverhalten aus Elbsandstein. In: *SFB 315 Jahrbuch 1993*. Universität Karlsruhe. Berlin: Ernst & Sohn

Sabha, A. and Weigert, A. 1996. Einfluss der Steinhöhe auf das Tragverhalten einschaligen Mauerwerks. In: *SFB 315 Jahrbuch 1995*. Universität Karlsruhe. Berlin: Ernst & Sohn

Schuller, M. and Hubel, A. 1995. *Der Dom zu Regensburg*. Regensburg: Verlag Friedrich Pustet

Warnecke, P. and Rostasy, F.S. 1995. Tragverhalten und Konsolidierung von Wänden und Stützen aus historischem Natursteinmauerwerk. *Mauerwerkkalender*, Berlin: Ernst & Sohn

Wolff, A. 1989. Das Vergießen mit Blei – im Mittelalter und heute. In: *Steinmetz und Bildhauer* 6/1989, München: Callwey Verlag

All figures are from the authors unless otherwise noted.