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Dynamic influence of a swinging bell on a traditional wooden structure of the Lemko orthodox church belfry

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Abstract. Paper treats about dynamic influence of a swinging bell on a traditional wooden structure of the orthodox church belfry (example calculations made for a bell and belfry of the Lemko's orthodox church). On the basis of the conclusions of the analysed belfry, there were made modifications aimed to improve its dynamic parameters. The brief summary provides comparison between the effects of such modifications and existing wooden structure.

1. Introduction

1.1. Lemko orthodox church

While settling in Carpathian region, Lemkos started to build specific type of the orthodox churches, very typical for the north Carpathian region (southern east Poland, north east Slovakia, west Ukraine and north Romania). Almost all of the Lemko orthodox churches structures were timber (most available resource), with traditional types of joints which are very common. Need to mention that before Austro-Hungarian regency orthodox churches did not included timber belfry, which nowadays is the most recognised part of the building. In most buildings, there could be found signs that belfry was built up to the existing building (such as old roof structures elements and claddings in belfry interior), so due to that fact they have independent structure – built as the column-and-struts structures [2][3].

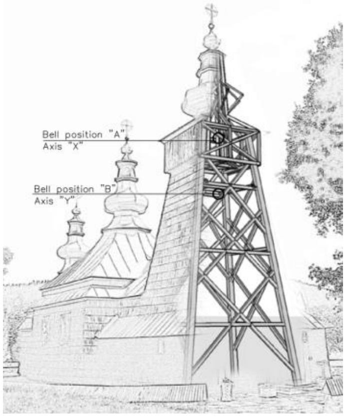


Figure 1. Analysed belfry structure.

Figure 2. Main belfry structure (columns, struts and head-piece).

1.2. Belfry structure

Main structure of the belfry is built as 4 columns (cross sections about 30x30cm to max 60x60cm) supported on the sandstone simple foundations. Columns are horizontally supported by struts and beams, so the main structure may looks like a truss, but due to the fact that the elements are not symmetrically connected, it works similarly to the frame – providing also momentum of force. On top of it, the belfry has mostly only one axis of symmetry (side walls are symmetrical, interior and exterior walls are asymmetrical to each other, due to main church door and existing main building beam structure in belfry interior) and has old traditional joints which in some aspects are rigid types, but with limited work angle (dependent on connection loose) and limited resistance to tension. The Highest part of the belfry is built as a turret, with convergent columns connected among themselves by struts, ended with a strut structure supporting cantilever (with a cross) [4].

1.3. The bell

Bell mostly is hanged on the higher interior part of the main belfry structure (around a level of the main columns' endings and turret) and by the special beam, which is supported by the main structure struts or top beams. Hanging axis varies, but mostly, there are two directions: perpendicular to the building and parallel with the building, same as the various types of bells (mass of bells and dynamical parameters are varying and should be approx. calculated in every case).

1.4. The problem

Presented calculations were provided for the timber belfry of the Lemko's Orthodox Church in Berest (Lesser Poland, Poland). The structure was chosen due to problems with usage of the belfry in the past (problems with instability of the main timber structure), so there is the question “what is the influence of a bell on a timber belfry structure?”. To answer that question, adequate calculations must be performed.

2. Assumptions, FEM model building

The belfry structure was measured, considering cross sections of the belfry elements, levels of the connections with struts and beams, characteristics of the connections, dead loads (timber cladding, roof steel panels and timber structure). Then, based on measurements was built calculation (FEM) model. Then the bell was measured, its diameters, thickness and approx. geometry to make assumptions of its dynamic characteristic (considered only low frequencies, high frequencies was not considered due to fact they have negligible dynamic influence on the belfry). The bell was hanged in two various positions, first on the highest part of the belfry (swinging parallel to the building main axis), then moved on a lower level (swinging perpendicular to the main building axis) and in the end taken out of a belfry (hanged on a tree, which broke under the bell). Mentioned hanging positions in the belfry were taken for consideration in calculations.

2.1. The bell

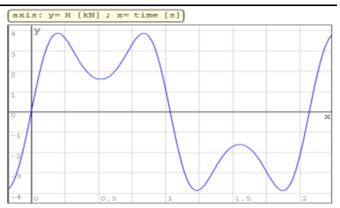
Parameters of the bell were determined by geometry measurements and based on [6].

Table 1. Approximated bell parameters, according to [6].

Diameter [mm]	930
Mass [kg]	400
Strike frequency [Hz]	1
Swinging angle (strike) [°]	65
Tone	gis' as'

According to the following bell parameters and [1], dynamic parameters and related loads have been calculated. Horizontal harmonic components are considered as the ones responsible for potential instability and/or resonance. Vertical harmonic components (i=2.4)are integrated as a bell gravity load (dead), considered in FEM model.

Table 2. Characteristics of the main harmonic horizontal components (i = 1,3,5).

Component	Period [s]	Frequency [Hz]	Component force [kN]	Proportion of components [%]	Summary horizontal force /static/ [kN]	Oscilation of the resultant horizontal force (x=[s]; y=[kN])
1	2	**0.5**	**1.66**	43.6	3.8	
3	0.67	**1.5**	**2**	52.7	3,8	
5	0.4	2.5	0.42	3.7	3,8	

Values presented in Table 2 shows dominating horizontal components with proportion, parameters and forces values related to each component. Mentioned components have major impact on belfry structure and their frequencies are close to belfry natural frequencies. Most dominating (for analysed bell characteristic) are i=1 and i=3 responsible for about 96% of total horizontal force, and those characteristic components frequencies must be compared with belfry natural frequencies while searching potential resonance.

2.2. The belfry

Belfry geometry, nodes type and elements relevance was converted to 3D model which is basis for FEM calculation. Some assumptions has been simplified (every node as pinned connection – various loose and rotation possibility, pinned support on footing, not included rigidity of cladding).

Table 3. Characteristic dimensions of the belfry and structure layouts.

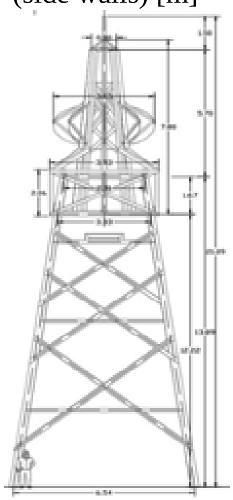
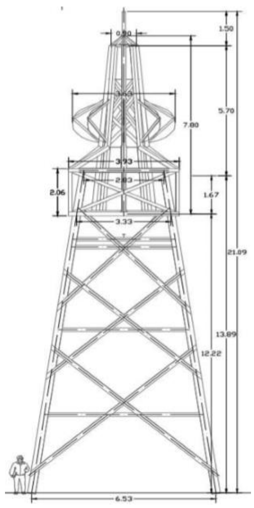
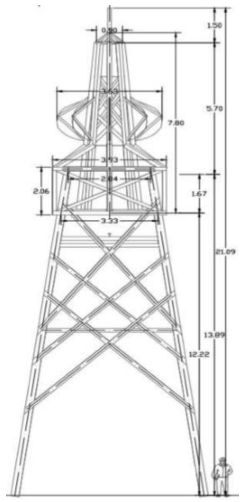
North and south side (side walls) [m]	West side (front side with main door) [m]	East side (church side) [m]
		

Table 4. Joints – nodes. Presented following traditional connections for the timber belfry.

		
Main structure columns and struts connection	Belfry interior	Head-piece of main structure
		
Belfry main column support	Support beams of the higher turret	Higher turret columns and struts

Table 3 shows dimensions of the belfry and structure layout according to measurements, Table 4 presents typical traditional connection solutions for presented structure. Traditional belfry's structures are complicated, so measuring of the structure and creating structural layout require time to acquire and analyse necessary data. Next step is to build model representing real structure as close as it's possible. Model main structure input data should be possibly accurate due the fact that every element (stiffness) and every node (released and blocked reactions, displacements) has considerable impact on model output data (especially natural frequencies). It took few attempts to build possibly accurate model, shown as Figure 3 and Figure 4.

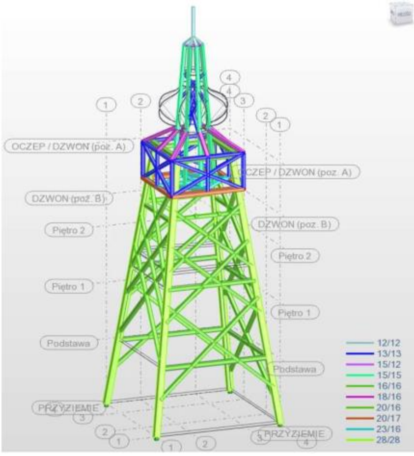


Figure 3. Completed model including eccentricity of connections.

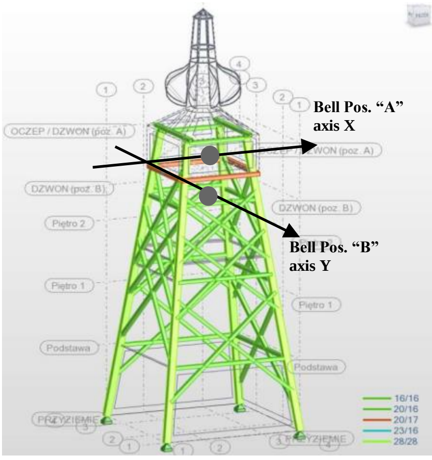


Figure 4. Main belfry structure (columns, struts and head-piece).

3. FEM model analysis
Model including dead loads (structure load, cladding load) and static bell loads was calculated for static forces and then converted to model with distributed masses for modal calculations.

Table 5. Belfry Eigenmodes.

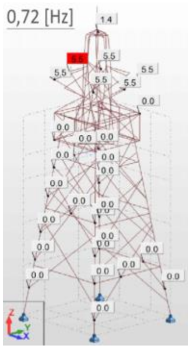
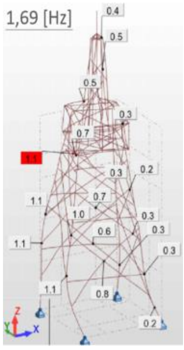
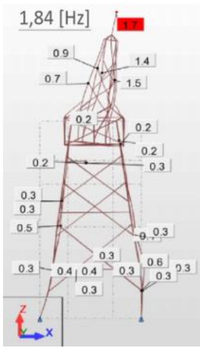
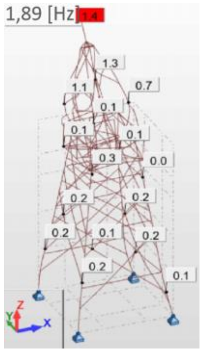
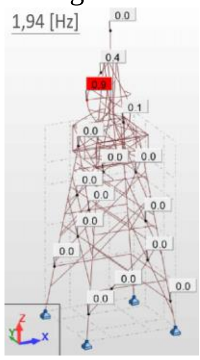
1 eigenmode	2 eigenmode	3 eigenmode	4 eigenmode	5 eigenmode
				

Table 6. Natural frequencies oscillating mass (related to axis).

Eigenmode	Frequency [Hz]	Related mass X axis [%]	Related mass Y axis [%]	Total mass [kg]
1	0.72	0	0.01	
2	**1.69**	0.07	**61.4**	
3	1.84	9.3	0.33	23406
4	1.89	0.35	1.1	
5	1.94	0	0	

Due to monosymetry of the structure natural frequencies has not exactly one directed character. The easiest way to describe the character of the frequency is to analyse related to each axis oscillating mass. Analysing masses one can deduce that dangerous is frequency 2 on the axis "Y" (due to mass taking action).

4. Resonance possibilities
Comparing bell components frequencies and belfry natural frequencies it's possible to find dangerous resonance situation and related equivalent static horizontal force generated while resonance.

Table 7. Frequencies comparison, convergence of frequencies natural-harmonic.

Comparison	Natural belfry		Related mass Y axis	Bell pos. "B" harmonic (axis Y)		Convergence
	Eigenmode	[Hz]	[%]	Comp.	[Hz]	[%]
1	1	0.72	0.01	1	0.5	69 (<80)
/Resonance/ **2**	**2**	**1.69**	**61.4**	**3**	**1.5**	**89 (>80)**
3	3	1.84	0.33	3	1.5	81.5 (>80)
4	4	1.89	1.1	3	1.5	79 (<80)
5	5	1.94	0	5	2.5	78 (<80)

According to Table 7 resonance may occur for impacting third harmonic component (related mass oscillating on the axis same as the bell and convergence of those frequencies), and it should be considered in calculations using dynamic factor for static forces. Convergence more than 80% is considered as 100% resonance due to uncertainty of calculation assumptions. In that fact dynamic factor for the third component is set as maximum: η=10, according to [1].

5. Resonance impact on the main belfry structure

Convergence of natural frequencies and harmonic vibrations for position "B" is critical for the belfry. Table 8 shows values of the forces in elements and impact descriptions when the belfry is resonating with the bell.

Table 8. Critical resonance forces impacting belfry with the bell situated on position "B" (axis "Y").

Force type	Value		Impact on the belfry
Rz (N) – main column support	(Max) 81.5 kN	(Min) -4.95 kN	**Instability of the main structure. Disconnection of the support.** Traditional support on the ground beam cannot afford tension. **Destruction of joints connections in main columns** (tensioned).
R (V) – main column support	Axis X (max) 12.9 kN	Axis Y (max) 14.7 kN	Shearing of the support pivot. **May lead to pivot destruction and change of the static scheme** leading to significant increasing of forces impacting belfry (destruction of sensitive tensioned joints).
N – struts, connections among elements	(Min) -8.1kN	(Max) 13.7 kN	**Destruction of joints sensitive for tension**, disconnection of the elements. **Compressed slim elements may lose stability.**

6. Modifications of the structure. Improving dynamic parameters of the belfry

Resonance situation according to Table 7 must be considered as unwanted and dangerous for the belfry. Need to mention that resonance can occurs while a standard swinging of the bell, when the bell has the same swinging angle as strike angle and vibrations are harmonic (bell ringer is actively preventing damping). Figures 5 and 6 shows two, separated kinds of structural approaches. Figure 5 presenting approach with inserting additional elements to make belfry structure close to bisymmetric. Figure 6 presenting reinforcing and modification of the main structure joints (rigid connections). Two mentioned approaches include also inserting small columns between turret and main structure struts.

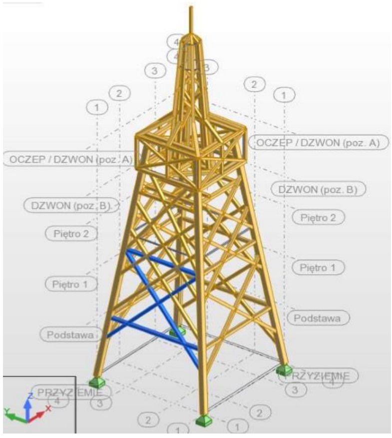


Figure 5. Bisymmetrisation of the structure (additional struts and beams in east side wall).

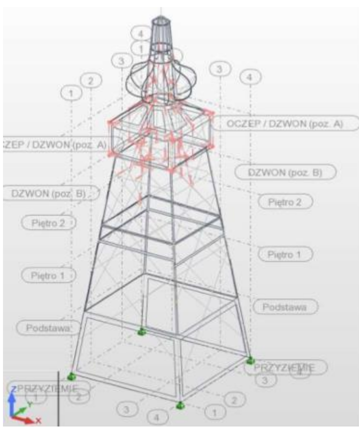


Figure 6. Main structure joints modification (rigid connections. Red appointed connections left as joints).

Modifications are aimed to improve dynamic parameters of the belfry (mainly to increase natural frequency of the belfry). Results of such modifications shows Figure 7.

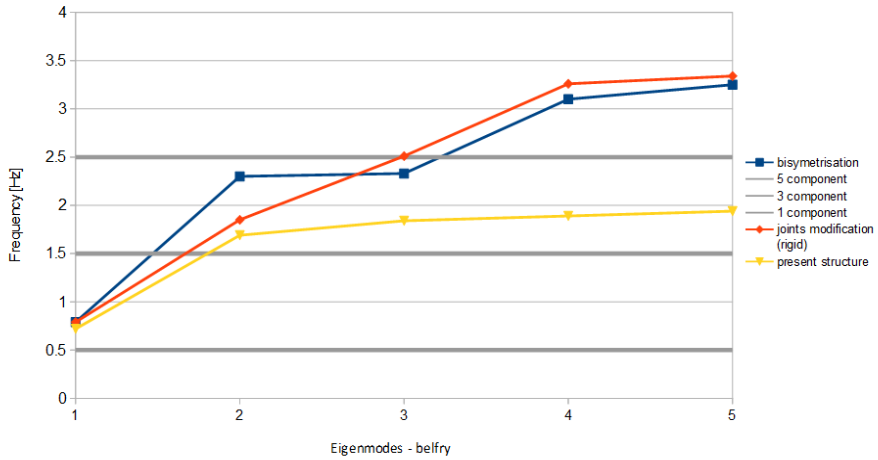


Figure 7. Comparison of eigenmodes frequencies changes.

Not only frequencies has changed due to modification, Table 9 show level of forces impacting the belfry structure. Both structural changes in the belfry structure led to a better forces redistribution among elements, and that is considered as very desirable result for a safety of the structure. Considering redistribution of forces, joints modification gave limited results, on the contrary bisymmetrisation gave as suspected the best results, allowing structure equable redistribution of forces (bolded in Tab.9).

Table 9. Comparison of characteristic forces impacting structure during considered hanging.

Force type	Present resonance		**Bisymmetrisation**		Joints modification (rigid)	
Rz (N) – main column support	(Max) 81.5 kN	(Min) -4.95 kN	**(Max) 45 kN**	**(Min) 31kN**	(Max) 50.7 kN	(Min) 25kN
R (V) – main column support	Axis X (max) 12.9 kN	Axis Y (max) 14.7 kN	**Axis X (max) 6.6 kN**	**Axis Y (max) 7.5 kN**	Axis X (max) 7.9 kN	Axis Y (max) 9.2 kN
N (tension) – struts, connections	(Min) -13.7 kN		**(Min) -3.8kN**		(Min) -4.7kN	

6.1. Modification summary
Both presented belfry modifications are increasing natural frequencies of the structure to the safe level (considered as non resonating with the bell 1 and 3 components) and more (bisymmetrisation) or less (joints modification – rigid) are ensuring equable redistribution of forces among elements. For 2 eigenmode resonance may occure with the component 5, but due to very low component impact on the total horizontal force (<4%) it's not considered.

7. Summary
Swinging bell has significant dynamic impact on considered timber belfry structure in the field of low frequencies, leading to the resonance, structural instability and potential structural failure. Conducted calculations gave results explaining problems with the belfry usage in the past and shows that direction of the bell swinging may have more impact on the structure than level of hanging due to resonance. Proposed structural modification by bisymmetrisation of the structure gave most

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satisfactory results, eliminating possibility of the resonance and ensuring equable redistribution of forces among belfry elements. Both modifications could be performed on a timber belfry with the column-and-struts structures struggling with an instability due to resonance impact and in general will lead to a significant improvement of the belfry dynamic parameters, force balance and ultimately possibility of restoring usability of the belfry.

For engineering (practical) use both methods should be undertaken on the structure at the same time (reinforcing of the main belfry joints (for rigid) and Bisymmetrisation of the structure) to ensure belfry stability and structural safety. It is essential due to disparity of the technical conditions among belfry elements and joints. From the author personal experience the highest parts of the belfry (turret structure) and main columns around foundation, including ground beam must be carefully revised due to possibility of leaking and various humidity conditions leading to a progressive biological destruction of the timber sections and joints.

8. References:

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[6] DIN 4178:2005-04 Glockentürme. Berechnung und Ausführung. Table A.1