RESTORATION OF DYNAMICALLY STRESSED OLD BELL TOWERS DAMAGED BY CRACKS.

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SUMMARY

For structural repair, the measurement of the dynamic behaviour of the structural unit tower - nave and its numerical simulation are an important basis. Identifying the numerical model on the basis of measured data and by subsequent parametric studies the best method of repair can be found. On the basis of measurements it will decided if the displacements have to be reduced. In case of cracks, the masonry of the tower has to be consolidated by cement injections and prestressed by steel bars in horizontal direction.

1. INTRODUCTION

Periodic forces caused by swinging bells, wind loads and loads caused by traffic and earthquakes stimulate bell towers to predominantly horizontal vibrations. If the safe stress of the masonry of the tower and nave which are usually built of cut or rubble stones is exceeded cracks occur. Cracks are a typical form of damage in old towers. They can grow to dimensions which endanger the stability of the building. It is hard to determine what kind of force is the cause of the first initial micro cracks. All forces mentioned above, especially the horizontal force component of the swinging bells, contribute to the propagation of existing cracks. A numerical determination of the problem is often not possible because in many cases the dynamic behaviour of the structure the material parameters and the surrounding soil are unknown. It is therefore necessary to carry out measurements to get real information. Identifying the numerical model on the basis of measured data and by subsequent parametric studies the best method of repair can be found.

The main forces acting on the tower are caused by swinging bells. A swinging bell can be interpreted by a physical pendulum with the mass of the clapper integrated within the mass m of the bell. The horizontal and vertical reaction forces of a swinging bell depend on the angle φ and are given by

$$H(t) = mg \cdot \sum_{n=0}^{\infty} a_{2n+1}(\varphi_0) \sin\left[(2n+1)\frac{2\pi}{T} t\right]$$
$$V(t) = mg \left[1 + \sum_{n=0}^{\infty} b_{2n+2}(\varphi_0) \cos\left[(2n+2)\frac{2\pi}{T} t\right]\right] \qquad (1)$$

The horizontal force component $H(t)$ of equation (1) consists only of odd numbered multiples of the pendulum frequency of the bell, while the vertical component $V(t)$ consists of even numbered multiples. Corresponding to equation (1) and experimental tests on bell towers show predominant portions of odd numbered multiples of the pendulum frequency of the bell in direction of the swinging bell - in the case of $\varphi_0 = 90^0$ the third harmonic and in the case of larger angles the fifth and seventh harmonic.

2. EXPERIMENTAL MEASUREMENTS

Measurements of the dynamic response of the tower and the bell frame were carried out at different levels of the tower and in attached vaults of the nave by piezoelectric transducers in order to obtain sufficient data for subsequent computing. When the tower was already separated from the nave by cracks the relative movement tower-nave was measured by inductive transducers too. The measurement system used consisted of a laptop, an A/D - converter card, amplifiers and accelerometers. Acquisition and evaluation of dynamic data were done by PC using DIA/DAGO software.

Following decisive criteria have to be determined by experiment or computation:

- natural frequencies and damping coefficient of the tower
- maximal horizontal displacements of the tower during the bells are swinging
- relative movements tower - bell frame and tower - nave
- pendulum frequencies of the bells
- calculation of the horizontal static resultant force

To determine the fundamental natural frequency and the damping coefficient of the tower, the tower was excited by impact. Fig.1 shows the decline of measured amplitudes in the time domain.

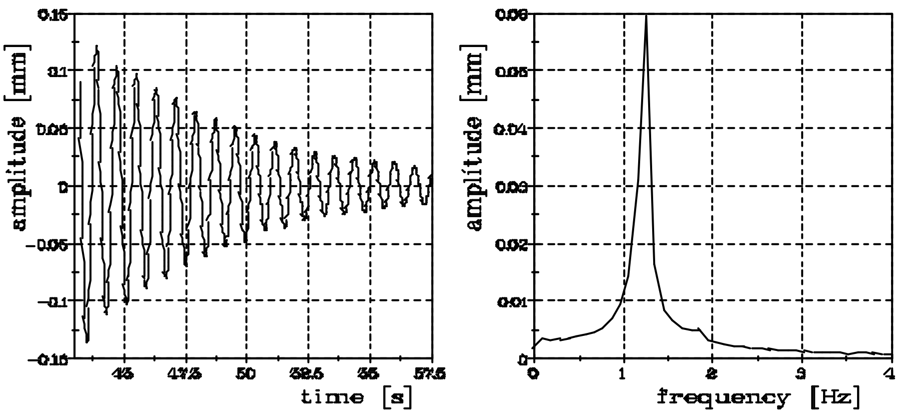

Figure 1: First natural frequency of bending of the tower excited by impact

3. METHODS OF RESTORATION

Often the masonry of the tower and the adjacent nave is damaged by cracks. Cracks occur in the central area of the walls and in the inside corners of the horizontal cross sections. The main direction is inclined at a small angle to the vertical line perpendicular to the principal tensile stresses.

Following measures have proved suitable for restoration of damaged bell-towers:

?? Prestressing the masonry of the tower by tendons at different levels and overpressure the cracks. Due to the almost vertical direction of the cracks, prestressing by four horizontal tendons at each selected level has proved most effective. The arrangement of the tendons is shown in Fig.2.

?? Use of an reinforced concrete lining inside the tower

?? Installation of reinforced concrete ceilings or steel frames at different levels of the tower

Each of the above mentioned preventive measures are appropriate to improve the stiffness of the tower against bending and torsion and to raise the natural frequency of the tower.

Because of unfavourable static construction, the vault of the nave is also often damaged by cracks caused by evasive movements of the sidewalls of the nave. When the tower is connected with the nave, the movements of the tower are transmitted to the adjacent vaults of the nave. Sometimes the tower has broken loose from the nave and causes impacts on the nave. This produces new cracks and a widening of already existing cracks.

For restoration it is necessary to reduce the motions of the tower and to save the walls by tiebacks. Fig.3 shows a possibility of an invisible tieback mounted in the roof space of the nave.

In addition to the structural restoration measures, the pendulum frequencies of the bells have to be tuned and adjusted to avoid resonance effects. Fourier analytical investigations of the horizontal force component (Equation (1)) show that the third harmonic term predominates in the range of swing angles between 70° and 110°. If the swing angle of the bell amounts to between 120° and 160°, the fifth harmonic term predominates. The frequency range of the third harmonic and fifth harmonic is found between 1,0 and 2,5 Hz. Also the natural frequencies of towers are situated in this frequency range. When the natural frequency of the tower and the third or fifth harmonic of a bell coincide, resonance will occur. Sometimes the reduction of the swing angle or an offset of the axis of rotation of the bell can change the pendulum frequency of

Figure 2: Bell tower with typical crack pattern and arrangement of the tendons.

Figure 3: Invisible tieback mounted in the roof space of the nave.

the bell and reduce the movements of the tower to acceptable amplitudes. The German Standard DIN 4178 requires a difference of 10% between natural frequency of the tower and the third harmonic of the bell. When the reduction of amplitude is not successful by the above named actions the installation of a counter pendulum is necessary. Because of limited space in bell chambers the counter pendulum has to be installed above or below the bell. To avoid additional bending moments, the distance between rotating axis of the bell and rotating axis of the counter

pendulum has to be as small as possible. On installation of a counter pendulum it has to be borne in mind that the vertical force is twice the weight of the bell. This requires restoration and often a remodelling of the bell frame.
For structural repair, measurements of the dynamic behaviour of the system tower nave and its numerical solution are an important basis. To get the elastic properties of the masonry of old towers for numerical calculation the numerical model has to be identified by the experimental determined dominant natural frequencies and the dynamic response measured at different levels of the tower. With the identified numerical model it is possible to investigate different restoration concepts.

4. RESTORATION OF BELL TOWERS

4.1 First example (Bell Tower in Raischach, Italy)

Because of extensive structural actions such as horizontal prestressing of the tower at eight levels, a new bell frame with high stiffness, and installation of counter pendulums for the bells No. 1, 2, 3, 4 and 5, the movements of the tower at the level of the bell chamber were reduced from 2,00 mm to 0,094 mm when all bells were swinging.

	before repair		after repair	
bell No.	averaged amplitude [mm] in swing direction of the bell	averaged amplitude [mm] perpendicular to the swing direction	averaged amplitude [mm] in swing direction of the bell	averaged amplitude [mm] perpendicular to the swing direction
1	1,125	0,21 (0,52)	0,052	0,033
2	0,90 (1,00)	0,47	0,048 (0,065)	0,054 (0,107)
3	0,575	0,15	0,029	0,027
4	0,22	0,055	0,019	0,028 (0,063)
5	0,12	0,044	0,037	0,034 (0,042)
6	---	---	0,023	0,008
1 - 5	2,00 (2,21)	0,65 (1,07)	0,094	0,12

Table 1: Comparison of amplitudes before and after repair

Because of horizontal prestressing of the walls, the natural frequency of the tower increased up to 2,15 Hz, i.e. much higher than the third harmonics of the bells. Table 1 shows the amplitudes of the tower at the level of the bell chamber measured before and after restoration. The values in brackets are resonant amplitudes which could be recognised when the bell was switched off.

4.2 Second example (Church in Altenmarkt, Austria)

The tower was reinforced by horizontal prestressing bars mounted in 8 levels. As both the nave and the apse had also many wide cracks, prestressing of nave and tower was combined as shown in Fig.4. The horizontal plates of reinforced concrete C1 and C2 create the abutments for the prestressing cables L1 and L2 that represent the reinforcement of the nave. The consolidated tower and the nave were pressed together by tendons S1 and S2. The contribution of the mass of the nave raised the fixing level of the tower and therefore its stiffness. The positive effect with regard to the measured frequencies and displacements of the tower is to be seen in table 2.

Figure 4: Scheme of measures for enhancement of the first natural frequency of a bell tower by prestressing

	First natural frequency of the tower [Hz]	Frequency range of the 3rd harmonics [Hz]	Frequency range of the 5th harmonics [Hz]	max. horizontal displacement [mm]
Damaged state	1,36	1,26 – 1,44	2,10 – 2,40	3,60
Completely restored state	1,76	1,26 – 1,44	2,10 – 2,40	0,48

Table 2: Measured frequencies and displacements of the tower 27m above soil level

5. CONCLUSIONS

Whether repair is necessary can be judged only by visual examination of the damage and by measurements of the amplitude of the tower and the movements of the vaults of the nave while the bells are swinging.

Successful repair of bell towers makes two steps necessary

?? repair of the cracks

?? tuning of the pendulum frequency of the bells to the dynamic properties of the building

Possibilities of repair of the masonry and tuning of the bells are given in section 4 of this paper. It is essential that repair work is done by experienced professionals and the chosen method of restoration is compatible with the guidelines of the authorities concerned with the protection of monuments.

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