Late Gothic Vaulting in the Canton of Grisons, Switzerland

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Introduction

The 15th century was a turbulent time for the region of what is today the canton of Grisons in south-eastern Switzerland, yet it was also a time of progress and change. With the establishment of new transit routes, such as the Via Mala as a connection to the Splügen and San Bernardino passes, the economy experienced a significant upswing, which also led to a considerable growth of population. However, the 15th century also saw the emergence of a sense of autonomy among the population, which subsequently led to the amalgamation of the judicial communes in the Free State of the Three Confederations, the predecessor of today's canton of Grisons.

Around the middle of the 15th century, ecclesiastical building also awoke from its almost two-century slumber and a growing number of churches were again built in the contemporary Late Gothic forms. This was not a local phenomenon, but can be observed throughout German-speaking Europe at this time. However, what is special for the region of today's Grisons is that due to the preceding stagnation in building, the Late Gothic architectural forms had not developed out of the local tradition itself, but were rather introduced from external influences. Furthermore, the building industry did not only change fundamentally in the capital Chur, but through the spread of this new construction knowledge – which can be traced amazingly well due to the alpine, mountainous location of this almost self-contained territory – the entire canton prospered within a few years.

In the course of a dissertation project [1], the intensive Late Gothic building period was scrutinised based on the executed vault constructions. The foundation of the thesis was always the building itself, which means that the conclusions and results of this study are not based on objective and aesthetic details, but can be verified by exact measurements with total station and laser scanner. In the present study, an overview of Late Gothic vaulting in Grisons will be given and the key results and major findings of the conducted research will be discussed.

A short history of vaulting in Grisons

The first church in Grisons to be completely vaulted in both the chancel and the nave was the Cathedral of St. Mary's Assumption in Chur (1150–1272). In retrospect, however, the vaults built in the early 13th century [2] in a Romanesque style seem outdated, since at that time the much finer and more precise Gothic ribbed vaults were already standard in most parts of Central Europe. After the completion of Chur Cathedral, vaulting developed hardly at all over the next two centuries, which is why the few churches from the 14th century and even the first Late Gothic churches around 1450 still have broad and heavy ribs with trapezoidal profiles (Fig. 1). The main reasons for the lack of a developing and evolving vaulting tradition in the High and Late Middle Ages were internal tensions in the diocese, which led to a complete standstill in ecclesiastical building after 1350, and missing connections to the western parts of Europe, which is why the Gothic architectural forms never even reached the canton of Grisons.

In the 15th century, profound changes took place in Grisons, sparked by the formation of the three leagues as well as their merger to form the Free State and the autonomous founding of new church parishes. The new parishes required their own churches, which led to the first slight increase in the potential building volume for churches after 1450 in the northern parts of the region. In the following years, however, only scattered churches were built. This was to change after a severe city fire occurred in Chur in 1464 [3], which destroyed many buildings below the bishop's court, including the parish church of St. Martin. At this time, Ortlieb von Brandis, a bishop who was particularly keen on building, was at the helm of the diocese, and so the rebuilding of St. Martin's was quickly pushed forward.

Figure 1: Vault in the Steigkirche on the St. Luzisteig Pass rebuilt around 1457 (M. Maissen)

For the reconstruction of St Martin's, the master stonemason Steffan Klain from Freistadt in Upper Austria was appointed by the city council. Master Steffan probably began his work in the early 1470s and completed the new chancel structure as early as 1473 [4]. Since the development of Late Gothic vault construction was already considerably more advanced in Upper Austria at this time, Master Steffan was able to establish a new architectural language practically overnight through the knowledge he had brought with him. The completion of the chancel vault of St. Martin's (Fig. 2) thus introduced a new standard of Late Gothic vault design that spread throughout Grisons within a short time. During his two decades of practice, Master Steffan passed on his construction knowledge and experience to young master stonemasons, among them Andreas Bühler from Carinthia and Bernhard von Puschlav. These young masters continuously improved the art of vaulting – however, such a significant technical advancement, as after the arrival of Master Steffan, was not to take place again.

Figure 2: Interior view of the Parish Church of St. Martin in Chur (M. Maissen)

The Late Gothic building stock

The Late Gothic period was an intensive age of church building in Grisons, the extent of which has not been equalled again in relation to the comparatively short time span of only 75 years. The vast majority of the completed building projects spanned an even shorter period of 55 years between 1470 and 1525. However, compiling a conclusive inventory of the Late Gothic period is a problematic endeavour, as no exact construction data or detailed studies of many of the smaller buildings exist. In addition, many churches were rebuilt again after the end of the Grisons turmoil, after destruction by town fires or for a variety of other reasons, which is why their Late Gothic features are no longer visible today, or at least only superficially.

The evaluation of the Late Gothic construction period has shown that between 1450 and 1525 at least 118 churches (Fig. 3) were either rebuilt from scratch or at least rebuilt or modified to a certain extent [5]. Additionally there were at least another eight built or modified within two independent construction phases, bringing the total number of completed projects to over 125. Of the 118 churches, 97 have a vault at least in the presbytery, corresponding to a share of 82%. From the available data, it can be assumed that at least 69 of the 118 buildings were entirely new buildings. This would correspond to a new-build share of 58.5%, which means that in slightly more than 40% of the existing Late Gothic building stock, at least one part of the predecessor building was included in the new construction. The intensity of the Late Gothic period in Grisons becomes even more apparent in relation to the total ecclesiastical building stock: today, there are 670 churches and chapels [6] in the territory of Grisons, which means that almost every fifth church was either built or at least fundamentally rebuilt in the Late Gothic period. Or to put it another way: the stock of churches in the middle of the 15th century probably doubled by 1525.

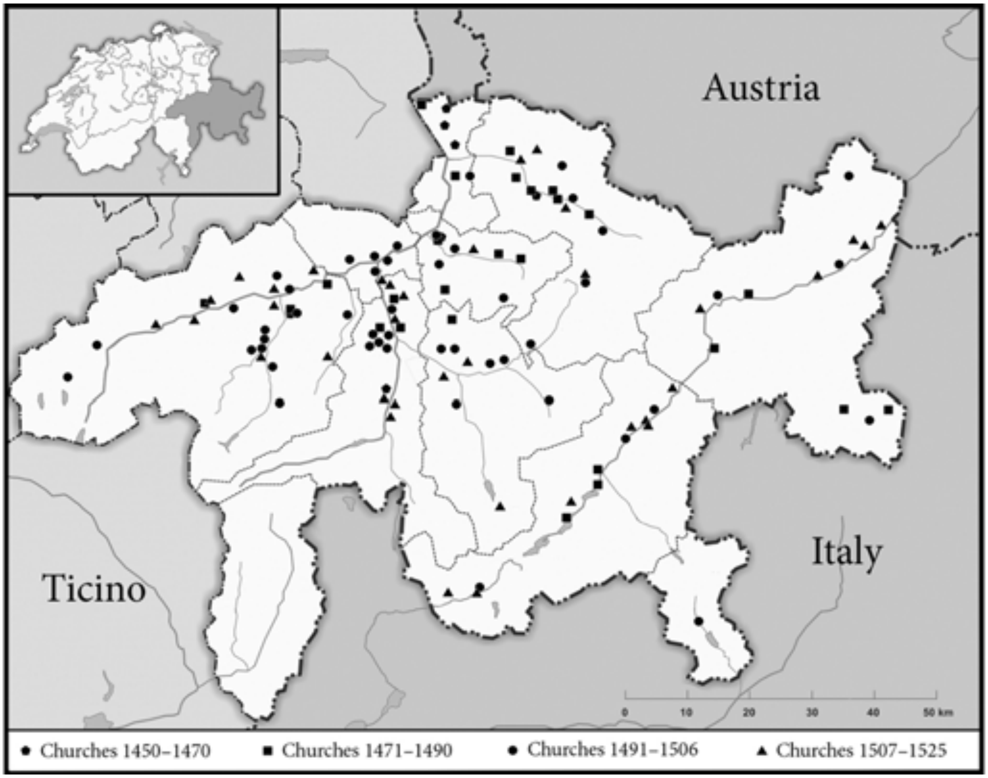

Figure 3: Spatial distribution of all 118 built or rebuilt Late Gothic churches (M. Maissen)

Design and construction of Late Gothic vaults in Grisons

With the arrival of Master Steffan in Chur, the comprehension of vaults and especially of ribs changed radically. Thus, geometrically accurately designed and precisely manufactured contemporary vaults promptly substituted the formerly rather rudimentary vaults with their ponderous-looking ribs. This new approach can already be observed in the chancel vault of St. Martin: The vault pattern derives directly from the proportions of the ground plan itself, which allows it to be designed solely with a compass and straightedge. This design process also works for more complicated vault patterns, such as the *'Haspelstern'* (roughly translates to a spinner's wheel) vault, which is widespread in Grisons and was also applied by Master Steffan in several churches [7]. To design such a pattern in the ground plan (Fig. 4), all bay dimensions AA must be sized equally. The same distance AA is then traced with a compass, which already defines all the needed intersection points and allows the pattern to be connected.

Another method, which can be verified for a range of vault patterns in Grisons, is the utilisation of auxiliary grids as the basis of the design. Once again, the bay dimensions were determined first, before the surfaces were proportioned in both longitudinal and transverse directions. The proportions were not random, but based on dimensions of the ground plan or on geometric principles, such as segment division with compasses. The application of auxiliary grids allowed for greater freedom in the design of vaulting patterns, thereby creating a greater variety of rib patterns and shapes. Even elaborate vault patterns, such as the chancel vault of the parish church of St. Maria Magdalena in Stierva, can be traced back to simple auxiliary grids (Fig. 5). In Stierva, the bays were quartered in the transverse direction and then divided longitudinally into five equal sections. The division of a reference line into *n* parts can be done with a compass by tracing *n* circles of arbitrary but constant radius on a second line, whose last intersection point is linked to the end of the reference line and shifted parallel to the other intersections (Fig. 5, No. 1). All the major intersection points of the rib pattern are already located on this auxiliary grid (Fig. 5, No. 4), while the remaining intersections can be defined by bisecting the zigzag path (Fig. 5, No. 5). To complete the design, the transition of the pattern into the apse is still missing, and this too could be resolved with only a compass in a few steps (Fig. 5, Nos. 6–8).

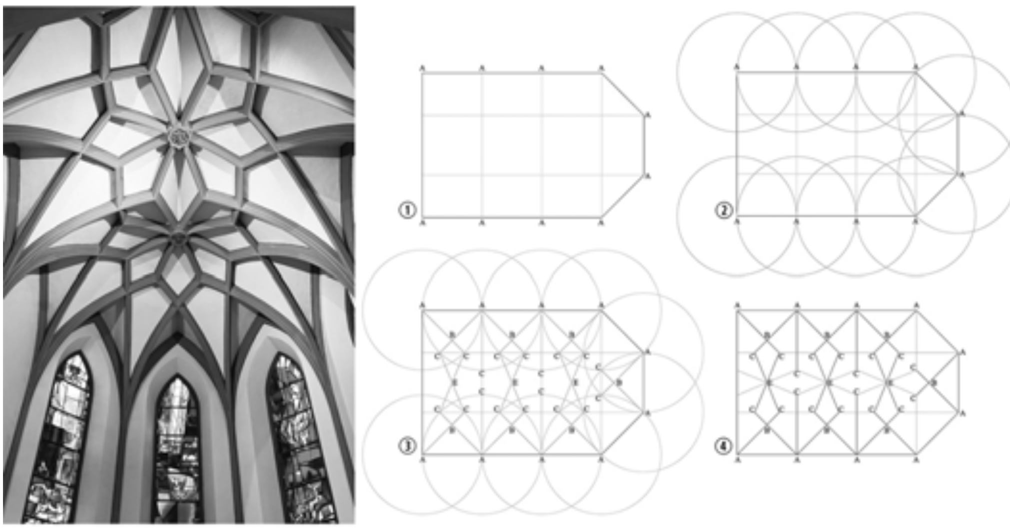

Figure 4: The chancel vault of the Church of St. Regula in Chur and a possible reconstruction of the design process of the rib pattern (M. Maissen)

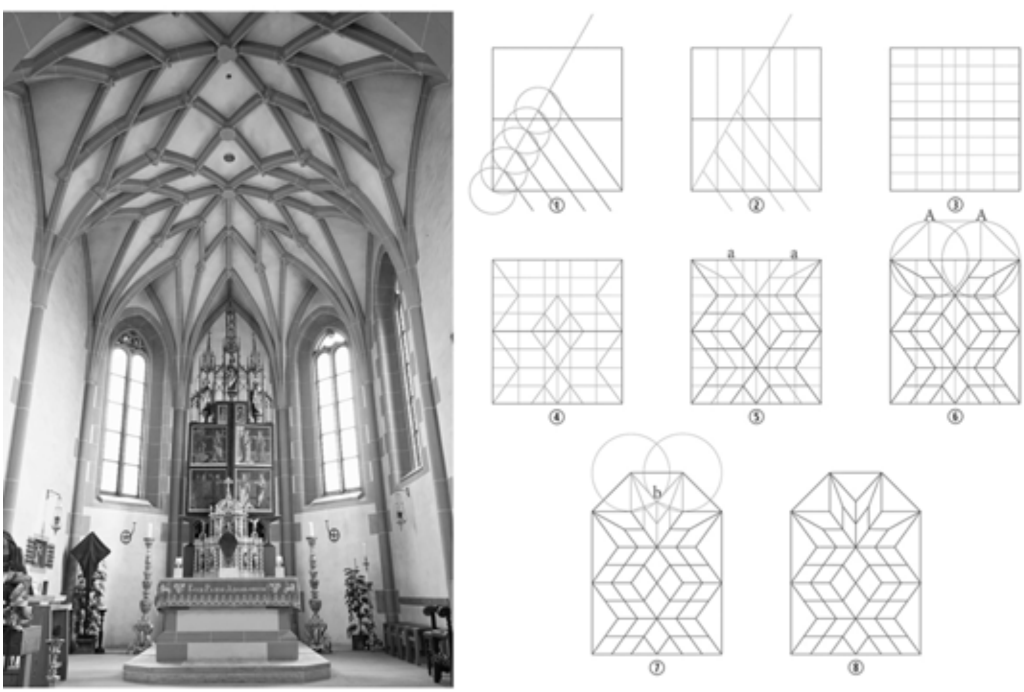

Figure 5: The chancel vault of the Church of St. Maria Magdalena in Stierva and a possible reconstruction of the design process of the rib pattern (M. Maissen)

The Late Gothic churches in Grisons reveal a diverse catalogue of vault patterns, most of which consist of a combination of simple geometric shapes – complex vault patterns, such as those in Stierva or Thusis (see Fig. 6), are an exception. As described in the few surviving contemporary German *'Werkmeisterbücher'* (master builder's books), the design often refers to the dimensions of the chancel [8], e.g. its clear width or the width of one bay. Nevertheless, as seen in the above case of Stierva, this reference can also be only indirect as a basis for the auxiliary grid. All vaults in Grisons, however, have in common that their rib patterns can easily be designed in the ground plan following basic geometric rules with compasses and straightedges.

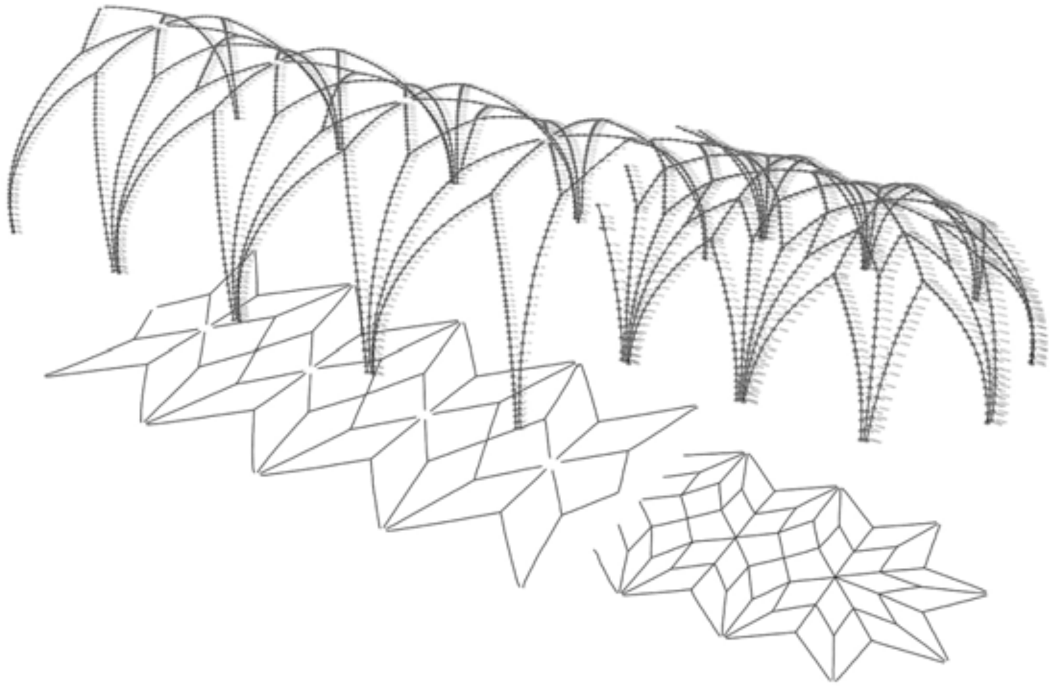

Figure 6: Total station survey of the vault ribs in the Reformed Church of Thusis (M. Maissen)

Ribs, geometry and radii

It was not only the shape of the ribs and the design of the vault patterns that changed through Master Steffan, but also the function of the ribs: Henceforth, the ribs no longer followed the groins of the vault in order to conceal and strengthen them, but rather defined the shape of the vault itself through their geometric definition [9]. For a more accurate analysis of the radii of the vault ribs, precise surveys of a number of previously selected vaults were conducted using a total station. The ribs were metered centrally along their extrados at short intervals of 5 to 10 cm, which resulted in several thousand individual measurements for each object. Thus, for the analysis of the vault ribs of the Reformed Church of Thusis, altogether 2682 individual total station measurements (1149 in the chancel and 1533 in the nave) were conducted (Fig. 6).

Table 1: Analysis of the rib curvature in the chancel vault of the Ref. Church of Thusis

Rib Sequence	Radius [m]	Max. Distance [m]	Mean Distance [m]
Rib 01	3.5942	0.0247	0.0149
Rib 02	3.5919	0.0078	0.0025
Rib 03	3.5902	0.0261	0.0110
Rib 04	3.6141	0.0201	0.0096
Rib 05	3.6017	0.0181	0.0048
Rib 06	3.6013	0.0178	0.0800
Rib 07	3.6307	0.0052	0.0018
Rib 08	3.6129	0.0137	0.0057
Rib 09	3.6167	0.0135	0.0052
Rib 10	3.6291	0.0094	0.0044
Rib 11	3.6351	0.0056	0.0022
Rib 12	3.6157	0.0283	0.0104
Ø Radius: **3.6111 m**	Mean deviation: **0.0127 m**	Ø max. distance: **0.0159 m**	Ø mean distance: **0.0127 m**

In a second phase, the radii of the rib sequences were computed using a programme based on the method of least squares developed by Prof. Dr.-Ing. Stefan M. Holzer. As rib sequences, we sought contiguous rib paths between the springers and the keystone. In the case of a *'Haspelstern'* vault, this is quite simple, since all rib sequences ACE are identical and extend from any springer A via a crossing point C to the respective keystone E (see Fig. 4, No. 4). The chancel vault pattern of the Church of Thusis, on the other hand, seems rather heterogeneous at first glance, but all possible rib sequences from any springer to the respective keystone can be formed from one tierceron and two lierne ribs (Fig. 6). This results in different rib sequences that describe a divergent path but cover the same distance.

The computed and evaluated radii of the rib sequences of the chancel vault of the Church of Thusis yielded surprisingly uniform results (Table 1): From the twelve analysed rib sequences, the average radius is 3.6111m with a standard deviation of only 0.0127 m. However, the rib sequences are also very precise in themselves, which is indicated by the two other values in the table: The value "max. distance" indicates the furthest distance of a single measurement point to the computed radius, whereas the value "mean distance" states the average distance of all measurement points to the computed radius. Both values of 0.0159 m, respectively 0.0127 m are equally astonishing for a half-century-old vault structure.

All rib voussoirs in the chancel vault of the Church of Thusis could thus be planned and manufactured with the same radius, which not only simplified the production of the voussoirs but also the preparation of the falsework – the same is true for the *'Haspelstern'* vaults, which also consist of only one uniform radius. However, in the research project, the application of two or more different uniform radii in the same vault could be verified for several objects [10]. Yet, the different uniform radii were never randomly applied, but rather attributed to specific rib sections. For example, in the intricate chancel vault of the Church of St. Maria Magdalena in Stierva, the tierceron ribs were built with a radius of 3.1431 m, the lower lierne ribs stretching in transverse direction with a radius of 3.6081 m, and finally the liernes extending longitudinally along the flatter apex with a radius of 3.9053 m [11].

Uniform radii could be proven for all examined vaults. The results of the measurements can be verified not only by the small deviations, but also by the fact that the uniform radii can be converted to integer contemporary foot measures in nearly all cases. The original Late Gothic foot gauge is still attached to the town hall in Chur and has a size of almost exactly 30 cm [12]. Thus, the computed radius of 3.611 m for the ribs in the chancel vault of the church of Thusis corresponds to 12 foot. In a few rare cases, however, the computed uniform radius is not convertible to integer foot measures, but refers directly to ground plan dimensions, such as in the chancel vault of the Collegiate Church of San Vittore Mauro in Poschiavo [13].

Webs, shapes and compositions

Along with the new conception of the rib, the shape of the vaults and the design of the webs also changed. The vaults were directly dependent on the curvature of the ribs, which determined the shape and course of the webs. However, the constructional design or composition [14] of the vault webs was primarily a matter of the material used. In the Late Gothic period, it was conventional in Central Europe to construct vault webs from bricks. As there were only major clay deposits in the immediate vicinity of the capital Chur, brick vaults can only be found here in the two parish churches of St. Martin and St. Regula as well as in the Hieronymus Chapel in the episcopal cathedral deanery. The main advantage of using bricks was that the vault webs could be vaulted freehand and without a full-surface formwork. For the two vaults examined in the churches of St. Martin and St. Regula, however, the suspicion is that here too the vaults were built on a formwork. This is a suspicion resulting from the geometric shape of the vault webs, which show negative curvatures that may have been caused by compression settling after the stripping of the formwork (see the elevation plan of St. Regula in Fig. 7).

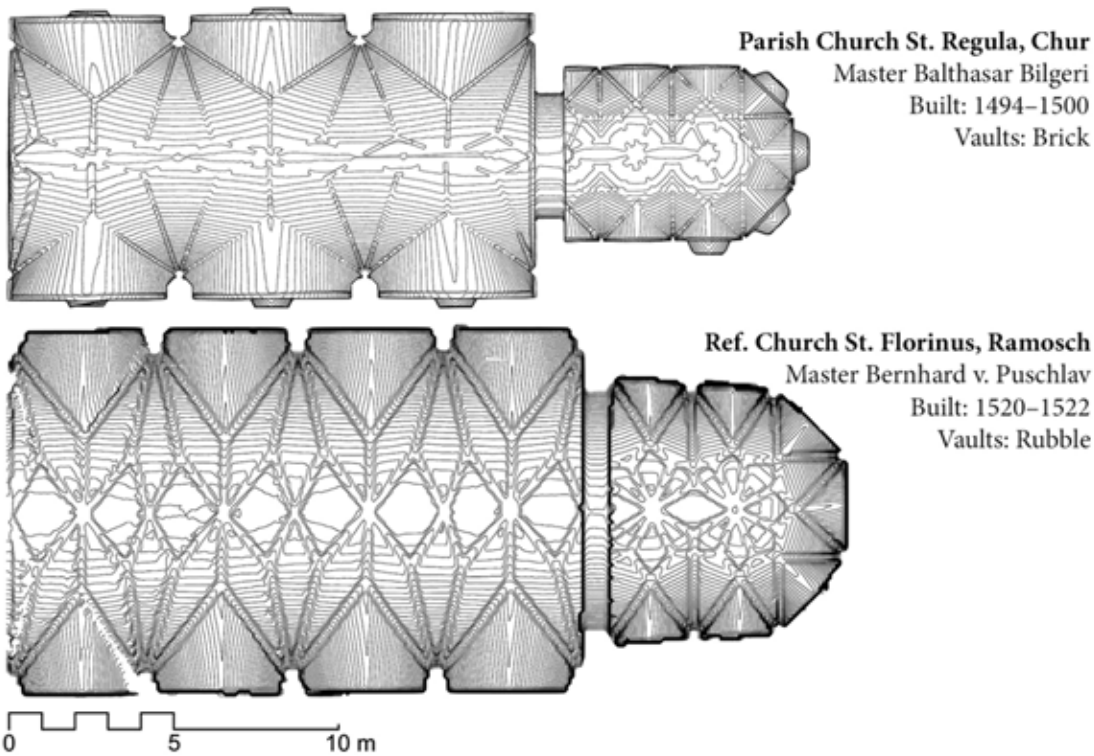

Figure 7: Elevation plans with intervals of 10 cm of the churches St. Regula in Chur and St. Florinus in Ramosch (M. Maissen)

Apart from the three vaults in Chur, all the other vaults were made of a compound of rubble stones and a high amount of mortar – similar to the Roman *'opus caementitium'*. The main disadvantage of this construction method was that a solid formwork was necessary, that was strong enough to support the massive load of the vault until it hardened. Furthermore, with a rubble stone vault, it was important to ensure that as many adjacent sections as possible, i.e. at least one full bay, were simultaneously vaulted, so that the scaffolding and the formwork were evenly loaded and the unfinished structure was always in equilibrium [15]. On the other hand, the advantage of vaulting with rubble stones and mortar was that the required raw materials could be quarried locally in vast quantities and did not have to be transported over far distances.

Since vault webs are larger surfaces, their shapes are better analysed with laser scans and the subsequent computed elevation plans (Fig. 7). The web, as already mentioned, is predetermined by the rib configuration, which means that not only continuously curved circular shapes are possible. The early vaults in particular reveal shapes that expand dome-like within the boundaries of each bay; around 1500, the shapes of the copings began to change, slowly converging towards barrel vaults with lunettes. If one compares the elevation plans of the churches of St. Regula (built 1494–1500) and St. Florinus in Ramosch (built 1520–22), this development becomes obvious in the nave (Fig. 7). Even more interesting, however, are the two chancel vaults, for they both show a *'Haspelstern'* rib pattern; though in Ramosch the ground plan was dimensioned wider, so that even here the webs approximate a barrel vault.

Not only the shape of the vault was decisive for its permanent safety, but also the strength or thickness of the webs, because in order to avoid dangerous cracks forming, the thrust forces must extend within the web masonry. In the studied objects, the cap thickness at the apex was between 20 and 30 cm, although this does not mean that this is a continuous cross-section throughout the web. Rather, it must be assumed that the thickness of the vaults webs was steadily increased from the apex downwards to the springers [16].

Subsequent vaulting

Crowning a liturgical interior with a Late Gothic vault was a challenging task requiring all the structural elements of a church to be tailored to the vault and the massive forces involved. With new constructions, the ground plans and the walls could be correctly dimensioned from the start, but as mentioned above, just over 40% of the churches were not built from scratch. In an existing structure, parameters such as wall thickness or ground plan proportions cannot be determined directly, which makes the subsequent vaulting of an already existing church even more complicated. So why were churches or some of their fabric reused at all?

The main reason for the continued use of the existing building fabric is obvious: by integrating existing architectural elements, material, time and thus costs could be saved. A central idea here was that if structures or elements, such as the exterior walls, were reused, the foundations did not have to be rebuilt either. The construction of foundations was certainly one of the more time-consuming and expensive sections of a new building. How elaborate the foundation of a church used to be is preserved in one of the rare *'Werkmeisterbücher'*, which bears the title "Unterweisungen" (English: Instructions) and was written around 1516 by the Heidelberg master builder Lorenz Lechler [17]. The basis of the foundation was a close-fitting pile foundation made of high-quality piles of oak, elm or alder timber. The spaces in between were then filled with crushed coal. Above this, a grate was erected from further timbers, which was stuffed with stones and poured over with hot mortar – only on top of this was the building's substructure constructed. This method remained practically unchanged until modern times, hence the treatise "Von wirklicher Baukunst" (1780) by Lukas Voch still contains some drawings of various pile foundation techniques on the first plate (Fig. 8).

Therefore, if the existing structure was large enough and did not need to be extended, integrating it into the intended new building was reasonable simply because no new foundations and substructures had to be built for it. In the objects studied in the thesis, it is striking that generally only the structure of the nave was reused, while the presbytery was built from scratch. This most likely relates to the ground plans and designs of the respective structures: The form of the nave on a rectangular ground plan hardly changed from the Early Middle Ages to the Late Gothic period and beyond, which is why the nave, unless it required enlargement, could simply be integrated into the new building.

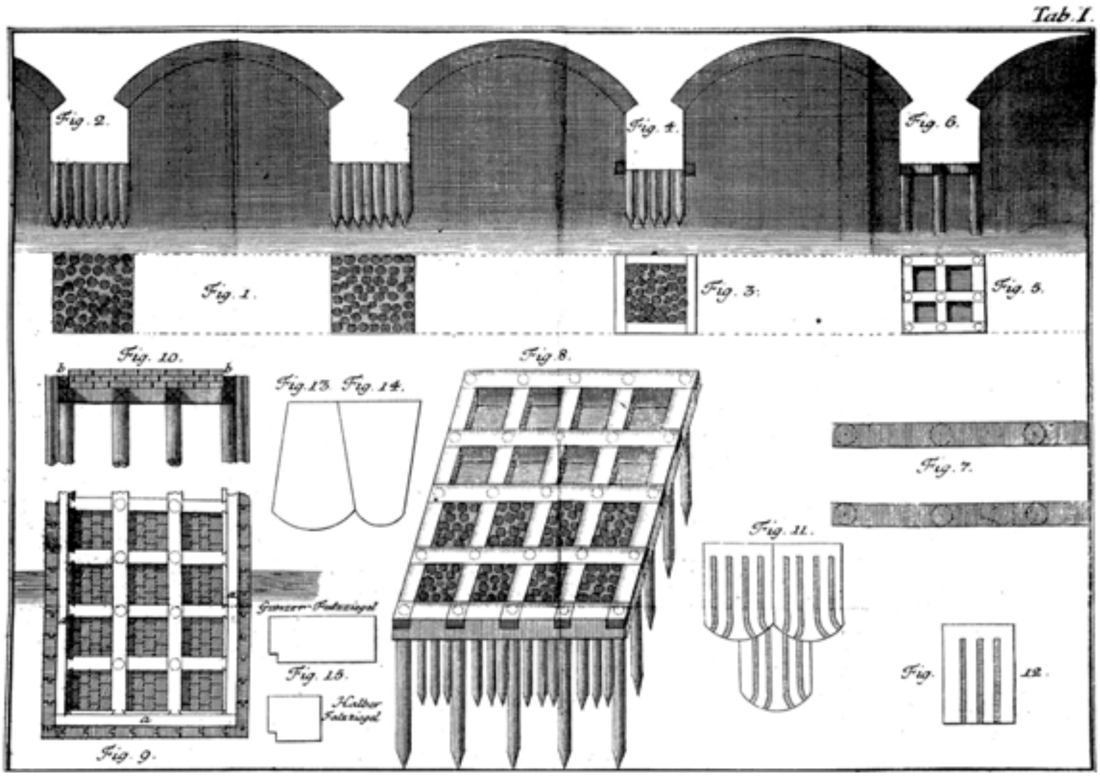

Figure 8: Different types of pile foundations (Lukas Voch, Wirkliche Baupraktik der bürgerlichen Baukunst. Augsburg: Matthäus Rieger, 1780, Plate 1)

If the conditions for a conversion were not met, the existing structures had to be adapted and modified to their new tasks. The addition of a vault primarily affected the walls through lateral shear forces, for which they were not intended. To counterbalance these forces, several solutions were possible, which could all be verified in multiple objects. For most objects, the addition of buttresses was sufficient to balance the forces emanating from the vault. Buttresses allowed the wall to be reinforced and extended at the points with the greatest forces – a principle that was obviously also applied to new vaulted buildings. However, due to adjacent buildings or lack of space, it was sometimes not possible to add external or internal buttresses. Another fundamental solution was therefore to deliberately position the vault springers very low on the wall so that the superimposed load on them would increase, which meant that some of the forces could already be counterbalanced [18]. This approach is best observed in the Collegiate Church of San Vittore Mauro in Poschiavo [19], but has been adopted in several churches in Grisons.

Beyond these two most commonly applied solutions, a third option was possible: converting the church into another architectural type. The most famous example of such a conversion is the Convent Church of St. John in Müstair. In Müstair, the adjacent convent buildings meant that buttresses could not be added and the 12 m wide interior could not be directly vaulted, as this would have disturbed the high apses (Fig. 9). The simplest solution was to inter-support the vault on columns, which resulted in the Carolingian hall church being converted into a three-aisled hall church from 1488–92. Since the middle nave and side nave vaults in Müstair are approximately the same height, part of the horizontal thrust forces are already equalised at the columns and the walls are less stressed. A similar solution can be found in the church of St. Maria and Michael of the former Premonstratensian monastery in Churwalden.

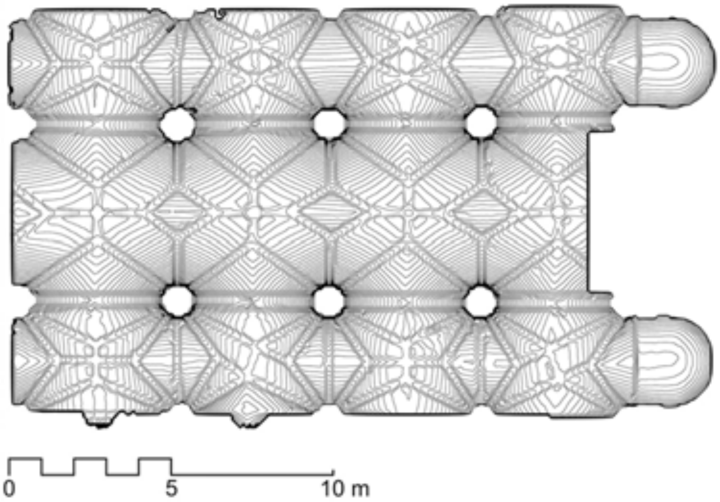

Figure 9: Interior of the Convent Church of St. John in Müstair and elevation plan with intervals of 10 cm (Photo: Foundation 'Stiftung Pro Kloster St. Johann' / Plan: M. Maissen)

After the existing structure had been optimised for the new tasks and for the acting forces, the further vaulting procedure no longer differed from a newly built structure. The use of uniform radii and an approximation of the vault webs towards a barrel shape can also be verified for all the subsequently vaulted objects.

Conclusion

The art of vaulting in Grisons did not evolve continuously from within itself, but was rather introduced from outside and thereby skipped several intermediate stages. Almost overnight, the fundamental understanding of ribs changed and a new level of aspiration for Late Gothic vault construction was established. The completion of the chancel vault of the Church of St. Martin in Chur not only served as a prototype, but above all as an impetus and incentive, after which the new architectural forms spread to all the valleys of Grisons within a very short time thanks to diligent master builders and their work crews. The steadily rising building volume demanded more efficient construction processes so that the churches could be built in the shortest possible time. Thus, building techniques imported from southern Germany or Austria were combined with local traditions, which subsequently created the basis for optimised construction practices.

A massive optimisation of the construction processes was possible by simplifying the procedures in the planning and execution of the vaults. When designing the vault patterns, the master builders used their profound knowledge of the Euclidean geometry, though all the patterns could still only be drawn with compasses, straightedges or an auxiliary grid. At the same time, a new standard in the production of the voussoirs and the construction of the vaults was established, which was adapted to the problem to be solved by a few parameters, such as the curvature radius and the selection of the material. However, these parameters were kept as simple as possible to ensure the most efficient construction workflow. When choosing the materials, locally available types of stone were used in order to reduce transport distances and to enable on-site processing. In addition, when applying the arch radii, a few uniform radii were used to simplify the fabrication of the ribs and the prefabrication of the falsework even further. The design and construction of a vault should therefore not be considered as a rigid method, but as an interconnected process [20] that could be adapted to the given circumstances.

After 1470, the approach to the design and construction of vaults in Grisons no longer differed from the Central European standard. In contrast, the subsequent vaulting of existing churches was rather specific to the Late Gothic construction period in Grisons. Whether the technique of subsequent vaulting also had a similar significance in Late Gothic construction outside Grison cannot be answered more precisely at this time due to the lack of data. The existing churches had to be adapted to the new forces, which in Grisons was mainly achieved by adding massive buttresses or low-lying springers to increase the superimposed load, and in a few rare cases, the church was even converted into a new building type.

An efficient and cost-effective construction industry caused and promoted the Late Gothic building boom in equal measure, without the interaction of which it would hardly have been possible to cope with the volume of building that occurred. The optimisation of costs and labour time by reducing transport routes, by simplifying the fabrication of voussoirs or of temporary auxiliary constructions, as well as building in existing fabric and the continued use of existing structures therefore are topics that were just as relevant 500 years ago as they still are today.

Acknowledgment

This present study is part of a doctoral thesis at ETH Zurich supervised by Prof. Dr.-Ing. Stefan M. Holzer. The research project was concluded in 2020 and the thesis is now publicly accessible via the Research Collection of ETH Zurich (www.research-collection.ethz.ch).

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