
The minaret in Jam, in Afghanistan

Structural analysis of historic constructions: Some notable examples

The preservation of historic constructions passes through the analysis of the actions that can affect the structure and a suitable structural modeling. This is based on the knowledge of the geometrical and mechanical characteristics, also with reference to foundations and soil. Past experiences are good lessons for future studies

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The preservation of architectural heritage is a delicate task, especially for structures exposed to relevant seismic risk, and requires a balance between the structural safety needs and the respect for the architectural and cultural values. Most of the historical and architectural heritage is made of ancient masonry constructions, characterized by a wide range of uncertainties and high seismic vulnerability.

The first step in the structural analysis is the evaluation of actions that can affect the construction. The correct and complete description of the seismic input for structural design at a given site is given by the acceleration components along three orthogonal axes, recorded on-site during a suitable number of real events or selected in world-wide accelerometric databases. In practical applications, when using linear analysis, the horizontal and vertical on-site response spectra can be used to determine the maximum seismic effects on structures.

The second step refers to the structural modeling, which requires a good knowledge of the geometrical and mechanical characteristics (De Stefano et al., 2016). The elastic and inelastic ranges influence the value of the behavior factor assumed in the analysis, which is a measure of the inelastic capacity of the building, i.e., its capacity to dissipate energy. Often the analysis is quite hard because of the little knowledge of the geometry of the structures and their materials, especially with reference to the foundations and soil characteristics, but often also to the elevation structure. As a matter of fact, the visible elements and materials do not correspond to the effective ones, so detailed analyses are fundamental and should be done preferably using non-destructive testing (De Stefano & Clemente, 2009). Among these, the experimental dynamic analysis represents a suitable tool for dynamic characterization and a first diagnosis (Clemente & Buffarini, 2009), and traffic-induced vibrations represent a suitable free source of excitation.

With reference to the interventions, it is well known that traditional techniques, based on the increase in strength and ductility, are not suitable for the seismic rehabilitation of cultural heritage structures. For these, using new technologies is advisable: seismic isolation, for example, is based on a terrific reduction of the seismic actions affecting the structure, instead of relying on its strength. In the following, some relevant cases in the field of structural analysis and preservation of cultural heritage structures are shown. Different structural types are considered: towers, monuments, bridges, religious and historic buildings. For each of them a different structural aspect is analysed.

Stability of a masonry tower

The leaning Minaret of Jam, one of the tallest in the world, was declared as the Afghanistan's first World Heritage Site by UNESCO in 2002. The global stability analysis of the tower against soil collapse was evaluated in its present configuration, in the hypothesis of increasing bending moment at the base section, assuming an elastic-perfect plastic behaviour for the soil. Then a finite element model was set up and used for the modal analysis and then for the seismic push-over analysis, based on both single and multi-modal approaches, assuming an elastic-perfect plastic behaviour in compression and no tension strength for the masonry.

The study showed that Minaret is stable under dead loads. However, the stability check is very sensitive to soil properties, which should be investigated in more detail, as well as the foundation depth. If the soil strength would be lower than the assumed value, a wide portion of the soil under foundation could be yielded. This implies that the structure could be closer to the collapse point than it appears.

The seismic check based on rigid tower modelling and deformable soil showed that the maximum acceleration value requested to reach the soil collapse is much lower than the spectral amplitude on site coming from seismic hazard assessment of the area, demonstrating the high vulnerability of the Minaret. Obviously, also the possible seismic loads are very sensitive to soil characteristics, which can significantly modify the amplitude and frequency of local likely expected ground-motion.

The push-over analysis, also based on a multi-mode approach and for two values of masonry strength, allowed to take into account the mass distribution along the height and the "weight" of each mode. The pseudo-acceleration spectra and the modal analysis highlight the major spectral amplitude of the second mode with respect to the first. The non-linear analysis shows that, depending on the soil-masonry strength ratio, the failure under seismic loads can occur for soil collapse or the collapse of the masonry in the top part can happen before.

Traffic-induced vibrations in a monumental structure

The Colosseum is the largest amphitheater ever built (Fig. 1). Concentric annular walls connected by a series of radial walls and vaults compose the structure. The outer wall is 48 m high and is composed of travertine blocks, originally connected by iron pins and cramps without mortar. The foundation consists of an elliptical ring, approximately 13 m thick, composed by a paving of about 1 m and two concrete layers with different characteristics, of about 6 m each.

The structure suffered extensive damage over the centuries, with collapses due to earthquakes, especially those having epicenter in the Abruzzo's Apennine. Important structural interventions were made in the 19th century, such as on the buttresses that support the remaining part of the external wall at the eastern side, designed by Stern, and that on the western-end wall, designed by Valadier.

In 1955, the first underground line in Rome, now called line B, was completed. It passes very close to the Colosseum and the extrados of the pipe is just below the present pavement. Furthermore, on the north side a new underground, the line C, is under construction.

The Colosseum was one of the monuments in Rome investigated by ENEA in the mid-'80s. The structure was instrumented to study the effects of the traffic-induced vibrations at different times of the day, as well as the vibrations from the near underground, and to determine its dynamic characteristics. The results allowed to point out the vibration amplitudes at different locations in the monuments as well as some of its resonance frequencies. More recently, in 2014, another experimental campaign was carried out, which interested the northern wall and also the hypogeum. The results pointed out some interesting features of the foundations.

Thermally-induced cracks in masonry arches

The Brooklyn Bridge in New York City is the only long-span suspension bridge of its kind that was built in the nineteenth century and is still in service. It took 14 years to construct the bridge, finally opened to the public in 1883. At the time the

Fig. 1 The Colosseum, in Rome

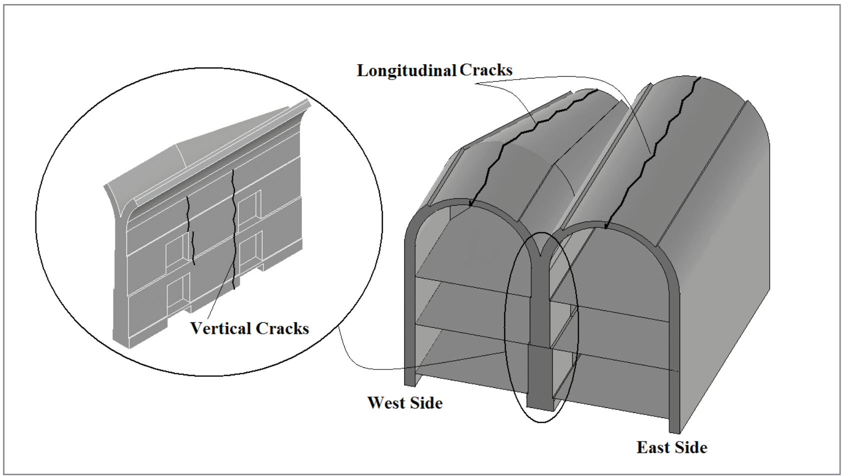

Fig. 2 Longitudinal cracks in the vaults and the supporting wall of the Brooklyn Bridge approach structures
Source: University of Illinois

bridge was constructed, the caissons used in the construction of the towers, the hybrid suspension/cable-stay system, and the air spinning of the suspension cables were innovative in size and method. Its span was also twice longer than any other previously built suspension bridge in the world (Talebinejad et al., 2011). A routine investigation of the approach structures that consist of masonry double vaults with span lengths of 10 and 10.5 m revealed large crown cracks covering the entire lengths of these cylindrical vaults (Fig. 2).
The cracks were large, with a nominal width of 1.5 to 2 cm. It seemed that these cracks took many years in making. From the structural point of view, crown cracks in arches are generally developed due to support movements. The question was why the cracks had occurred in these vaults, since the near surface bedrock on the Manhattan side of the bridge provided a very rigid foundation for the vaults. Subsequently, a structural health monitoring approach based on fibre optic Bragg Grating (FBG) sensors was employed in order to investigate the problem (Ansari, 2007). The FBG sensors consisted of tilt meters, displacement, crack, and temperature sensors. The tilt meters were placed along the height of the wall supporting the two vaults in order to detect the wall movements. The crack and displacement sensors were used along the length of the vault cracks for monitoring the crack movements. Temperature sensors were placed next to the other sensors. The structure was remotely monitored over a period of 12 months. While the structure did not indicate any significant daily and or weekly movements, the results of the investigation revealed that the over the twelve months period of study, the wall and vault crack movements were in direct correlation with the seasonal changes in temperature, i.e. winter through summer. The long-term monitoring results depicting the crack opening displacements and the thermal variations are shown in Fig. 3. It was concluded that the vaults had gone through thermal cyclic fatigue since the time of their construction in 1883, resulting in gradual growth. The vaults were consequently repaired.

Experimental vibration analysis of a religious building

Orvieto's Cathedral is a Gothic-Romanesque style church, built between 1290 and 1320. The very famous façade is a mix of marble and mosaics. The 59 m long nave is covered by a wooden truss roof, supported by masonry walls. Each wall is supported by six arches stemming from circular masonry pillars, which separate the nave from each aisle. The Duomo was interested by the 1997 Umbria-Marche seismic crisis. Three main shocks were recorded on September 26th, the first at 2:33 a.m. (Italian time, Ml=5.5), the other two at 11:40 (Ml=5.8) and 11:46 a.m. (Ml=4.7), respectively, with epicentral area about 70 km far from Orvieto. The first shocks caused the opening of cracks in the structure. ENEA was involved in the experimental analysis of the structural behaviour, in order to evaluate the health status and locate any damage. The structures of the Corporale's Chapel were particularly studied.
The structure showed a good performance both during ambient vibration and forced tests. The velocity amplitudes due to ambient vibrations were very low if compared to that obtained in other cases or suggested as allowable ones. The analysis of the recorded data relative to ambient vibration tests allowed to identify the resonance frequencies of the structure. The behaviour of the vaults was also analyzed by means of forced vibrations. The main structure of the nave showed a good performance, even though there was no rigid connection between the longitudinal walls. Horizontal constrains between the

wooden roof and the masonry walls are missing. Several structural resonance frequencies related to different modal shapes were identified.
Forced tests of the vaults showed resonance frequencies slightly different from those pointed out by ambient vibration tests. More significant differences were observed in the records obtained on the vaults of the choir and on that of the transept during earthquakes, probably due to the mechanical non-linearity of masonry. The presence of some cracks in the vaults also played an important role.

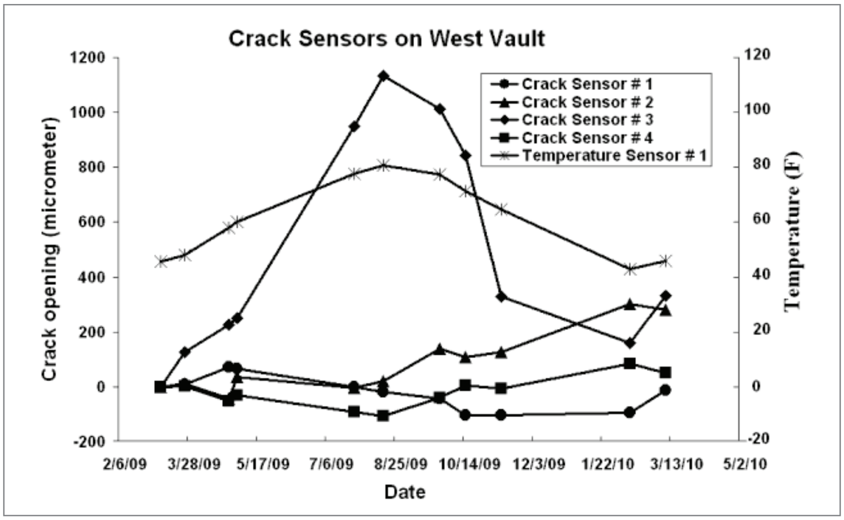

Fig. 3 The crack temperature and sensor readings, west vault
Source: University of Illinois

Application of seismic isolation to a historic building

The Iran Bastan Museum, designed by André Godard and completed in 1936, was conceived as a modern building with a traditional façade inspired by the pre-Islamic architecture of the Sasanian period. The large main entrance archway replicates the famous arch in Ctesiphon and the building's brick-works recall the Persian tradition of brick constructions. At the present time, the Museum building is part of the historical and cultural heritage of the city of Tehran and contains lots of rests of Persepolis.

The seismic vulnerability of the Museum in its present state was analysed by means of a simplified procedure, which allowed to evaluate a seismic vulnerability index. This index was then used to estimate the peak ground acceleration values $a_{gi} = 0.024g$ and $a_{gc} = 0.240g$, corresponding to the onset of damage and to the collapse, respectively. These values are much lower than the maximum peak ground acceleration expected at the Museum site, equal to $a_g = 0.5g$ for an exceedance probability of 10% in 50 *years*. So the building presents a very high seismic vulnerability, which calls for urgent and comprehensive remedial works, aiming at its seismic rehabilitation (Clemente et al., 2009).
The retrofitting strategy was organized in two steps. The first one consisted in improving the seismic performance of the structure using traditional systems; the second one in designing a suitable base isolation system. The traditional works proposed, i.e. the placement of steel bracing systems in the courtyards and the realization of rigid horizontal diaphragms, should guarantee a good seismic performance respecting the architectural and functional requirements.
Obviously, the consolidated building presents a higher seismic resistance, which was evaluated accounting for the dynamic behaviour of an isolated building. The analysis was carried out by using a finite element model, taking into account the combination rule for the seismic actions and the torsional effects due to variable loads. The value of the spectral amplitude, which causes the onset of damage to the structure, resulted to be equal to $S_{ei} = 0.15g$. This value has been used as limit value for the check of the superstructure in its ultimate limit state.
For the insertion of the isolation devices two beam systems were designed at the foundation level, one placed directly by the soil, the other just under the masonry. The isolation devices were accommodated between them. The proposed isolation system was composed of 100 lead elastomeric isolators and 247 sliders, deployed in order to optimize the dynamic behaviour of the structure. The fundamental period of the isolated structure was $T_{is} = 2.40$ *s*, the damping factor was 25% and the maximum seismic displacement was $d_E = 400$ *mm*.

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