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Stability Analysis on the Roof Trusses of the Broumov Group of Churches to Underline Statical Sense of Dientzenhofers

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Abstract The Broumov group of churches represents an integral part of Bohemian baroque architecture. The famous Dientzenhofer family of architects, that helped define the Bohemian baroque style in the early 18th century, designed the Broumov group for the governing Benedictine abbey of St. Wenceslaw in Broumov. This report summarizes a structural investigation, using FIN10 finite element software, into the stability and efficiency of the roof trusses design. The structures age and current state were taken into account in calculating both the applied loads and structural capacity by increasing loads and reducing material strength. A damage analysis, including identification of fungi species, was performed, documented and implemented in a three-dimensional model for comparison with undamaged results. Magnitude and distribution of axial and bending forces were determined using both two dimensional and three-dimensional models for several load cases. Using the comparison of 1st order and 2nd order structural analysis results and Eurocode specified criteria, critical and unnecessary members of the roof system were identified and evaluated. Classical linear elastic 2nd order theory was used based of Eulerian principles, ignoring geometrical non-linearity and non-linear material effects. The main analysis was performed on the St. Ann church in Viznov and St. Barbora church in Otovice.

Keywords: Stability, roof truss, second order theory, baroque, critical load, deterioration, fungus and insect infestation

Introduction

The vast quantities of culturally relevant and historical constructions within not only the Czech Republic but all of Europe, is staggering yet it is not always economically possible to maintain all of them. The lack of scientific or engineering knowledge available during the construction of these structures lead to the development of a unique group of architects and builders who were frequently trained in Italy and relied solely on empirical methods or traditional “rules of thumb”. Frequently, this meant that buildings were significantly over-designed in comparison to today’s design codes. It is also the principle reason why many structures survived over long periods of time, even when improperly maintained. Such is the case in the Broumov region of Bohemia, where the Dientzenhofer family constructed a group of churches in the 18th century for small agricultural villages (Prokop et al. 2007). With the major development of structural analysis techniques not only in the past hundred years but even the last ten to fifteen, much more in-depth analysis is possible. This paper will make use of the finite element method (FEM) software, FIN10, to analyze the roof of the St. Ann church in Vižňov, Czech Republic comparing 1st and 2nd order results. From this comparison the design adequacy of individual members will be determined and critical sections of the roof design identified. It is commonly accepted that if the internal forces of a member differ by less than 15% between 1st and 2nd order analysis then the member has been adequately designed and constructed. Analysis of the roof structure based on this assumption makes it possible to gain greater understanding of the Dientzenhofers’ and other builders’ of their time methods and level of structural knowledge.

It can also identify critical members in the structure’s stability that should be kept free of debilitating damage that frequently occurs in the timber roofs of ancient buildings. The similarities in design

between St. Ann's and the other Broumov churches permits many of the conclusions found to be transferred to the others.

Figure 1: The church of St. Anne - view, roof truss and floor plan

Description of Geometry, Anamnesis of the Structure and Damage Survey

An initial survey done of the roof identified damaged areas, type of fungus and the truss geometries next used in the FEM models. Consistent neglect since the Second World War has left these churches damaged, frequently with moisture and fungus problems. Recently a temporary roof was installed and the fungus eradicated but more funding is needed to properly restore this structures (Fajman et al. 2008, Fajman 2009, Kuklik 2008).

Figure 2: Deterioration of the roof and small square hole for drying the roof

Five large major trusses make up four main bays spaced at 3.32 meters with minor trusses between every 1.1 meters and complex hexagonal structures at the ends of the roof.

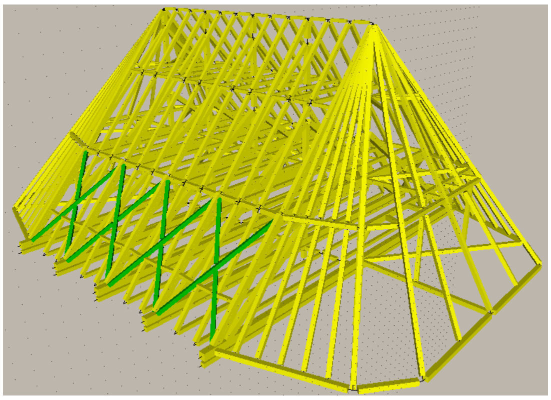

Figure 3: 3D Model of roof with highlighted X-cross bracing

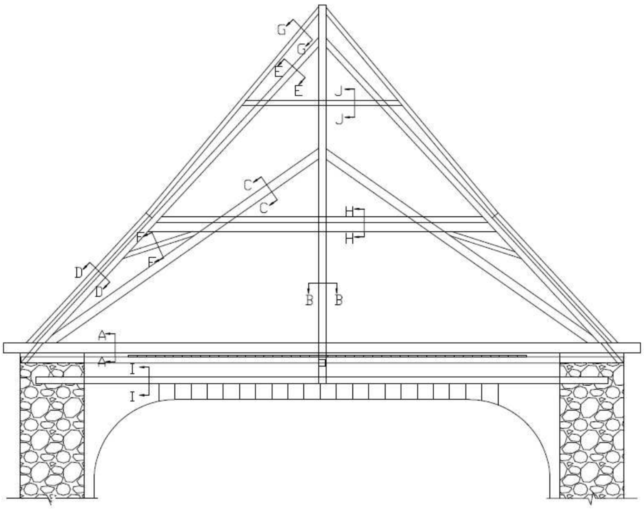

Figure 4: Cross sectional view of roof (major truss)

Table 1: Member summary for cross sections

Cross Section	*b* [cm]	*h* [cm]
A-A	28	32
B-B	23	24
C-C	27	27
D-D	19	38
E-E	19	19
F-F	14	14
G-G	19	19
H-H	19	37
I-I	19	19
J-J	17	17
X-Cross Bracing	17	17

Figure 5: Typical "end of member" and mid-span connections

Loads and Load Cases Estimation and FEM Analysis Results

The resulting load combination and loads that were used for the initial analysis of the structure in both the 2D and 3D model are shown below in Table 2 and Table 3. The imposed load was taken from the code for infrequently used spaces in storage and roofs of structures. It is a relatively high value considering that the frequency of anyone going up into the roof of St. Ann's is extremely low.

Table 2: Loading combinations (EC5, 2007)

#	*ULS Loading Combinations*
1	1.35DL + 1.5LL
2	1.35DL + 1.5SL
3	1.35DL + 1.5(SL or LL) + 0.75WL
4	1.35DL + 1.5WL (pressure) + 0.75SL
5	1.0DL + 1.5WL (suction)

Table 3: Normal and exceptional load values

Type	*Load* [kN/m^2]
Roof Dead	0.93
Ceiling Dead	0.50
Snow	0.62
Wind (pressure)	0.79
Wind (suction)	-0.26

Type	*Load* [kN/m^2]
Roof Dead	0.93
Ceiling Dead	0.50
Snow	3.60
Wind (pressure)	1.14
Wind (suction)	-0.38

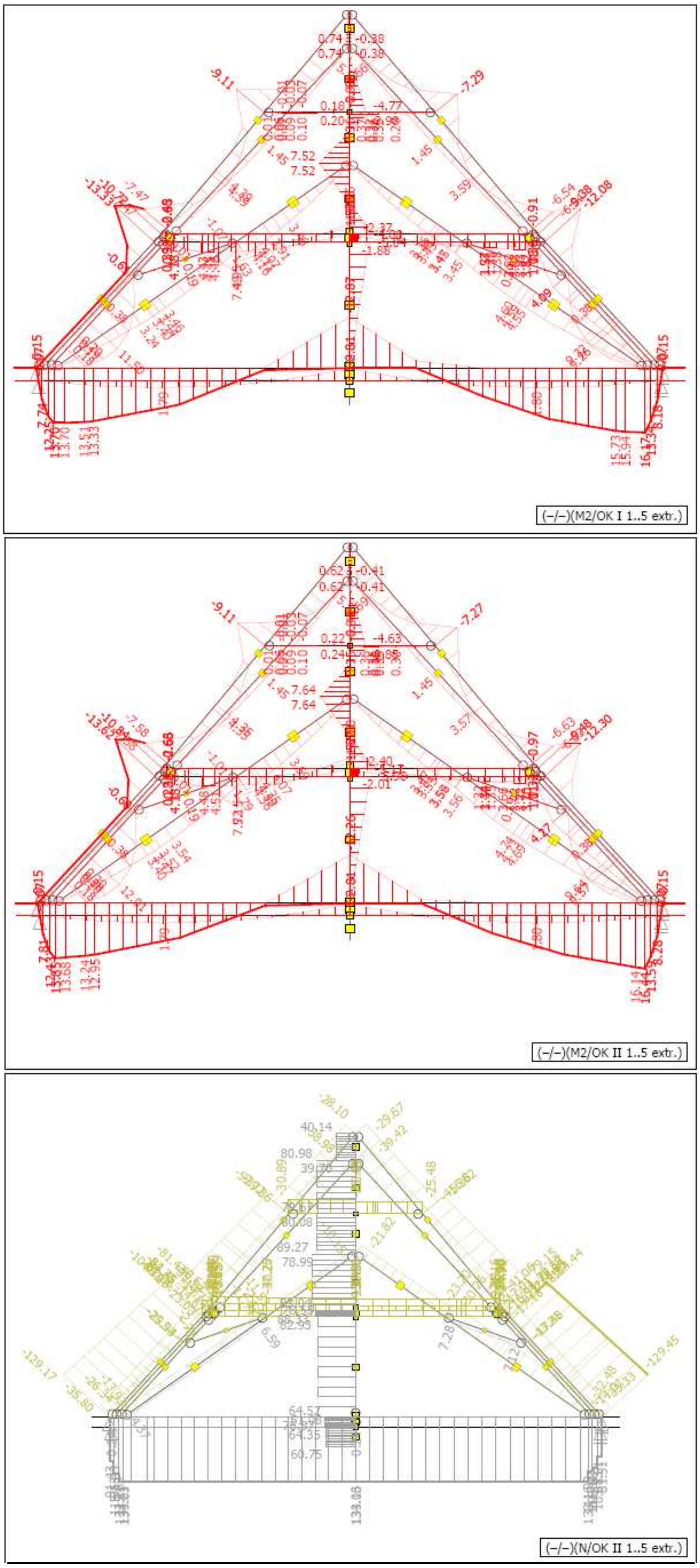

Figure 6: Envelope of exceptional combinations: the bending moments by the 1st order, by the 2nd order and the normal force

The substantial reserve in bearing capacity was considered after stress calculation. The current normal stress state influenced by exceptional loads in the lower part of the major truss rafter was

$$\sigma_x = \frac{N_{II}}{A} + \frac{M_{II}}{W} = \frac{-129{,}2}{2(0{,}19.0{,}19)} + \frac{-13{,}65}{2\left(\frac{1}{6}0{,}19^3\right)} \doteq -7760 \text{ [kPa]},$$

in the upper part it slightly increases in the upper part

$$\sigma_x = \frac{N_{II}}{A} + \frac{M_{II}}{W} = \frac{-59{,}72}{0{,}19.0{,}19} + \frac{-9{,}11}{\frac{1}{6}0{,}19^3} \doteq -9623 \text{ [kPa]}.$$

There is no significant difference between the bending moment calculating by the 1st and 2nd order theory. It highlights the phenomenal structural sense of Dientzenhofers.

Conclusion

Ancient structures that remain standing at present do so mainly from their builders conservative design process. With relative certainty it may be stated that the Broumov churches are all over designed and have considerable reserve but they have had a history of neglect. Possible deterioration of certain members identified in this report may lead to premature collapse or serious, irreversible and costly problems with these integral pieces of Bohemian history. Likewise some members are capable of substantial deterioration without repercussion. Interpretation of both instances of members has revealed some view of the Dientzenhofers, and builders, understanding. Second order analysis, combined with factors applied to material strength, but not slenderness, was found to be the most accurate structural adequacy check. The results from this method demonstrated the conservatism of the stability factors prescribed by the Eurocode 5. Using these results, in combination with the percent differences, certain elements of the roof were identified as potentially stability threatening and some structurally unnecessary. The overall stability of the roof suggests that even under exceptional, worst-case scenario loads the structure would withstand 260% of applied loads before losing stability. Although several members had high differences from first and second order, the majority were extremely low, averaged less than 5%. The majority of members were over-designed but this does not discredit the Dientzenhofers for using insightful design details in several areas that suggested their knowledge extended beyond simple "rules of thumb".

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