THE DESIGN OF WOODEN CHURCHES ROOF; AN EMPIRICAL SOLUTION AGAINST WIND AND RAIN DAMAGES. CASE STUDY: *BUDEŞTI-JOSANI, MARAMUREŞ* COUNTY, ROMANIA

MIGDONIA GEORGESCU

Abstract. In *Maramureş* County, Romania, there are eight wooden churches inscribed on the World Heritage List. The special shape of the roof permits the fast flowing down of the rain water and the sliding of the snow. The churches in *Maramureş* County are built, generally, on the top of the hills directly exposed to weathering. Wind effects on structures can be conveniently separated into background and resonant components. The leaking velocity of the rain water and snow is calculated taking into account the shape of the roof and the tribological behavior of the wood.

Key words: wooden roof, wood shingles, wind pressure, rain exposure, dynamic response analysis, Maramureş wooden church.

1. INTRODUCTION

In Maramureş County, Romania, there are eight wooden churches inscribed on the World Heritage List. These wooden churches represent a selection of eight outstanding examples of vernacular religious wooden architecture, resulting from the interchange of Orthodox religious traditions with Gothic influences in a specific vernacular interpretation of timber construction traditions [1].

The church of *Budeşti-Josani*, built in oak wood in 1643 (according to the inscription incised in the door frame), with some modifications brought in the 18th century, was dedicated to Saint Nicoară (the old Romanian name of Saint Nicholas). It is a typical church for *Maramureş* County with a rectangular design, polygonal apse, tall tower on the *pronaos* provided with cover, four turrets and a saddle roof. Inside, the walls are adorned with murals in the folk style dating from the 1762. Displaying the features of local art from *Maramureş* County on the wooden portal of the church in *Budeşti-Josani* are carved ancient solar symbols, rosettes, Christian crosses and the relief rope which is considered by specialists to represent the snake as a protector of the sacred room [2].

The special shape of the roof permits the fast flowing down of the rain water and the sliding of the snow. The churches in *Maramureş* County are built, generally, on the top of the hills directly exposed to weathering.

National Museum of Romanian History, 12 Calea Victoriei, 030026 Bucharest

Wood-frame buildings have an established record of long-term durability.

These kinds of churches were designed with pitched roofs to shed the rain and they were constructed with great attention to detail. The primary consideration is to keep the wood dry. Wood is a hygroscopic material, which means it has the ability to release or absorb moisture to reach a moisture content that is at equilibrium with its surrounding environment. As part of this natural process, wood can safely absorb large quantities of water before reaching a moisture content level which is favorable to the growth of decay fungi. To ensure durable wood-frame buildings, the design of the structure and envelope should be based on an understanding of factors that influence the moisture content of wood and changes that occur due to variations in moisture content.

Fig. 1 – *Budeşti-Josani* Church (http://www.panoramio.com/photo/29066985).

2. WOODEN CHURCHES ROOF SOLUTIONS. CASE STUDY: *BUDEŞTI-JOSANI*, *MARAMUREŞ* COUNTY

Wood shingles were popular in that region of Romania in all periods of building history. The size and shape of the shingles as well as the detailing of the shingle roof differed according to regional craft practices. People within particular regions developed preferences for the local species of wood that most suited their purposes. The oak was frequently used in *Maramureş* County.

Fig. 2 – Wooden shingles.

Fig. 3 – *Budeşti-Josani* roof.

Some historic roofing materials have limited life expectancies because of normal organic decay and *wear.* For example, the surfaces of wood shingles erode from exposure to rain, wind and ultraviolet rays. Ideally, shingles are split with the grain perpendicular to the surface. This is because if shingles are sawn across the grain, moisture may enter the grain and cause the wood to deteriorate. Prolonged moisture on or in the wood allows moss or fungi to grow, which will further hold the moisture and cause rot. During some periods in the history, the roof imparts much of the architectural character. It defines the style and contributes to the building's aesthetics. The typical roofs of Maramureş churches architecture, the turrets of *Budeşti-Josani* church are examples of the use of roofing as a major design feature.

But no matter how decorative the patterning or how compelling the form, the roof is a highly vulnerable element of a shelter that will inevitable fail. A poor roof will permit the accelerated deterioration of historic building materials – masonry, wood, plaster, paint – and will cause general disintegration of the basic structure.

Wind effects on structures can be conveniently separated into background and resonant components [3].

3. DYNAMIC RESPONSE ANALYSIS

Typically, the dynamic response analysis is conducted in modal space for computational efficiency. In general, while only a few number of modes need to be included for the resonant response; the background component requires larger number of modes. Therefore, direct calculation of the background response using quasi-static analysis enhances computational efficiency over the modal analysis approach. The background component of a specific response $y(z_0,t)$ (i.e. displacement, shear force, moment) and its mean square value can be given as

$$y_b(z_0,t) = A\,p(t) = A\Phi\, a(t)\,, \tag{1}$$

$$\sigma_{y_b}^2 = A R_p A^T = A\Phi\Omega\Phi^{\mathrm{T}} A^{\mathrm{T}} = \sum_{n=1}^{N_R} c_n^2\,\Omega_n\,, \tag{2}$$

where $c_n = \sum_{j=1}^{N} A_j \Phi_{jn}$, A is the $1\times N$ influence vector, $p(t)$ is the $N\times 1$ external wind load vector, $a(t)$ is the $N_R \times 1$ expansion coefficient vector of POD (Proper Orthogonal Decomposition), Φ is the $N\times N_R$ eigenvector matrix of the covariance matrix of R_p of $p(t)$, and $N_R << N$ are the numbers of the discrete loads and the eigenvalues (wind loads modes) considered, respectively.

Based on the load-response-correlation approach proposed by Kasperski (1992) [4], the background component for the equivalent static load distribution for the peak response $y_{\max} = g\sigma_{yb}$ (where g is the peak factor) is expressed as

$$F_{eb} = g\,R_p A^{\mathrm{T}} \big/ \sigma_{yb} = g\,\Phi\Omega\Phi^{\mathrm{T}} A^{\mathrm{T}} \big/ \sigma_{yb} = \sum_{n=1}^{N_R} c_n\,\Omega_n\,\Phi_n \big/ \sigma_{yb}\,. \tag{3}$$

The background response and the associated equivalent static load can be expressed as a sum of the contribution from wind loading modes. The contribution of each mode depends on the influence function, loading mode shape and eigenvalue.

The resonant components can be calculated using modal analyses technique. Considering the first q modes of the structural system, the equations of motion are reduced to q uncoupled equations in terms of the modal coordinates $X(t)$. The XPSD (Cross Power Spectral Density) is given by

$$S_x(f) = H(f)\,\Theta^{\mathrm{T}} S_p(f)\,\Theta H^*(f) = D_x(f)\,D_x{}^*(f)\,, \tag{4}$$

$$D_x(f) = H(f)\,\Theta^{\mathrm{T}} D(f)\,, \tag{5}$$

$$H(f) = \mathrm{diag}\left[H_j(f)\right], \quad H_j(f) = \frac{1}{m_j\left[-\omega^2 + \omega_i^2 + 2\mathrm{i}\left(\xi_j + \xi_{aj}\right)\omega_j\omega\right]}, \tag{6}$$

where $D(f)$ is the $N_s \times N_s$ decomposed matrix. In the case of decomposition based on the eigenvectors of XPSD matrix, $D(f) = \Psi(f)\sqrt{\Lambda(f)}$; Θ is the $N \times q$ structural natural modal shape matrix; m_j, $\omega_j = 2\pi f_j$ are the mass and frequency in *j*-th mode; ξ_j and ξ_{aj} are the structural and aerodynamic damping ratios in *j*-th mode ($j = 1, 2, ..., q$) and $i = \sqrt{-1}$.

The mean square value of *j*-th modal response is expressed as

$$\sigma^2_{X_j} = \int_0^\infty \left|H_j(f)\right|^2 \Theta_j^{\mathrm{T}} S_P(f)\,\Theta_j\,\mathrm{d}f = \sum_{n-1}^{N_S} \int_0^\infty \left|H_j(f)\right|^2 \chi^2_{jn}(f)\Lambda_n(f)\,\mathrm{d}f\,, \tag{7}$$

where $\chi_{jn}(f) = \Theta_j^{\mathrm{T}}\,\Psi_n(f)$. The resonant response component can be evaluated assuming that the forcing function is placed by a white noise with a constant spectral density at the structural natural frequency (Kareem 1987) [5]:

$$\sigma^2_{X_{jr}} = \sum_{n-1}^{N_S} \frac{\pi f_j\,\chi^2_{jn}(f_j)\,\Lambda_n(f_j)}{4(2\pi f_j)^4\left(\xi_j + \xi_{aj}\right)m_j^2}\,. \tag{8}$$

The resonant component of $y(z_0, t)$ is given by

$$y_r(z_0, t) = \sum_{j=1}^{q} e_j X_{jr}(t), \quad \sigma^2_{y_r} = \sum_{j=1}^{q} \sigma^2_{y_{jr}} = \sum_{j=1}^{q} e_j^2 \sigma^2_{X_{jr}}\,, \tag{9}$$

where $e_j = AM_0\Theta_j(2\pi f_j)^2$ is the participation coefficient of *j*-th mode to the response $y(z_0, t)$ and M_0 is the mass matrix in physical coordinates. Accordingly, the *j*-th mode resonant equivalent static load distribution can be expressed in terms of inertial force distribution as:

$$F_{erj} = gM_0\Theta_j(2\pi f_j)^2 \sigma_{X_{jr}}\,. \tag{10}$$

The resonant modal response and equivalent static load can be expressed as a sum of the components associated with frequency dependent loading model. The contribution of each mode depends on the structural dynamic characteristics, loading mode shape and eigenvalue.

4. CONCLUSIONS

The wind pressure on a structure depends on the location of the structure, height of structure above the ground level and on the shape of the structure. The code gives the basic wind pressure for the building. The design of envelope's assemblies must be based on an evaluation of the stochastic exposure to moisture. For exterior walls, design exposure, moisture load, is primarily a function of three conditions: macro-climate – regional climatic norms; micro-climate – site-specific factors such as solar exposure, wind exposure, and the relationship to surrounding buildings, vegetation and terrain; building design – protective features such as overhangs and cornices [6].

The leaking velocity of the rain water and snow is calculated taking into account the shape of the roof and the tribological behavior of the wood.

Because very few wind-loading codes address the specific requirements of this kind of buildings, wind tunnel testing is the standard method of determining wind loads on the roof and structural frames. The action of wind over structure will be the subject for farther investigations, using the wind tunnel.

Received on December 16, 2010

REFERENCES

1. BÂRCĂ, A., *Eight Wooden Churches from Maramures Inscribed on the World Heritage List*, Transylvania Nostra, **1**, march 2007.
2. DINESCU, D.I., *Monasteries and Churches of Romania. Transylvania*, Bucharest, 2005.
3. CHEN, X., KAREEM, A., *On The Application Of Stochastic Decomposition In The Analysis Of Wind Effects*, Proceeding of the Int. Conf. on Advances in Struct. Dyn., Hong Kong, 2002, pp. 135–142.
4. KASPERSKI, M., *Extreme wind load distributions for linear and nonlinear design*, Eng. Struct., **14**, pp. 27–34, 1992.
5. KAREEM, A,. *Wind effects on structures: a probabilistic viewpoint*, Prob. Engrg. Mech., **2**, *4*, pp. 166–200, 1987
6. * * *, *Moisture and Wood-Frame Buildings*, Building Performance Series, No. 1, Canada, 2000.