Artistry and Ingenuity of Gothic Vaults at the Example of St. Georg in Nördlingen

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INTRODUCTION

The parish church "St. Georg" in Nördlingen is one of the last late-gothic hall churches **(fig.1)**. This masterpiece of ecclesiastical architecture was built from 1427 to 1519 (Petzet 1998, p.150). The following text deals with the vaults of the gallery above the western entrance. The gallery was built by Stephan Weyrer, master-builder of the nave's vaults, from 1506 to 1508. The examination of the gallery was prompted by the extension of the organ in 2004. This raised the question of whether the vaults' construction would support the additional loads. A survey of the construction was done including test apertures and an analysis of the structural behaviour. In course of the examination, several damaged parts were found and restored. The restoration works gave the opportunity for further scientific studies of the original medieval structure. The rib-vaulted structure forms a synthesis of ornament and structure. In this respect, it can be compared to the large gothic tracery window of the church's choir (Barthel 2003).

THE VAULTS OF THE GALLERY

The gallery structure comprises four bays. The vaults span between the main nave's large columns and from there to the walls of the tower and the aisles. Tension rods connect the columns at the height of the imposts. In the aisles, the vaults form "protruding" bays. These are tied back to the apex with further tension tie rods.

The complex rib pattern consists of branched and bent ribs. The rib pattern can be described as a superposition of several different patterns **(fig.2)**:

- ridge ribs span from column to column and to the walls
- the cross ribs do not continue to the center of each bay: they provide support for a spheric quadrangle, projected on the ground plan as a square.
- bent, approximately circular ribs form , in plan view, a shamrock-like pattern. These bent ribs intersect with the square pattern in the centre of its sides.
- The "free" protruding fringes at the gallery's east side are supported by enforced ribs with a short connecting rib between the recoiling corner and the column **(fig.6)**.

- An additional system is formed by a series of straight ribs, forming triangles together with the ridge ribs. These ribs, running from the columns to the centre points of the squares, do only exist at the fringes of the vault.

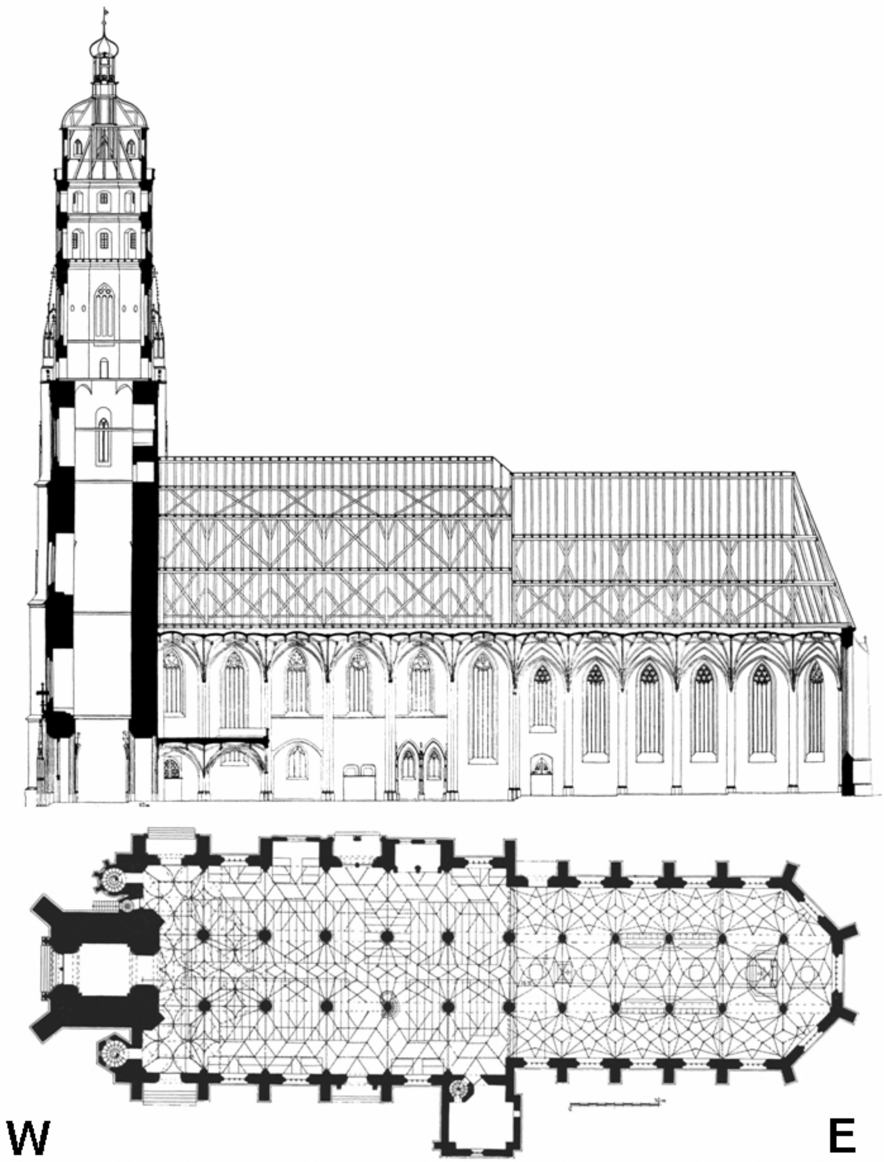

Figure 1. St. Georg in Nördlingen, ground plan, cross section

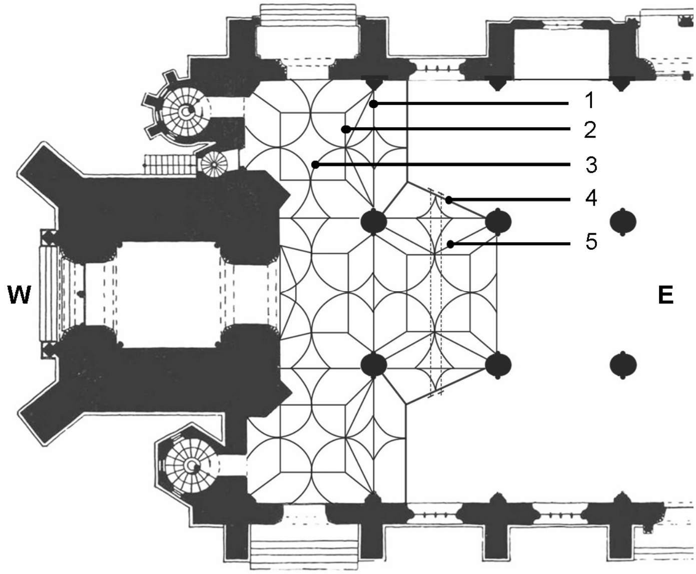

Figure 2. Ground plan gallery, rib pattern: 1 ridge rib, 2 cross rib and interiour square, 3 bent rib, 5 “strutted frame”

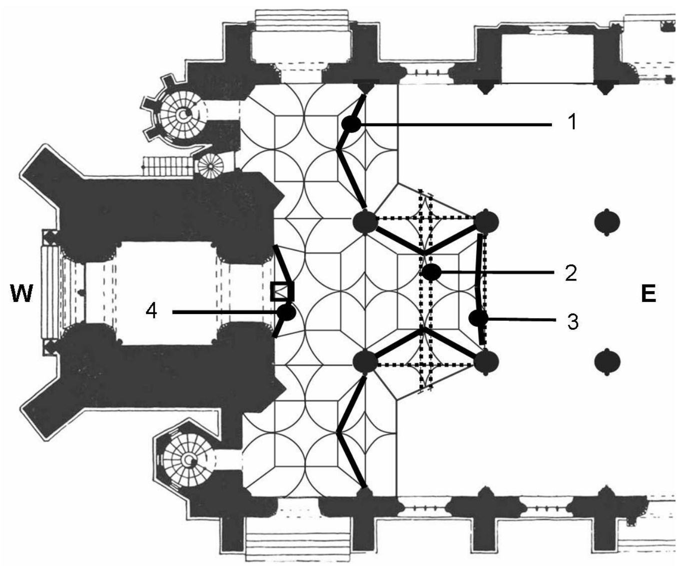

Figure 3. Ground plan gallery, rib pattern: 1 “strutted frame”, 2 tension tie, 3 enforced fringe rib, 4 strutted frame with large keystone at the tower

Figure 4. Gallery, view to the west side

All ribs show nearly identical profiles. No hierarchical order is established between the ribs. Only the ribs on the vault's "free" fringes and the connecting pieces from the corners to the columns have larger profiles **(fig.5, 6)**.

The vault springers are not symmetrical in all directions. All of the church's columns have on their north and south side responds added. The ridge ribs spanning north south and the cross ribs start from there. The ridge ribs spanning east west, parallel to the main nave connect to the columns without capitals and responds. The additional straight ribs show a remarkable characteristic they do not start from the vault springers but higher up in the vaulting and run distinctively flatter.

The vault shells consist of brickwork with a thickness of 120 millimetres. The vaults are formed slightly concave. The middle apex is about 500 millimetres higher than the transverse arches' apexes. The sectroids are also slightly concave; the rib pattern is visible from above. Examinations of the construction in the area of the main tower allow the reconstruction of the construction sequence: At first, the ribs are placed on a scaffolding. Afterwards, the sectroid's brickwork is brought up between the ribs. At that moment the ribs act as support for the brickwork. Due to the sectroid's concave from, the brickwork can be laid free-handed without additional scaffolding. The constructive connection between ribs and shell shows a certain variety. In some areas, no connection between the parts is established at all; in other areas, the ribs' ridges are embedded in the brickwork.

Figure 5. Gallery, view to the east side with nave

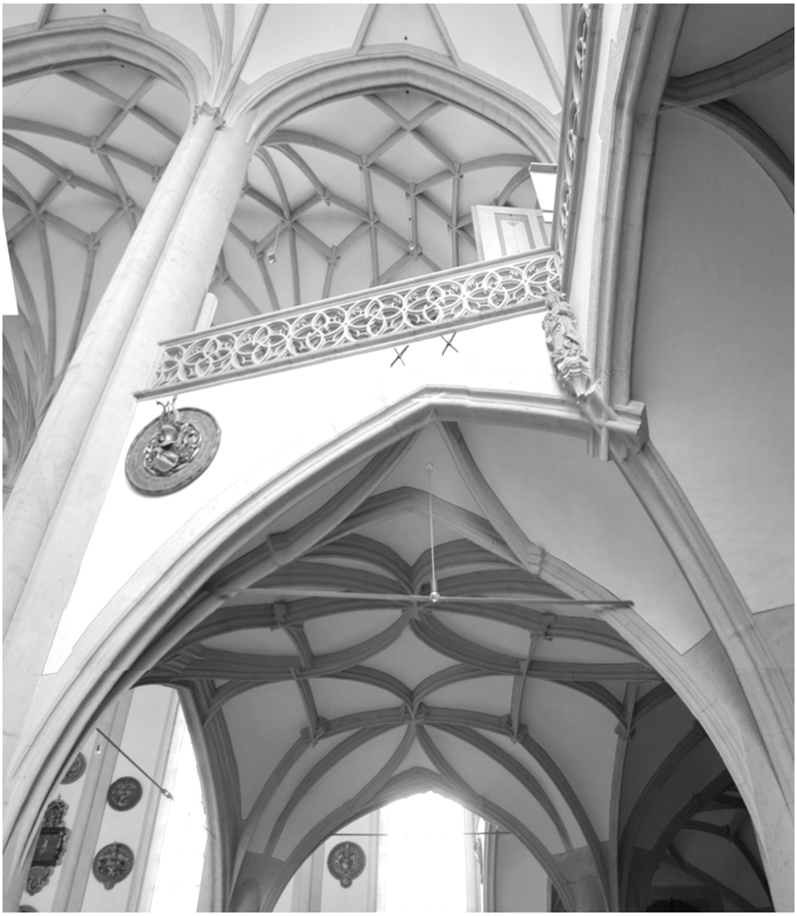

Figure 6. Gallery, view to the south side

Above the ridge ribs between the nave's columns exist wall-like brick structures. The brickwork of these walls is not connected to the columns. The walls act as support for the gallery's joists.

CONSTRUCTION OF THE VAULT NEAR THE MAIN GATE

The western vault ends at walls of the tower **(fig.7)**. The apex of the central vault does not reach the height of the main gate. Therefore, the vault has a free-spanning fringe of about 4 metres length. In this area, it is supported neither in vertical nor in horizontal direction which renders necessary a special stabilizing construction.

In this area, the rib's course differs from the regular pattern. The square pattern in this bay is modified, the rib end points are shifted to the massive tower walls beside the main entrance of the church. From these stable supporting points starts an additional rib, forming a triangular form together with the fringes' rib. This form can be compared to the triangular bays at the gallery's eastern edges. However, the rib on the western gate forms a special intersection with the central vault's bent ribs.

A thorough evaluation of the construction in this area revealed the basic constructive design:

1) The additional ribs form a strutted frame. This frame is able to transfer the vault's horizontal forces to the tower **(fig.8)**.

2) The frame's "keystone" is formed in a special way. Its size is 0.80 by 1.30 metres and it is completely embedded in the vault's brickwork. The ribs on its bottom side are carved out of the monolithic stone. Stretching to the bay's free-spanning fringe, the stone has the function of a tension tie. It stabilizes the ribs on the fringes and ties them horizontally to the strutted frame **(fig.8, 9, 10)**.

3) It was a surprise to detect that the vault's bent ribs are also carved out of larger, straight-formed workpieces **(fig.14)**. These stones are also embedded into the brickwork. Only their visible part has a bent shape. Therefore, bending moments in the rib can be avoided. Additionally, the embedding in the brickwork enables the rib to support the vaulting horizontally.

4) All joints in this area are filled with lead. The vault's other joints are only filled with mortar.

DAMAGED PARTS AND THEIR REPAIR

The examinations were prompted by damage and deformation of the arch beside the tower wall. The arch had lowered and showed deformations in direction of the open main gate.

The rib arches showed damage on the bottom side, near to the apexes, in form of deep, gaping fissures at the joints. On the supports at the tower's walls spalling and longitudinal fissures in the ribs were apparent. This indicated a horizontal displacement of the supports. Vertical cracks in the tower's walls indicated that the tower's northern and southern foundations had drifted several millimetres apart. These deformations may have happened soon after the erection of the tower. The flat arch reacted highly sensitive to the supports' displacements: the apex had dropped about 50 millimetres. The original shape was ascertained from the ridge rib's curvature.

Figure 7. Gallery’s central vault at the main gate

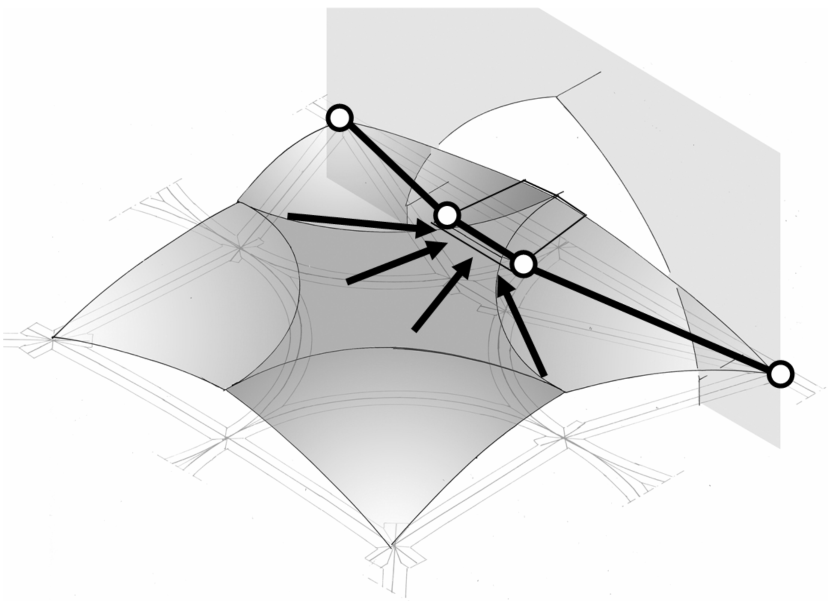

Figure 8. “Strutted frame” at the main gate

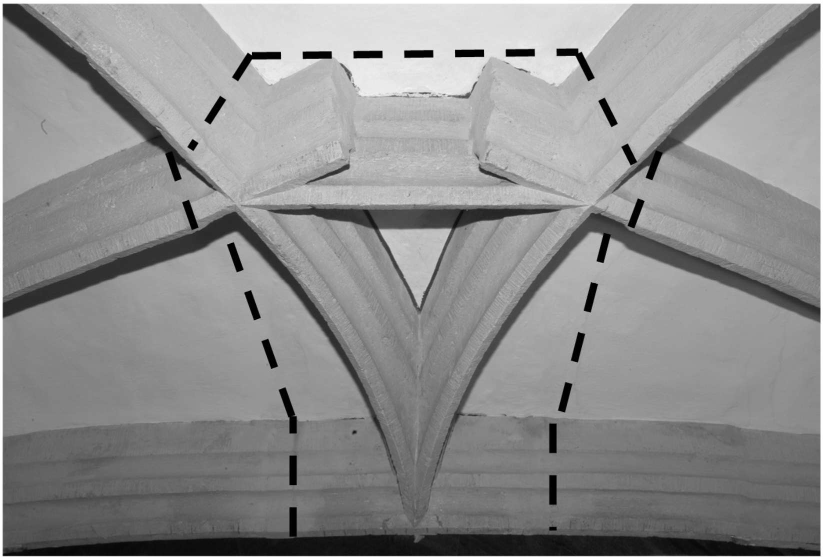

Figure 9. Keystone at the main gate with marked limitations

Figure 10. Keystone at the main gate

The pressure on the ribs' edges resulted in spalling and fissures on the arch's supports. In that area, the profile was already thoroughly damaged **(fig.11)**. With another minor displacement of the walls or additional loads, the heavy keystone might have given way.

Simultaneously, the span of the "strutted frame" had widened. As a result, it gave way and the keystone shifted horizontally in direction of the main gate **(fig.12)**. Accordingly, the bent rib's joints showed gaps and spalling. The result was a complex state of deformation.

Many different possibilities of restoration were discussed. For an instance, the heavy keystone could have been tied to the tower walls with using a steel. In this case, it would have been necessary to create also a horizontal support for keystone and vault. This construction would have destroyed the structural behaviour of the arch. The artificial anchor point would have counteracted the vaults' load-bearing system.

In the end the decision was made to raise the whole area back into its initial position necessitating the erection of scaffolding under the vault. The vaulting could then be lifted vertically on jacks **(fig.13)**. During the process, the keystone had to be supported in its horizontal position. The rib joints opened during the operation. "Leaden wool" was pressed into the open joints. The damaged parts of the ribs were then replaced. During the operation, a number of cracks appeared in the brickwork above the rib structure. They formed a regular pattern that corresponded to the calculations. The straight-formed "backsides" of the ribs became clearly visible. All cracks and fissures were filled with a special mortar from above.

Figure 11. Deformed arch at the main gate with marked joints and the resulting thrust line

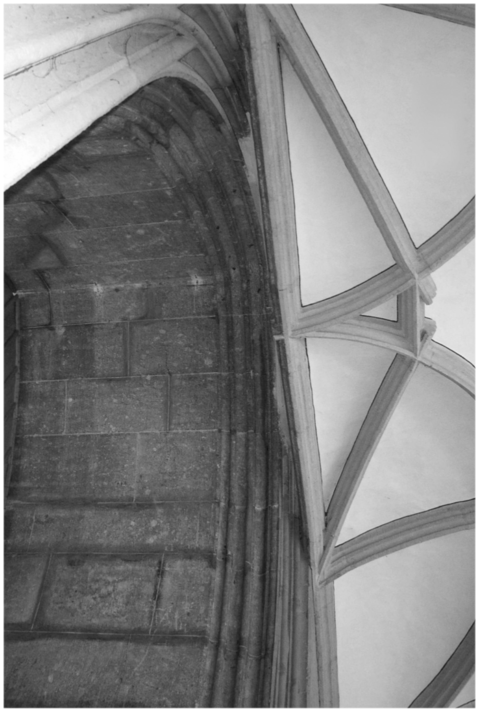

Figure 12. Horizontal deformation of the edge rib at the main gate

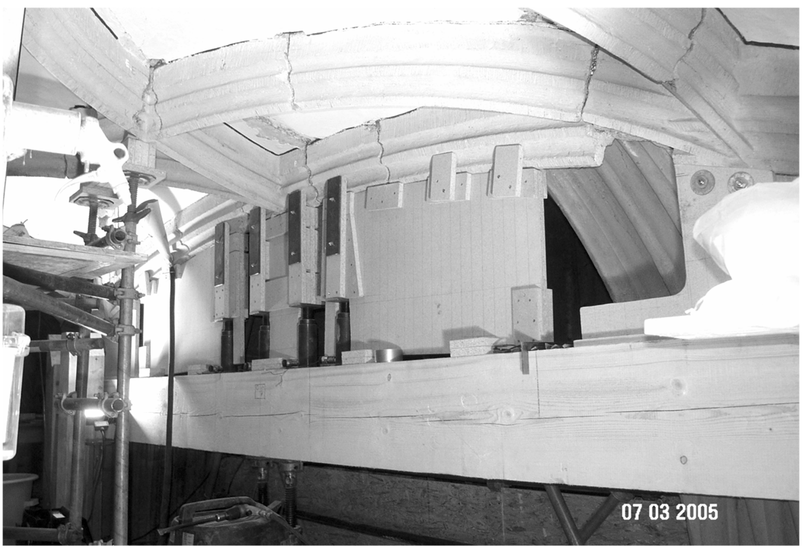

Figure 13. Raising of the central vault

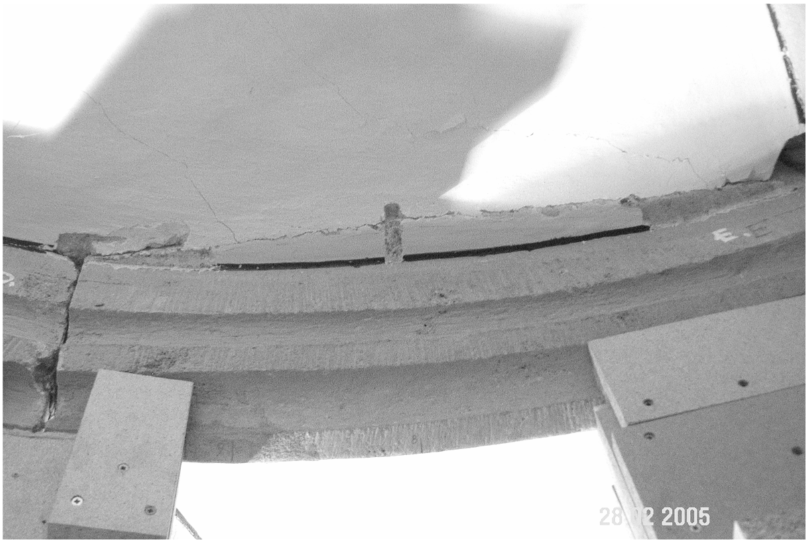

Figure 14. Bent rib with straight, embedded backside

All deformations and positions were simulated using finite-element-analysis, especially the replacement of damaged rib material which meant a considerable weakening of the profiles. Complex calculations were necessary.

The works were led by the Nördlingen stonemason and restorer Michael Scherbaum. He also led the examinations of the historic structure. His extensive experience was a key factor in the planning and implementation of the restoration.

STATICAL INTERPRETATION OF THE RIB PATTERN

The results of the western bay's constructive analysis can be transferred to other parts of the gallery vault. The ribs forming in plan the triangular patterns mentioned above do only exist in bays without adjacent bays **(fig.3)**. They have to direct the vault's horizontal loads to the supports. Acting as horizontal "strutted frames", they can be compared to the system in the central vault. Since the adjacent bays are "complete", the rib pattern is, in contrast to the central vault, regular. The frame ribs meet in the center of the square pattern's sides **(fig.15)**.

With this knowledge, another characteristic attracts the viewer's attention: the ribs of the "strutted frames" do not start from the vault springers. Their intersection with the vaulting is situated much higher, it is only connected by paint to the vault springers. At first glance this seems to be an irregularity. But if the ribs' primary function is to take up the horizontal forces, this "imprecision" can be explained: The ribs connect straight to their support at the columns. Thus, they are much more rigid than the bent ribs. The forces are transferred straight and directly to the columns.

The structure of vault and ribs is based on stringent and logical construction concept. In the area of the Western entrance it could be proved that the concept was consequently implemented. The structural effect in reality follows the intended model. In other areas, the ribs' "frame effect" is certainly also intended. It would be interesting to conduct further research in aspects of the construction. There are still several unanswered questions: do the bent ribs in these areas also have a straight "backside"; does a comparable "keystone" exist in these areas (which would be of considerably larger dimensions!)? The existing tension ties are, as well, a consequent solution **(fig.15)**. The existing ties are of recent date; but probably they act as substitutes for historic predecessors.

Figure 15. Gallery, view to the east side. "Strutted frames" and tension ties

The results contradict the common beliefs that late Gothic vaults and their rib patterns are merely ornamental in character. The reality is much more complex:

1.) In this case, the ribs are employed to influence the load-bearing structure of the vault. Without the "strutted frames" it would not be possible to balance the forces, at least in the central vault. Without the ribs, the vault would have to be a very different shape.

2.) Also in the vault's other parts the ribs are not just a decoration added on the bottom side. Even as an ornament, they must form a coherent structural system acting as arches. An interaction of forces between the ribs and the vault's shells is possible. By leaning against the sectroids, the interaction perpendicular to the ribs is possible. If the ribs or singular keystones are embedded in the brickwork, a shear transfer is possible.

3.) The shape of the shell depends on the rib pattern and the construction sequence. The free-handedly laid brick structure between the ribs lead to a certain concavity of he sectroids. However, the arch rise of the concavity is just a few centimetres, so the vault normally would be stable even without the supporting rib structure.

The flow of forces in Gothic cross vaults and the interaction between ribs and shell had been already examined by an extensive Finite-Element analysis (Barthel 1989).

CONCLUSION

Gothic construction methods are said to have developed over centuries. It is a popular belief that stonemasons' lodges have passed on their building secrets from generation to generation. This led to the widely held belief that these construction methods followed ancient rules and traditions rather than rational designs. The example described above shows the availability of a profound understanding of structural systems.

However it has to be made clear that were no contemporary "structural calculations" in the modern sense.

When dealing with Gothic structures, it has to be pointed out that efficient solutions appropriate for the materials involved were "invented" for very specific building tasks. Often, these constructions are without any direct model or were employed in a completely new combinations. In this case, the construction principle of a strutted frame was applied to a three dimensional situation. The original construction must have been consciously designed, developed and implemented. This would not have been possible without an astonishing capacity for abstract thought as well as a clear and full understanding of structural effects. Therefore, "intuitive" knowledge was by no means sufficient. The master-builder must have been aware of his concept. The synthesis of ornament and structure to that extent is a daring and outstanding masterpiece.

REFERENCES

Petzet, M. (ed.) 1998. *Denkmäler in Bayern, Denkmaltopographie Bundesrepublik, Deutschland*, München: Karl.M.Lipp Verlag.

Barthel, R., Schiemann, L. and Jagfeld, M., 2003. "*Static Analysis and Evaluation of the Construction System of a Gothic Choir-Window consisting of a Filigree Tracery and Slender Stone*

Ribs" in Huerta, S. (ed.), *Proceedings of the First International Congress on Construction History*, Madrid: Instituto Juan de Herrera.

Barthel, R. 1989. *"Analysis and Structural Behaviour of Masonry Cross Vaults"* in Brebbia, C.A. (ed.), *Structural Repair and Maintenance of Historical Buildings,* Basel: Birkhäuser