Morup Church: a Case Study on Structural Behaviour of Historical Roof Trusses

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Abstract

In Sweden, roof trusses in churches all over the country form a large and interesting category of ancient wood constructions that is relatively unexplored. Today, lack of knowledge about these constructions threaten their existence, as they are often radically changed or even demolished when churches are being restored. Morup church in Halland, Sweden, has been examined as a representative example of a particular type of church with a wide nave and a relatively flat roof. Morup church has been examined on site and the structural behaviour of the roof trusses has been investigated.

Research on historical roof trusses in Swedish churches

The great number of historical timber roof trusses preserved in Swedish churches form a rich material for studies in the development of carpentry from the 12th century and onwards. Unfortunately, today, roof constructions are rapidly being removed or altered through repair measures. Modern methods and materials are used, although constructions built with traditional techniques has proved to stand for hundreds of years. There is a lack of knowledge about the structural behaviour of old timber constructions and about the safety aspects on them. In addition, methods are needed to evaluate the structures accordingly. There is also a need for an inventory of restoration problems affecting roof constructions. The author is co-operating with the Swedish Central Board of National Antiquities in a research project concerning these questions.

The research is carried out in two steps, where the first is concluded and the second is in progress. In the first step, a survey was made to identify what knowledge there is concerning the shape of old roof trusses, their structural behaviour and restorations problems associated with them. [1] The study comprised literature studies, interviews with engineers and architects working with restoration and a case study.

It was found that the shape and structural behaviour of the preserved mediaeval roof trusses are comparatively well known. There are basically two different types; early medieval trusses with tie beams and later ones without tie beams. The roof trusses are connected to different spatial concepts. Early
churches had visible roof trusses, and later flat ceilings. In the 14<sup>th</sup> and 15<sup>th</sup> centuries, most churches were altered by the addition of vaults which lead to the removal of tie beams, or replacement of the whole roof construction. A common cause for problems in medieval churches is the outward thrust from roof trusses without tie beams. The consequences are stability problems for the walls, too high tensile forces in the joints of the trusses and too high bending moments in the rafters.

It was also found that very little is known about constructions built after the Reformation (i.e. from about 1530).

Moreover, little is known of the shape of joints and how joints have been chosen to fit different load types. This applies for the whole period of time, from the Middle Ages to the time for industrialisation (1850:ies).

In the second step of the research on historical roof trusses in churches the studies are directed towards later constructions. The aim is to develop knowledge about shape and structural behaviour, common restoration problems and suitable repair methods for these structures. The design of details such as joints will be explored. The research will mainly be carried out by using actual buildings as resources. This phase of the research has been started with an investigation of Morup church in the province of Halland in Sweden.

**Historical-technical survey of Morup church**

Morup church was studied in a "historical-technical survey", that is an investigation comprising:

1. A historical description (the formation of the building throughout times, alterations and repairs made).
2. A documentation of the present shape and state of the building.
3. Analysis.

The study has two aims: to diagnose the state of the church and to generate new questions for further studies. Morup church was chosen as an object of study since, although the oldest parts of the building are mediaeval, it represents in its present state, a large group of churches that were built in the end of the 18<sup>th</sup> and beginning of the 19<sup>th</sup> century. These churches are rectangular in shape and have a rather wide nave and large windows. The church rooms are often covered by barrel vaults made of wood panels. They are sometimes somewhat disparagingly referred to as "Tegnér barns"; the resemblance of barns relates to their simple shapes and large, light church rooms. (Esaias Tegnér (1782-1846) was bishop in Växjö and was a spokesman for the construction of this kind of new, light churches.) The roofs are less steep than those covering older Swedish churches. The antiquarian authorities suspect that stability problems often occur in this type of building due to the concept of wide naves and flat roofs.
Brief history of Morup church

Morup church is situated by the sea, about 20 km north of the city of Falkenberg on the west coast of Sweden. The church was erected in the beginning of the 13th century and was built in red brick, contrary to most churches in the region from that time, that were built in grey stone. [2]

Originally, the church had a flat ceiling hiding the roof trusses. This indicates that the roof trusses were of one of the known early medieval types with tie beams. The church has never had masonry vaults. The spatial concept of Swedish and Danish churches were otherwise frequently altered during the late Middle Ages by the introduction of vaults. The roof structure was then normally rebuilt by cutting off the tie beams of the trusses, or replaced.

The mediaeval church was probably only slightly altered until 1804, when it was rebuilt to have twice its previous length. The new part of the church was built with large windows. Similar windows were put in also in the old part of the church. New roof trusses were erected, without doubt those that are present today. A roofing of slates on a wooden panelling was laid and the same kind of roofing covers the church today.

In 1810, a tower of grey stone was added to the west church gable. Prior to its erection, a large crack was observed in the west gable. Thirty years later, there were problems with cracks in the tower, and in the 1850ies it started to lean. In 1854 the tower was provided with counterforts.

Except from the opening of two doors, the alterations that have been made to the building since 1854 consist mainly of ordinary maintenance.

Figure 1 Painting by R. S. Bengtsson from 1918, showing Morup church. [2]
Present state

The geometry of the church was measured in order to produce a cross section and horizontal sections. The measuring was made with simple tools, such as measuring-tapes, strings and plumbs.

The cross section shows that the walls are leaning about 10 cm outwards in that section, but that the windows are more upright, figure 2.

The roof trusses are made of pinewood. They are cut together with simple halving joints fixed with wood dowels or wrought-iron nails and mortise joints. The trusses are not fixed to the walls or to the wall plates, they merely rest on them. This means that horizontal forces from the roof trusses have to be transmitted through frictional forces to the walls. There is a gap between each roof truss and the outer wall plate, so that no transmission of forces can take place there for permanent loads. The roof trusses are therefore only supported in the position of the inner wall plate for this load case. In a few roof trusses, the joints connecting the collar beam to the rafters are pulled apart. In one roof truss, the dowel in this connection is broken. The rafters are slightly curved.

Figure 2 Cross section of Morup church. The indication A-A refers to figure 3.
In order to illustrate the global deformation pattern of the walls, two horizontal sections were produced at different levels in the nave; one section at breast-height and one just below the external cornice. A Cartesian system of coordinates was arranged with the aid of a theodolite. The system of coordinates was marked with strings. Distances between the strings and chosen points on the walls were measured.

The drawings show that the walls form slightly bent curves at both breast-height and at the height of the cornice. Figure 3 shows a simplified drawing of the deformation pattern at breast-height in an exaggerated scale. In order to determine the position of the roof trusses on the top of the wall, a horizontal section showing the lower rafter ends was produced. The positions of the rafter ends were measured in relation to one string at each side of the wooden vault. The drawing showed that the lower end of the rafters describe curved lines similar to those of the wall.

The geotechnical prerequisites are important when the whole load bearing system of the church is studied. The earth layers are, from ground level and downwards, medium dense sand, mud, peat and clay. The foundation of the tower is unfortunate, as it is founded practically on the level of the mud and peat, while the nave and the chancel are founded on the sand layer. [3] Large cracks can be observed between the tower and the nave and smaller cracks are visible above the windows of the nave and chancel. Obviously, the tower is settling. It is less obvious to decide whether the rest of the church is settling or if the cracks above the windows are related to the curvature of the walls.

Figure 3  Simplified horizontal section showing the deformation pattern of the church walls at breast-height.
Analysis

The observed deformations raise the question of whether the roof trusses are pushing out the walls or not.

The structural behaviour of the roof trusses was investigated with the aid of CALFEM, a toolbox for MATLAB.[4] The trusses were modelled with first order beam elements. The halved joints and mortise joints were assumed to allow free rotation and thus act as pinned joints. The loads were determined according to Swedish building codes.[5] Two load cases were modelled – one case with permanent loads and one case with a combination of permanent loads, symmetrical snow and wind.

The structural behaviour of statically indeterminate structures like this one depends on the support conditions. Different models of supports were assumed – hinge supports on both sides of the truss, hinge and roller supports, and finally, hinge supports with prescribed translations.

Hinge supports on both sides. - It has previously been mentioned that the roof trusses are supported at only one point on each wall, in the position of the inner wall plate. In a first model, hinge supports were modelled in the position of the inner wall plate. The deformation plot in figure 4a shows however, that additional supports are needed in the position of the outer wall plates.

The deformation and normal forces calculated for a case with permanent loads, hinge supports in the position of the inner wall plate and roller supports in the position of the outer wall plate are shown in figure 4b and 4c.

For this model, only small normal forces appear in the truss. Two joints will be exposed to tensile forces. It should not cause large problems though, as it concerns the mortise joints in the end of the rafters, where tensile forces can be transmitted through direct contact between the connected members.

An examination of the reaction forces give at hand that the values of the horizontal forces from the roof trusses are so high, that the trusses will probably slide on the walls plates and on the masonry. The ratio of horizontal to vertical reaction is 1.48. A value of the coefficient of static friction for wood to wood can be assumed to be $\mu_{\text{wood-wood}} = 0.6-1.0$. For wood to masonry one can assume $\mu_{\text{wood-masonry}} = 0.8-1.0$.[6] (As no friction values for wood to masonry could be found, values for wood to concrete were used.) Thus, this model does not seem to reflect the true structural behaviour of the roof truss. In addition, studies of the construction on site showed, that no force can be transmitted to the outer wall plate for this load case.

Hinge support and roller support. - In another model, the truss was assumed to be supported by a hinge support and a roller support in the positions of the inner wall plates. For this model, the pattern of the calculated deformations (figure 4d) corresponds to the deformations that were observed in the real trus-
ses. The translation of the lower end of the scissor brace was calculated to 4.4 cm for the case of permanent loads and to 10 cm for the case of permanent loads, wind and snow.

The normal forces are shown in figure 4e. The figure shows that a number of joints become subjected to tensile forces as the truss slides apart. A critical point is the connection between the collar beam and the rafter where the tensile force is transmitted only by a wooden dowel. The tensile force in this point reach 3.8 kN and 7.7 kN respectively for the two load cases.

Swedish building codes tell nothing about how to predict the load bearing capacity for this kind of joints. A possible way would be to consider the dowel as a beam and predict its shear force capacity. The dowels have diameters of about 25 mm and are made of coniferous wood. Assuming that the dowels are made of clear wood with a shear strength $f_{sk} = 8$ MPa we get:

$$F = f_{sk} \cdot A = 8 \cdot \frac{\pi \cdot 25^2}{4} = 3.9 \cdot 10^3 \text{ N}$$

(1)

The dowels are consequently close to failure for permanent load and will fail for the case of simultaneous wind and snow. In the real structure, the joints between collar beams and rafters are damaged in some of the roof trusses.

Recent research carried out in Germany show however, that two different types of failure occur in halved joints fixed with oak dowels.[7] One type of failure is initiated when the bearing value in the jointed members is exceeded. Another type is initiated by bending failure in the dowel. If this is true also for dowels made of pinewood, then the load bearing capacity determined above would not be accurate and should probably be higher.

The model with one hinge and one roller support appears to reflect the true structural behaviour of the trusses for the case of permanent loads. However, it does not seem to be a good model for the case of simultaneous permanent loads, wind and snow.

**Fixed supports and forced deflection.** The results presented above show that on one hand, the friction force that can be assumed to be present between roof truss and wall is not sufficient to prevent the roof truss from sliding, thus discriminating a structural behaviour of the trusses like the first one (with hinge supports on both sides). On the other hand, the structural behaviour for a truss on one hinge and one roller support does only seem to be true for the case of permanent loads. Therefore, in a last model, it was assumed that the rafters have slid apart 4.4 cm due to permanent loading (in accordance with figure 4d) and that, in this position, the walls will carry the horizontal forces from the trusses caused by wind and snow.

Figure 4f and 4g shows the results for the load case with both permanent loads, wind and snow. The horizontal reaction force does not exceed the friction force that can be assumed to exist between roof truss and support. Also,
the walls were found to be stable for this model, as the bearing capacity of the soil exceeds the load.

Figure 4 Deformations and normal forces for different supports models and load cases. C = compression, T = tension.
A) Two hinge supports. Permanent loads. B) and C) Two hinge supports and two roller supports. Permanent loads. D) and E) One hinge support and one roller support. Permanent loads. F) and G) Prescribed translation. Permanent loads, wind and snow.
Conclusions

The structural behaviour of the roof trusses is such that the collar beams are permanently subjected to tensile forces. This explains the occurrence of damage in the joints connecting the collar beams to the rafters. One could say that the walls do not need to carry the horizontal forces caused by permanent loads, on the expense of the roof trusses.

For higher loads, the walls carry part of the horizontal forces from the roof trusses, without risk of the roof truss sliding or the walls being unstable.

Possibly, these horizontal forces have, in combination with settlements in the mud and peat layers of the soil below the church, caused some deformation of the walls. However, it seems like most of the deformation of the walls was present already before the existing roof construction was erected. The deformations may have been caused partly by an earlier roof structure.

Further studies of Morup church are needed in order to confirm the proposed structural behaviour. Archive studies will hopefully tell the age of the present windows, as this will help dating the observed deformations of the walls (the windows are more upright than the walls themselves). Also, the age of the plaster will help dating the cracks in the walls.

Moreover, a monitoring program need to be started in order to find out whether the deformations of the trusses, walls and tower are still going on or not.

Probably, repair measures will be necessary. These will, as a suggestion, comprise the establishment of steel ties connecting the lower ends of the rafters in order to eliminate the tensile forces acting in the collar beams.

This first study of Morup church generate some questions to be answered in the future. For example, there is a need for studies on the behaviour of traditional wood joints fixed with dowels of pinewood. Furthermore, comparative studies of similar churches will show how the problem of bridging a wide room with flat roofs has been solved and if the same kind of damage that were observed in Morup church is frequently occurring.

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References


