The structural behaviour of spires

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ABSTRACT: In spite of the fact that there are plenty of examples of historic spatial roof structures – in spires, castle towers, etc. – in the technical literature information about this kind of structure can rarely be found, especially about their structural behaviour. The development of computerised 3D programs of analysis and modelling helped us to improve our understanding of this. This paper offers a guide to assist in the understanding of the structural behaviour of the load bearing structure of spires, offering a typology, followed by a detailed presentation of these structural analyses.

1 INTRODUCTION

To build a shelter against sun, wind or rain is one of the most fundamental of human needs. Since the earliest times, people have joined together pieces of wood, forming the first spatial structures – conical timber huts or dwellings. Later on, the construction of towers of fortifications and churches continued the still ongoing development of spatial roof structures.

Following technical development over centuries, architectural styles also had their remarks on spatial roof structures.

The authors of the present lecture represent the PhD Studies School within the Technical University of Cluj-N. (Transylvania), where since 1998 a number of PhD topics addressed the scientific study of various historic roof structures of the Gothic, Baroque and Eclectic periods. Spatial roof structures (especially spires) from the same periods are described in this paper.

2 STUDYING SPATIAL ROOF STRUCTURES

2.1 Definitions

So that we have the same terminology, we would like to offer a few definitions:

Spire: a tapering conical or pyramidal structure on the top of a building, particularly a church tower with the proportions between width and height of the spire being between 1/1,3–1/5.

Historic roof structure: built of timber by an empirical-intuitive load-bearing structural concepts, without the support of designed or calculated engineering theory, characterized by its support coming exclusively from supporting load-bearing sub-units (such as walls, pillars, columns), usually located on the external face or edge of buildings [6].

Spatial system: the spatial system of a historic roof structure is formed from different load-bearing structural materials (hardwood or softwood timber) connected by joints between lineal elements, so forming a stable truss system. The spatial systems of a historic roof structure can either be jointed together with frames (particularly if the layout is rectangular), or it is a real spatial system, which cannot be divided into frames; to split up these roof structures into frames would imply a forced procedure, which can cause errors in the creation of the mechanical model [6].

2.2 Classification and components

Requirements:

a) prevention from overturning;
b) the basic horizontal framing system with secure joints to rafters and other elements;
c) a suitable bracing system to act against wind loads.

The spires generally are four or eight sided, high, conical roof structures. The whole height of the spire is distributed in levels by horizontal framing systems (less then 4,50 m one from the other). The lowest framing system is the base of the spire, connected to the walls of the tower through wall plates. All the other elements start here, so this decides the structural concept of the spire.

Two different systems of spatial roof structures have been developed in Europe: one with long Kingposts (Figure 1a.) and the other with short Kingposts (Figure 1b).
2.2.1 Spires with long Kingposts

The kingpost, the “spine” of the spire, is supported by the basic framing system and supported vertically by the angle braces or scissor braces, is the most “mysterious” element of the structure. Structural analysis shows the real purpose of this element.

The basic framing system can have diagonal or orthogonal (parallel with the sidewalls) main timber beams. The secondary timber beams are connected to header beams, or directly to the main beams. (Figure 2.)

Only two beams can span across, so holding the Kingpost at the crossing.

2.2.2 Spires with short Kingposts

Usually these have eight faces. The basic framing system can have two different forms: orthogonal connecting across corners (not diagonal), or polygonal system having an open space in the middle of the spire. (Figure 4.)

The next two or three or upper levels are constructed with similar framing systems (Figure 1b).
Preventing the spire from overturning is provided by a similar system to that described previously, using metal bars at the corners.

The main difference is in the bracing system acting against wind-loads. Supported by the framing systems, there are lower and upper purlins, connected by scissor bracings, set out at two or more levels (Figure 5). If the spire is the typical eight sided model, these scissor bracings above the second level are set out alternately in four-four sides. If the spire is four-sided, these braces are set out on each face, but they can be missing at the top level.

Common rafters are connected at the top to the short Kingpost, which is supported by the last (or last two) framing systems.

Regarding the construction of spires, we have found a description in a nineteenth century carpenter’s book, written in the period when a lot of spires of this type were constructed: “The spires should not be very rigid; they should allow a small amount of movement during storms. For this reason the beams of the framing systems should be screw fixed to the common rafters, but the roof bracing system’s beams should not be screw fixed to the common rafters, rather they should finish a few centimetres from the rafters. The basic framing system should be well fixed into the sidewalls of the tower. The main common rafters (spanning from the corners) are connected to the short Kingpost, which is secured firmly at the bottom of the framing system. The other common rafters are connected either into the main common rafters, or to header beams”. [2]

2.2.3 A third type of spires can be defined as a combined structure

As the spire of Bela tower of the Mathias Church, from Budapest (from 1896) with a long Kingpost, and a similar bracing system as described for the short kingpost styled spires (Figure 6).

2.2.4 Other elements affecting the structural behaviour of a spires

Additional elements affecting the performance of spires are: the pinnacles at the four corners, the tympanum-windows at the centre of the facades, clock-ledges, other ornaments (especially in the case of baroque structures). All of these elements can disturb the direction and intensity of loads and so the structural behaviour of the spire’s main structure.

2.3 Numerical (computerised) modelling

The main aspects of the structural behaviour of the spatial roof structures which can be resolved by modelling are as follows:

a) supporting arrangements – whether the structure is supported mainly at the top of the wall, or lower down and by the fixings or “building in” systems;
b) effectiveness of joints – whether the timber connections allow the parts of the members to rotate freely or provide restraints against rotation;
c) the role of the different components of the structure (especially the Kingpost).

Other considerations which are not subject of this paper:

a) consideration of the applied loads, especially the wind-loadings – whether the loads act as the simplified European Standards states, or whether account should be taken of the distortion effect of the wind-loading;
b) the role of the additional elements: pinnacles, windows, galleries, other ornaments (baroque roofs);
c) the effect of irregularities and missing elements to the structural behaviour of the spires.
2.4 Case studies

We will present the results of the structural analyses for the two different kinds of spires (with long and short kingpost), presenting the similarities and differences, and also the difficulties of research and analyses of these structures.

2.4.1 General problems of building the model of a spire

a) Survey problems: generally the roof structures of the spires are not accessible; the general dimensions can be taken by using laser instruments but the joints, especially the higher ones are very difficult to access either because of the narrow space, either because of height;

b) Building the model geometrically: the model of spires with long kingpost can be easily built using parallel lines with the basic railing system started from the kingpost, the beams of the horizontal levels meets the common rafters having an exact joint. (Figure 7).

In the case of the spires with short kingpost, the horizontal railing system is not follows the common rafter’s directions. The software what we used is based on the theory of finite elements, making the calculations in joints of the axes and can not deal with elements which are crossing each other but not in the axes. There so, finding the joints between common rafters and upper horizontal railing systems is difficult, and the program cannot deal with plans crossing with lines. This is why we had to include a serial of contact elements in the model (Figure 8). These contact elements permit to give different rigidities for these joints.

c) Consideration of loads: Roofs must be able to withstand a multitude of actions. In our analyses we considered the dead loads and wind loads, and we ignored the snow and ice loads – because of the pitch of the spires which are more than 60°. We also ignored the temperature fluctuation or the actions during construction, etc.

We considered the loads according to the European standards adapted for the spires as presented below:

The permanent actions were taken into account by way of an average value, the time-dependent, variable actions are specified by characteristic values what were multiplied by partial safety factors during analyses of the load-carrying capacity (for dead loads this is 1.35, for wind loads is 1.50). For serviceability analyses the partial safety factor for dead loads is 1.00, for variable loads are reduced by factors and frequency values – which for wind loads are \( \Psi_0 = 0.60, \Psi_1 = 0.50, \Psi_2 = 0.00 \).

Dead loads are permanent and immovable actions caused by the self-weight of load-bearing and non-load-bearing components and the roof covering, what was considered being profiled aluminium sheeting, considered together with the roof decking (0.25 kN/m²).

The wind load is made up of pressure, suction and friction effects. Pressure and suction act perpendicular to the surface of the building. Pressure act on the windward side, suction on the leeward side and friction effects could be on the parallel side of wind load. The wind loads were considered with theirs reference speeds taking account also to the local surroundings, as follows: topography category 4 – urban district; height above ground level z(m) = 36.0 m, the dynamic pressure of the wind for these surroundings is \( q_p(z) = 0.655 \text{ kN/m}^2 \).

In order to determine the distribution of wind pressure on the surface of an eight-sided spire (as far we had no possibility to carried it out in wind tunnel tests...
in which the wind pressure could be measured at the surface of a model neither to make useful measurements with setting sensors at the different faces of the spires), we adapted the example given in the European standards for hipped-roofs, as follows.

2.4.2 Results

a) Spires with long Kingpost – the roof structure of the tower of Reformed church from Barabas.

The joints have been considered in two ways: with free rotation and with restraint against rotation, but this – as you can see it below – had only a minor effect in the stresses of the different elements.

The other question was the role of the different elements (especially the Kingpost) in the structural behaviour of the spire.

The role of the Kingpost:

In spite of the fact that the Kingpost is an extremely slim element, with its cross-section very much weakened by the joints with other elements, the Kingpost is very important to the structure, working for both vertical and horizontal actions (such as roofing and wind-loads).

For dead-loads the Kingpost is working as usual – resulting only axial stresses. What is unusual is that wind-loads producing bending moments in the Kingpost especially in the joints with the compound rafters, but also at joints with knee-braces and collars. This is why the bracing system of the spire should not be screw fixed to the common rafter, permitting a little movement during rugged wind.

The other elements, such as common rafters, compound rafters, collar beams etc. are working – as usual – in both compression or tension and sometimes common rafters also for bending moments.

The spires with long Kingpost are not very sensitive to the rigidity of the joints. The distribution of loads are very much depends of the rigidity of the Kingpost, and the possibility of movements of the bracing elements during storms.

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Figure 9. Distribution of wind load for eight-sided spires.

Figure 10. Stresses in the Kingpost – $N_x(kN)$ – for Dead-loads (1)/Wind-loads (2) for fixed joints (a)/joints with articulations (b).

Figure 11. Bending moments in the Kingpost – $My (kN m)$ – for Dead-loads (1)/Wind-loads (2) for fixed joints (a)/joints with articulations (b).
b) Spires with short Kingpost

The joints similar to the first case were considered in two different arrangements. This had an important effect in the structural behaviour of the spire, increasing substantially the stresses in the elements.

3 CONCLUSIONS

In our lecture we tried to present a typology of these structures and also the structural behaviour of these, using the knowledge collected from the technical literature and self-experience. There are a lot of questions which were not answered (especially concerning the distribution of wind loads), what needs experimental studies in wind-tunnel and also by farther measurements on extant structures.

Historic spatial roof structures have considerable historic value. It is our aim to study and create an inventory of these beautifully built structures, in order to understand their structural behaviour and to preserve them for future generations.

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