Structural definition and comparison of early medieval roof structures

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**ABSTRACT:** Few roof structures remain unscathed from the 12th and early 13th centuries. The relatively large amount of well-preserved early roof structures in churches in Sweden is used as a point of departure to structurally define medieval Romanesque roof structures and to make comparisons within North-Western Europe. Investigations of actual roof structures along with study of written sources provide the basis for the study. The structures are defined and compared according to load-carrying system, included parts, centre distances, slope of roof, connection with wall, joints, outer roofing and decorations. We found many structural similarities and the structures seemingly belong to the same building historical context while also showing regional differences. The early medieval roof structures of North-Western Europe can generally and concisely be described as common rafter roofs with tie beams, without longitudinal bracing systems and having strut beams and collar beams in different combinations to support the rafters.

1 INTRODUCTION

In Sweden there are a large number of well-preserved roof structures from as early as the beginning of the 12th century. They represent an advanced building technology of the time. There are few written sources from the early Middle Ages to rely on, making us today highly dependent on physical artefacts for understanding the society and culture of that period. The medieval roof structures are an important and valuable cultural heritage, which can inform people of today of the development that occurred, the craftsmanship that existed, the materials available, the techniques of putting together and erecting buildings, knowledge of structural design and the creation of shelter, and the will to create spaces. The structures that remain represent a unique contribution to the European heritage of medieval timber structures.

There are at least two important incentives to raise knowledge of historic roof structures: To facilitate their interpretation and preservation. Preservation involves maintaining these structures for coming generations. Interpretation concerns their use as sources of information in order to obtain knowledge of the past. Taking appropriate restoration measures and interpreting them both require a proper understanding of the structural principles applying to such structures and the structural behaviour they display.

The aim of the paper is to present a synthesis and structural definition of early medieval types of Swedish roof structures originating in Romanesque architecture and make comparisons between countries in North-Western Europe. Since historic timber roof structures are working structures and often have complex structural properties, an engineering approach has been used in surveying them and analysis of structural behaviour have been carried out. Their structural action and structural components have been used for definition and classification of structural types. Seventy actual roof structures provide the basis for the study.

2 EARLY MEDIEVAL ROOF STRUCTURES IN SWEDEN

The oldest remaining roof structures in Sweden are found in churches. Maybe as many as 270 medieval roof structures are still in place, mostly in southern Sweden. Out of these, maybe one hundred are of Romanesque type. However, the figures are not completely reliable; no comprehensive inventory of medieval roof constructions has been compiled in Sweden. The majority of the medieval structures have not been satisfyingly investigated or recorded, probably some are not even identified yet. Identified and believed to be Swedish medieval roofs were surveyed and described by Linscott (2007) in a recent report. Linscott’s report is based on an earlier listing and reports of medieval roof structures (Sjömar, 1990, 1992, 1995, Thelin 2005) and newer,
unpublished, recordings and surveys of about 40 church roofs. The information was put into a database together with dendrochronological dating (www.timmerdraget.org/php_takkons4) and the report also refers to searches in this database. Roof structures of the same type were raised during several hundred years in Sweden. The oldest known roof structure is in Herrestad church 1112+5d (Bartholin 1990). Investigation and dating so far show that as many as 24 medieval churches have roof structures that most likely were raised in the 12th century.

Several varying types of early medieval roof structures are found in Sweden. The different types can be divided into two major groups, which are found in two geographical regions. In southern Sweden the builders raised roof trusses with tie beams, struts and later collar beams. In northern Sweden roof trusses with passing braces and collar beams were raised instead (Sjömar & Storsletten 1993). Only four roofs of this type remain in Sweden. They have not been included in the definition of structural type below since they are a different structural type even though they are contemporary. At the same time, the roof structures from the 12th and the 13th centuries show many similarities. The tools that were used are the same, axe and draw-knife “skave” and the wood is prepared in the same way. The craftsmen used a special hewing technique, “sprätältäjning”, whereby the axe cut back and forth along the side of the log, which makes a very characteristic herringbone pattern. Some surfaces are also very finely planed with the draw-knife. The different parts in a roof truss are also put together in the same way, with straight lap joints. The builders, in both northern and southern Sweden, had the same basic idea of how the wood should be treated and how a roof should be put together and raised. They seem to have belonged to the same building tradition.

The very oldest remaining roof structures are technically fully developed and the craftsmanship is excellent. The builders, in both northern and southern Sweden, that raised the roof of a remote parish church in the first half of 12th century mastered the materials and the construction completely. The highly developed skill of craftsmanship shown in the structures, the permanence of the building tradition over several hundred years, and the spread of the same building tradition in such a large geographical area indicate the existence of an older (wood) building tradition in Sweden that had existed for a long time before the 12th century.

Dendrochronology was developed in the 1980s in Sweden (Bartholin, 1994). There are references to pine and oak. From the dendrochronological dating we can get a picture of how the roof structures developed over time in Sweden, even if very few of the younger roof structures, connected to Gothic architecture, have been investigated. In principle, the builders changed during the 14th century, from raising Romanesque roof structures to building roof structures without tie beams adapted to high Gothic vaults. The two different systems were used in parallel for at least 150 years. In the middle of this period, the second half of 14th century, it seems as if very little was built at all, probably as a result of the Black Death. The use of the special hewing technique, “sprätältäjning”, that is found in all the 12th- and 13th-century structures terminates completely in this period.

### 3 DEFINITION OF STRUCTURAL TYPE

In order to find and to define the characteristics of the structural types used in the early Middle Ages in Sweden 70 roof structures have been used. The name of the church, which part of the church (nave or chancel) the roof structures are standing on, their geographical location and the type of structure are presented in Table 1 and in Figure 1. Of the 70 roof structures 46 have been dated according to the database described above. Unfortunately, many of these datings still have uncertainties. The uncertainties are due to a part of the roof structure being dated but not enough investigations of it having been carried out in order to certainly ascribe the dating to the entire roof structure. Eighteen have parts dated to before 1150, fifteen to before 1200, nine to before 1250, one to before 1300 and three to before 1350. Of the 70 roof structures 21 have been examined and documented by the author. Thirteen roof structures have not been examined by the author in person but there is documentation in drawings and descriptions. For the final 36 roof structures the information consists solely of written documentation. This data cannot be considered as certain as in the other cases.

To identify possible common characteristics of the early Swedish medieval roof structures several criteria have been used: load-carrying system, elements and shape, centre distance, slope of roof, connection with wall, joints, outer roofing system and decorations.

All of the 70 roof structures carry the vertical (gravitational) load cross-wise to the longitudinal direction of the building from wall to wall, with trusses of the same design and size which are generally repeated consecutively at a close distance, see Figure 2. This system of carpentry is called common rafter roof or uniform scantling.

The roof structures have tie beams that connect the bases of the roof trusses and provide support for the horizontal thrust. They do not have a separate structure for longitudinal stability. Longitudinal stability is achieved by boarding (Fig. 10) below the outer roofing, which possibly provides a stabilizing plate together with roofing material and in many cases connects the roof trusses with stone gables. In
the early roof structures the tie beam is commonly
embedded into the masonry on top of the walls
which can also provide some longitudinal stability,
see Figure 3.

Table 1 and Figure 1 show the inner parts of the
roof trusses. The oldest roof structures have strut
beams (angle braces) that connect the rafters with
the tie beam, for example Herrestad church and
Garda church, see Figures 4 and 5. There is a great
variety in number of struts and how they are placed
in relation to each other. There are a large number
of roof structures with crossed strut beams, for example
Asby church and old Jät church, see Figures 6 and 7.
One interesting aspect is the lack of collar beams in
the early roof structures from the 12th century. The
collar beam becomes common during the 13th cen-
tury.

Table 1. Churches with roof structures that have been part
of the study and their type.

<table>
<thead>
<tr>
<th>Type</th>
<th>Church, part and province</th>
</tr>
</thead>
<tbody>
<tr>
<td>BX</td>
<td>Flistad nave ÖG, Granhult chancel SM, Kinne-Vedum chancel VG, Skalunda chancel VG, Söne nave VG, Torpa nave SÖ. Visseltofta chancel S.</td>
</tr>
<tr>
<td>BSX</td>
<td>Hagebyhöga nave ÖG, Råda nave VG, Söne chancel VG.</td>
</tr>
<tr>
<td>B2S</td>
<td>Herrestad nave ÖG.</td>
</tr>
<tr>
<td>B2Xa</td>
<td>Asby nave and chancel SM, Asby nave ÖG, Bringetofta nave SM, Eriksberg nave VG, Granhult nave SM, Göteve nave VG, Hemmesjö nave and chancel SM, Jät old chancel SM, Kinne-Vedum nave VG, Mularp nave VG, Persborg chancel S, Skepperstad nave SM, Suntak nave VG, Tidersrum nave ÖG.</td>
</tr>
<tr>
<td>B2Xb</td>
<td>Marka nave VG, Norra Solberga nave SM, Väversunda chancel ÖG.</td>
</tr>
<tr>
<td>B3Xa</td>
<td>Jät old nave SM, Mosjö nave N, Visseltofta nave S.</td>
</tr>
<tr>
<td>B3Xb</td>
<td>Forsby nave VG, Forserum nave SM, Marum nave VG, Väversunda nave ÖG.</td>
</tr>
<tr>
<td>B3Xc</td>
<td>Gökhem nave VG, Mjäldrunga nave VG.</td>
</tr>
<tr>
<td>BS2Xa</td>
<td>Skalunda nave VG</td>
</tr>
<tr>
<td>BSH</td>
<td>Gräve nave N, Pelarne nave SM, Stenberga nave SM, Torpa nave ÖG.</td>
</tr>
<tr>
<td>BS2H</td>
<td>Känna nave SM, Lyngsjö nave S.</td>
</tr>
<tr>
<td>BXH</td>
<td>Kumla nave ÖG, Roma nave G.</td>
</tr>
<tr>
<td>BS2H</td>
<td>Björka nave S, Källunge nave G, Vireda nave SM.</td>
</tr>
<tr>
<td>BSHS</td>
<td>Drev old nave SM, Nävelsjö nave SM.</td>
</tr>
<tr>
<td>BSHX</td>
<td>Dädesjö old nave SM, Bälayan nave? SM.</td>
</tr>
<tr>
<td>BSH2X</td>
<td>Edestad chancel B.</td>
</tr>
<tr>
<td>BSHSH</td>
<td>Linde nave G.</td>
</tr>
</tbody>
</table>

*Province: ÖG Östergötland, VG Västergötland, G Gotland, S Skåne, SÖ Södermanland, SM Småland, N Närke, B Blekinge.

Other elements that exist in the early medieval
Swedish roof structures are ridge beams and steering
plates (see Figure 8). A ridge beam is a longitudinal
beam that connects the roof trusses at the ridge. Fif-
teen roof structures still containing ridge beams were
identified, nine of them dated to the 12th century
and one to the 13th century, while the remaining five
lack dating. A steering plate is a beam that lies be-
tween the tie beams or collar beams of the roof truss
in the longitudinal direction of the building. It is not
known whether the steering plate has had any func-
tion other than being decorative. It can possibly con-
tribute to keeping the tie beams and collar beams in
place in the structure and keeping them from turning
over.

The material used is pine or oak. The historic
timber material used is generally of high quality but
can in some cases be damaged by biological or other
causes, making it difficult to estimate its actual
properties. Timber pegs and iron nails were both
used in joints throughout the Middle Ages in Swe-
den. The joints commonly are straight lap joints, see
Figures 9 and 10.
The roof structures are generally placed rather close with a centre distance less than a metre between the tie beams. There are a few examples with longer centre distances, up to 1.25 metres. The centre distance can also show great variations within the same roof structure. Most of the early medieval roof structures on stone churches in Sweden have a slope of the roof between 37 and 50 degrees. There are some exceptions, for example the old Jät church, Småland, and Garda church, Gotland, having a slope of 59 and 53 degrees respectively, see Figures 5 and 7. The oldest dated roof structure has the flattest roof, see Figure 4. The timber churches generally have a steeper pitch between 55 and 60 degrees.

The tie beams of the early medieval Swedish roof structures usually lie more or less embedded into the masonry of the top of the walls, see Figure 3. There is usually one wall plate situated at the outside of the wall, to which the tie beam is connected by a notched joint, see Figure 9. The close relation between the wall and the tie beam leads to the assumption that the roof structure has a vertical support along the width of the wall which provides a shortening of the span since the walls usually have a thickness of about one metre. The connection with the wall plate as well as with the masonry gives good possibilities for transferring horizontal forces by friction between the roof trusses and the wall. This works as proved by examples where the tie beams have been cut off for various reasons. The situation is different for timber churches where the tie beam lies notched over the top timber of the wall, and it is probable that the tie beams also act to hold the timber walls together.
Figure 7. The nave roof structure of Old Jät church, Småland. It has three pairs of crossed strut beams between the rafter and the tie beam. The tie beams lie embedded into the masonry on top of the wall. In the middle of the structure above the tie beams there is a steering plate.

Figure 8. The image to the left shows the ridge beam in the Garda church, Gotland, from above and the image to the right show the steering plate in the Old Jät church, Småland.

Figure 9. The connection between the rafter and the tie beam and between the tie beam and the wall plate at Forshem church, Västergötland. The wall plate and the tie beam was originally embedded into the top of the wall but has been exposed since the church was vaulted and cross-arms were added.

Figure 10. Timber joints of the straight lapped type and cleaved boarding in the nave roof structure of Old Drev church, Småland.

Figure 11. Decorations in the nave roof structure of Gökhem church, Västergötland.

Different types of outer roof were used. In most cases they have been changed or replaced several times. Common types today are shingle, wood, tiles, slate and tin. Below the outer roofing material there is boarding. If the original boarding is preserved it is usually of cleaved and cut timber, see Figure 10. Later types are sawn, and if they are replaced in modern time planed boarding is normally used.

Studies of roof structures from the 12th century show that the church interior originally was open to the roof (Sjömar 1992). An investigation of Hagebyhöga church, Östergötland, raised in the 12th century with walls of stone, shows that the interior both in the nave and in the chancel originally had no ceiling; the roof structure was visible. The wooden roof construction probably gave the room a character like that in the Norwegian stave churches today. Several roof structures from the 12th century are given sculptural forms (see Figures 5 and 11). Some parts were probably painted. Other signs of open roofs are plaster that remains on the walls above later vaults or ceilings, see Figure 3. This means that the wood
craft was an important means to create character in the interior, also in the stone churches. Later a flat ceiling made of planed boards was put up in Haga-byhöga church before, finally, some hundred years later, stone vaults were built. Traces of such wooden ceilings are also found in other churches and some still exist today. In many Swedish parish churches vaults were built in the 14th and 15th centuries.

4 COMPARISONS WITHIN A NORTH-WESTERN EUROPEAN CONTEXT

When comparing the early medieval Swedish roofs with other North-Western European roofs that were raised about the same time, it is clear that they are all part of the same context. Published surveys and studies, in Denmark (Aaman Sørensen 1995, Madsen 2007), Norway (Storsletten, 2002), England (Smith, 1975, 1981, 2006, Hewett, 1981, 1985, Walker, 1999, Courtenay 1993), France (Corvol-Dessert et al. 2002, Epaud, 2003, Courtenay 1993) and Germany (Binding 1991, Lohrum 2006) show that the constructions in all these countries and Sweden have similarities. Also eastern parts such as Romania seem to have some similarities (Szabó 2005). The studies show, just as in Sweden, that the roofs were raised by skilled craftsmen and that the crosswise load-carrying system of the common rafter roof with tie beams on every truss seems to have been used throughout Europe for the early medieval Romanesque roof structures.

Most sources refer to the early medieval (Romanesque) roof structures as having collar beams often in combination with strut beams (Fletcher & Haslop 1970, Corvol-Dessert et al. 2002, Courtenay 1993, Szabó 2005), but there are exceptions in France, Belgium, Denmark and Germany of early medieval roof structures without collar beams similar to those in Sweden. Binding (1991) describes a similar development to that in Sweden where the earlier roof structures lack collar beams. The collar beams seem to appear in Germany in the second half of the 12th century. Courtenay (1993) and Epaud (2003) describe the roof structure of St Gertrude at Nivelles, constructed in 1046, which no longer exists, and Binding (1991) describes the monastery church in Billigheim constructed in 1180/1190. Both St Gertrude and Billigheim are very similar to the roof structure at Herrestad church in Sweden dated to 1112. It has four angled struts connecting the rafters with the tie beam, see Figure 4. The roof structure of St Denis in Liège is also similar but has one extra pair of struts (Corvol-Dessert et al. 2002). In France there are several examples of roof structures with vertical struts, as in the roof structure of Saint-Barthélemy, Liège, and Saint Pierre-de-Montmartre, Paris (Corvol-Dessert et al. 2002). Randerup church in Denmark (Madsen 2007) and St Martin in Sin- delfingen (dated to 1132) in Germany (Binding 1991) are of the type with only one pair of strut beams, like for example Garda church in Sweden, see Figure 5. There are also examples of roof structures with crossed strut beams in France and Denmark. The church of St Christophe in Chabris, France, has a roof structure with six crossing strut beams (Epau 2003), similar to the old Jät church (Fig. 7). Vester Nebel church in Denmark has a roof structure with four crossing strut beams (Madsen 2007), similar to Asby church (Fig. 6). Both the Danish examples mentioned have in later times been reinforced with collar beams.

The use of ridge beams (or ridge pieces) in some of the Swedish roof structures is interesting, see Figure 8. Courtenay (1993) claims that ridge beams cannot be found in England or France from 1050–1300 when discussing the late Norwegian stave churches that contain both ridge beams and purlins. Maybe the ridge beams on the early medieval roof structures demonstrate a connection between the different Scandinavian roof structure types.

Courtenay (1993) thinks that lack of longitudinal bracing is characteristic of the early medieval roof structures. This is also described by Corvol-Dessert et al. (2002) and Binding (1991). Examples of diagonal elements on the inside of the rafters to provide longitudinal bracing are described by Fletcher & Spokes (1964), Corvol-Dessert et al. (2002) and Madsen (2007). This type of longitudinal bracing is used in later medieval times in Swedish roof structures but generally not in the early medieval types.

The centre distance between the roof trusses, normally being less than a metre, as well as the slope of the roofs, normally between 40 and 50 degrees, seem to be generally similar across Europe for the early medieval roof structures. Joints are generally described as being of the simple lap type (like the Swedish ones) or being notched or having dovetailed profiles (Courtenay 1993, Fletcher & Spokes 1964, Fletcher & Haslop 1970, Szabó 2005, Madsen 2007).

Courtenay (1993) describes the earliest Romanesque roofs in Northern Europe as being open and visible from the inner space or intended to support a panelled ceiling. In contrast to the Swedish ones, these types of roof structures are rare and only fragmentary preserved. Evidence of decorated roof structures from early medieval times outside Sweden is difficult to find. Binding (1991) says that the question of open roofs in Germany is debated and many roofs of churches without vaults have or show evidence of earlier ceilings. There are later examples of open roofs from the 13th century but they are of a different structural type. In England the tradition of open and visible roof structures was developed in later medieval times (Smith 2006). Smith also describes the use of a “locking-plate” in Lincoln cathedral from around 1200 that seems to be similar to the Swedish steering plates.
The connection between the roof trusses and the wall normally consists of wall plates in order to distribute loadings more uniformly to the top of the walls. Examples of the use of masonry-embedded tie beams and rafter feet exist in Germany, Denmark and France (Binding 1991). One German example very similar to the Kaga church (Fig 3) is St Agidius in Mittelheim, which was lost in the 20th century. There is one English example in the nave roof of Kempley, dated to 1120–1150 (Smith 2006). There are also examples of roof structures totally devoid of wall plates (Courtenay 1993) although most seem to have double wall plates.

5 STRUCTURAL BEHAVIOUR

The simplest type of roof structure consists of two single rafters that rest on each other with a hinged joint at the top. In carrying vertical load such a structure creates both vertical and horizontal forces that act upon the supports. The horizontal forces need to be supported to avoid collapse of the structure. The early medieval roof structures have tie beams that provide such a support, see Figure 12. If the tie beam is missing or has been cut off the roof structure becomes dependent on an outer support provided by the walls to avoid large deformation and stress or even collapse.

With an increase in span the problem of deflecting rafters with high bending moments soon becomes evident, see Figure 12. The early solution was to put strut beams between the rafters and the tie beam to support them. Figure 12 and Table 2 presents the results from computations made on roof trusses with an outer span of nine metres and a roof angle of 47°, which is a typical size and shape of early medieval roof trusses. The support conditions are based on a one-metre-wide wall where the vertical support is given at the outside, 150 mm from the outermost part of the roof truss, and on the inside of the wall. The tie beam has 230×150 mm cross-section and the other parts have 150×100 mm cross-section. The strut beams are connected to the tie beam 3.87 m from the joint between the rafters. The tie beam and the joint between the strut beams and the rafters are halfway to the ridge in the vertical direction from the tie beam. The centreline of the collar beam is 2.70 m above the centreline of the tie beam. The material is wood with an E-modulus of 10 GPa. The load is vertical and symmetrical and consists of the timber (density 500 kg/m³) and the weight of the outer roofing consisting of boarding and tiles which weigh 53 kg/m². The roof trusses stand one metre apart.

<table>
<thead>
<tr>
<th>Truss type</th>
<th>Normal force in tie beam by rafter foot (kN)</th>
<th>Normal force in strut beam (mean value) (kN)</th>
<th>Max moment in rafters (kNm)</th>
<th>Max moment in tie beam (kNm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>1.83</td>
<td>–</td>
<td>2.20</td>
<td>0.59</td>
</tr>
<tr>
<td>Case B</td>
<td>1.70</td>
<td>-1.62</td>
<td>0.42</td>
<td>2.70</td>
</tr>
<tr>
<td>Case C</td>
<td>3.20</td>
<td>0.18</td>
<td>0.61</td>
<td>0.65</td>
</tr>
</tbody>
</table>

The moment diagram in Figure 12, case B, shows that the strut beams are successful in providing support, by compression in them, against deflection of the rafters but at the expense of a greatly increased deflection and moment load of the tie beam, see Table 2. The support provided by the strut beams thus becomes dependent on the bending stiffness of the tie beam. The problem of too much deflection and bending in the rafters is transferred to the tie beam instead. This led to the use of tie beams with large dimensions in such roof structures.

The collar beam is a clever innovation that makes the rafters support each other by compression in the collar beam. If it is combined with strut beams it can mean, depending on the placing of the collar beam, that the strut beams act as hanging elements supporting the tie beam instead of loading it, since the support of the rafters has been taken care of by the stiffer load path provided by the collar beam, see Table 2. The use of collar beams also gives an in-
creasing horizontal thrust at the base of the roof that has to be transferred by the joint between the rafters and the tie beam, see Table 2. The collar beam does not provide any wind bracing more than making the rafters act together. The strut beams, on the other hand, can act as wind braces in the roof structures.

6 CONCLUSIONS

It seems that surprisingly many Romanesque roof structures remain in Sweden. Of the very few North-Western European standing roofs that were raised in the first half of 12th century, at least 10 still exist in Sweden. These, together with the rest of the well-preserved medieval roof structures, are an important and valuable cultural heritage in a European perspective. The remaining roof structures from early medieval times in North-Western Europe clearly show that they are part of the same context and have many structural similarities but also some differences. They are common rafter roofs that carry their load crosswise to the longitudinal direction of the building; they have tie beams on every roof truss and in many cases consist of similar inner elements. The sources indicate that the chronology of early roof structures without collar beams is true also outside Sweden. The collar beam is shown to be an innovation that improves the load-carrying system for vertical loads.

Additional studies are needed to complete the picture of early medieval roof structures, not least in Sweden. More systematic investigation and surveys of the medieval roof structures in combination with dating methods could provide a means to achieve a more comprehensive overview that would shed further light on this significant heritage of carpentry.

REFERENCES