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Understanding the dynamics of Vulci's Devil's Bridge

Accurately measuring the state of conservation

This white paper recounts a survey that was conducted by Essebi Srl Measurement and Monitoring Services and later upgraded in collaboration with Siemens PLM Software to provide a measurement that identifies the current state of the Badia Bridge (also known as Devil's Bridge). The monolithic ensemble was found to correspond to all the modes involved in the central stack, demonstrating the effectiveness of static rehabilitation that recently took place. Engineers in the future can accurately compare the state of conservation, especially to check for any damage due to possible new load scenarios.

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Executive summary

Operational modal analysis (OMA) is a technique used for conducting experimental investigations into the dynamic characterization of an artifact. It is based on the dynamic response of the structure when stressed by a stochastic source. In this case the excitation source is the wind that consistently blows through the gorge where the famous Etruscan Roman Bridge stands, generated by the Venturi effect, which is prevalent in this cross section of the valley. In addition, throughout the day in which the measurements were carried out, a strong north wind blew continuously, with frequent sharp gusts that shook most of the bridge.

The purpose of this analysis was to define as accurately as possible the modal parameters so that useful and constructive comparisons could be made in future years about the state of conservation and the maintenance of structural integrity. The OMA was also applied to evaluate the behavior of the entire bridge and identify areas of discontinuity in order to see if there were any serious structural problems. The monolithic behavior of the stack, which was recently restored, was also verified. Special attention was paid to the two portions of masonry with different stiffness, sharply separated along a vertical joint, constituting the base portion of the stack.

The Badia Bridge (also known as Devil's Bridge because the construction is so bold only a daredevil could have built it) is located in the archaeological site of Vulci, Italy, which includes the bridge, a castle, an important natural park with archaeological excavations of the Etruscan-Roman city and a necropolis. In the current configuration, it looks like a three-arched stone bridge, with the central arch larger in diameter than the two lateral arches.

Subjected to structural consolidation

The bridge was built in stages as shown by the different materials and construction techniques. The two main stacks supporting the central arch in red tuff based directly on the Fiora riverbed date back to the Etruscan period. It is believed the Romans completed the bridge because of the central arch and two side blocks of travertine square, which includes perimeter blocks of peperino (magmatic rock that abounds in the territory where the bridge stands) at the cells containing the original nucleus of tuff blocks. The bridge has three rounded arches; the central one with a diameter of 19 meters (m) and the two lateral with a diameter of 6 m each. On the upper walkway, the deck has a width of approximately 1.7 m and a variable altimetrical profile with maximum slope in the center of approximately 10 degrees. The keystone height, measured from the base of stacks, is approximately 30 m.

The artifact has just been subjected to a structural consolidation focused on the right stack of the central arch, significantly damaged as a result of heavy flooding on the Fiora River in November, 2012. The sediment transport and high strength produced by the current violently impacted the structure and penetrated through the joints between the blocks of stone, resulting in the expulsion of a significant portion of tuff, thus putting at risk the stability of the bridge. At the date of the test, the repairs and consolidation had just been completed, restoring the original section of the stack and giving a better binding to the blocks of stone with a series of mortar injections.

This work represents the final report of dynamic investigations and is intended to integrate the current knowledge of the artifact, which will be useful for any future developments and serve to support structural finite element modeling (FEM) for future validation. It will enable engineers to compare data and conduct periodic monitoring in order to verify the state of conservation of the artifact over time.

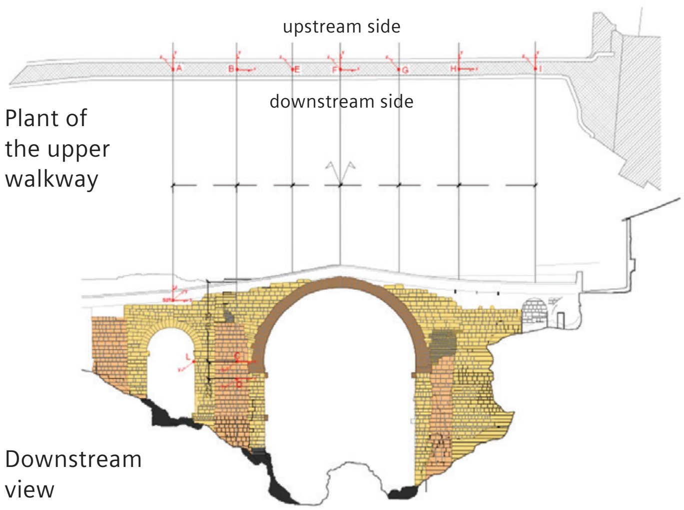
Using the wind

The investigation was carried out by means of OMA with the intent to dynamically characterize the bridge in terms of natural frequencies, damping and mode shapes. The source of dynamic excitation used for the execution of the measures was provided by the natural environment in which the structure is situated, in particular wind action. During the day, measurements were made when the wind action was particularly high and gusts persisted throughout the duration of data acquisition.

In fact, the wind was the only source of dynamic excitation used to execute measurements. It persisted with particular virulence and random gusting in all directions throughout the data acquisition process. The dynamic magnitude chosen for the measurements is the response of the structure in terms of acceleration at a series of points, suitably defined and located in an area corresponding to the deck and along the stem of the stack, which was the object of the recent intervention. This was done in order to investigate the presence or absence of discontinuity along the height, especially related to a vertical joint situated at the interface between soft and hard blocks.

The measurement points were arranged at the base of the three arches in correspondence with the vertical axis of the two stacks of the central support arch and at the haunches of the latter one. The figure to the right demonstrates the dislocation of the measuring points, indicating the direction of the measuring axis and of the conventionally adopted reference system. This is assumed to have originated from the center of the arch on the right bank side (the bridge is viewed from downstream in the figure). The X axis is oriented along the longitudinal axis of the deck, the Y axis is orthogonal to X assuming as positive the upstream face and the Z axis is acting in vertical gravity direction. There were seven measurement points along the deck and three along the stem of the stack, two of which were positioned at the same height, while one was at a lower level: C,D and L were placed on the stack, while A, B, E, F, G, H and I were placed on the upper part.

Dislocation of the measuring points



These points were instrumented with high-sensitivity seismic ICP® accelerometers (PCB 393 B12 model). The points in the keystone of side arches, including those in the stack axis and two of the three points along the stem, were instrumented with accelerometers arranged in a bi-axial configuration with measurement axes oriented according to axes X and Y. The measuring point in the keystone of the central arch was instrumented with accelerometers arranged in tri-axial configuration. The points in the haunches were instrumented with uni-axial accelerometers in configuration with the measuring axis vertical and, finally, the third measuring point along the stem stack was instrumented with a uni-axial accelerometer with the measurement axis oriented along Y (to capture any interruption of the stack in that direction). Overall, 18 axes (channels) have been arranged, two of which (point B on the deck aligned with the stack object of intervention) are common to both runs and are used as reference points.

Performing OMA with a multi-run technique

The measurements were conducted according to two sessions, referred to as run 1 and run 2. Each run consists of acquiring the signal of a sensor group for a period of at least 40 minutes. The first run refers to the transducers placed on the deck, and the second run to the stem stack. The reference point B, with the accelerometers disposed in bi-axial configuration with measurement axes in the X and Y direction, was kept fixed for both runs. In the OMA performed with the multi-run technique, this common point is necessary for data postprocessing for scaling and assembling the results obtained from each run in such a way as to obtain a set of global vibration modes of the structure.

For each channel, the measures have been carried out with a frequency of sampling (fs) equal to 200 samples/second (s) with appropriate analog anti-aliasing filter and consequent bandwidth up to 100 hertz (Hz), thus providing an adequate frequency band that is typically significant for civil applications. The accelerometers were mounted on specially-made metal supports (sideburns) and blocked with a stud. The accelerometers arranged on the deck were fixed by means of mastic rubber with strong adhesive power (applied to the surface of the base metal) to ensure perfect coupling. The accelerometers arranged on the stem of the stack were fixed to the walls by means of metal expansion plugs (to ensure the attack) and were made integral with the surface of the walls with the same mastic rubber.

Piezoelectric seismic accelerometers were employed (high sensitivity and capable of sampling at low frequencies) for the measurement. The measuring chain was completed by a data acquisition system for integrated electronics piezoelectric (IEPE) sensors, with a 24-bit analog-to-digital (A/D) converter with a dynamic range up to 150 decibels (dB), which provides powering and conditioning for the accelerometers connected to it and records the data collected using LMS™ SCADAS™ Mobile hardware.

With OMA, the output spectrum is known, but assuming the system under investigation receives input such as white noise, as it is a random excitation caused by wind, the measured response spectrum can be treated from a computational point of view in the same way as classical modal analysis. Therefore, the spectrum of the response of the system, which is derived from the measured quantities and with the modal parameters that characterize it, can be defined in detail.

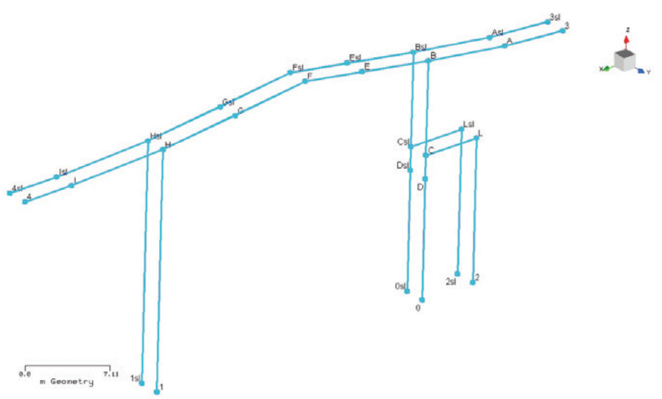
The quantity called gi is the operational reference factor, which is a function of both the modal parameters of the system and the constant input spectrum to the system. Based on knowledge of the first member (left side of the equation), modal parameter estimations are used to determine the quantities in the second member (right side).

$$\left[S_{yy}(j\omega)\right] = \sum_{i=1}^{n} \frac{(v_i)\langle g_i\rangle}{j\omega-\lambda_i} + \frac{(v_i^*)\langle g_i^*\rangle}{j\omega-\lambda_i^*} + \frac{\langle g_i\rangle(v_i)}{-j\omega-\lambda_i} + \frac{\langle g_i^*\rangle(v_i^*)}{-j\omega-\lambda_i^*}$$

LMS Test.Lab™ Operational Modal Analysis software from Siemens PLM Software was used for data processing, defining cross-spectrum functions and extracting modal parameters. PolyMAX is the algorithm included in this software that is operating in the frequency domain. It processes in polynomial terms the most accurate possible approximation of the quantities of the cross-power spectrum functions matrix, starting from the acquired measurements and proceeding to the determination of the modal magnitudes in the addition in the second member of the calculation above.

Setting a value of time lags until 2048

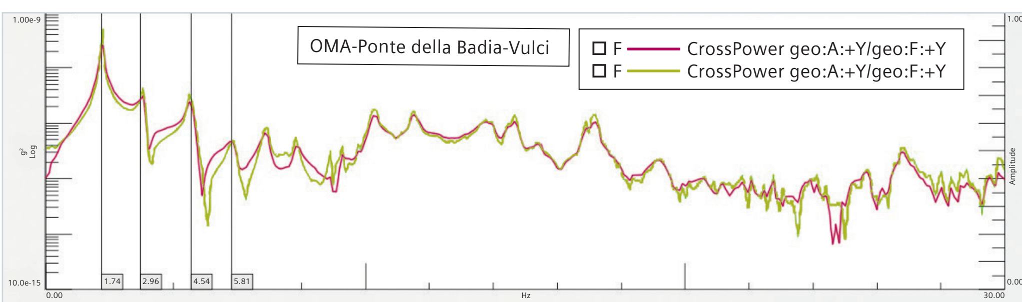
The picture below shows a three-dimensional image of the geometric model with in an upstream view. In order to improve the display of mode shapes, additional points have been added to simulate the thickness of the bridge. These points have the same reference as the corresponding measurement points. The suffix sl (slave) and their degrees-of-freedom (DOF) have been implemented according to the corresponding instrumented points. Further points have been added to simulate the base constraints of the stacks.

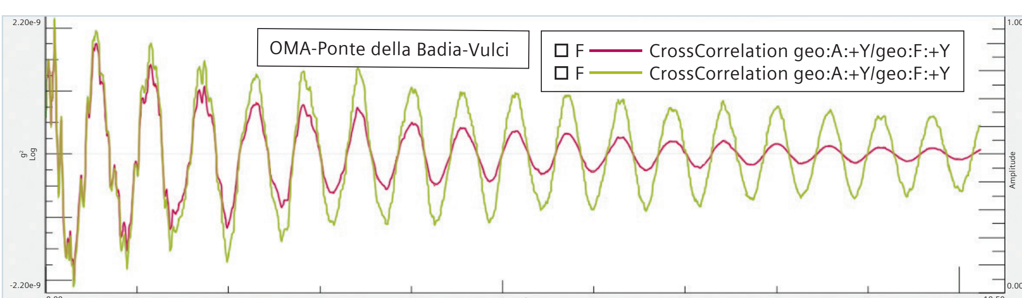


The analysis was conducted by setting a value on time lags (the number of lags with which we calculate the response/reference cross correlation throughout the time history) until 2048 with a resulting cross-spectrum resolution frequency equal to 0.098 Hz, with a 15 percent window. The graphs below show the cross-correlation function and the cross-spectrum function of point Ay with respect to the reference Fy (the red curves are both windowed).

For the first nine modes, the following table shows a summary of the results for frequency and damping.

Mode	f [Hz]	ζ	[%]
1	1.75	0.9	
2	3.07	1.04	
3	4.56	1.15	
4	5.84	1.03	
5	6.86	1.13	
6	7.52	0.92	
7	9.23	1.33	
8	10.23	0.94	
9	11.42	0.8	

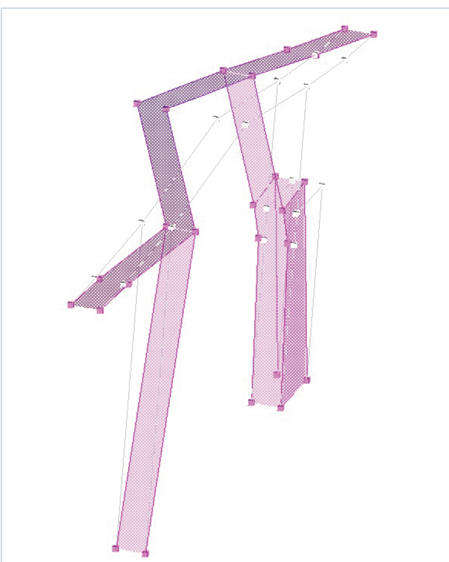
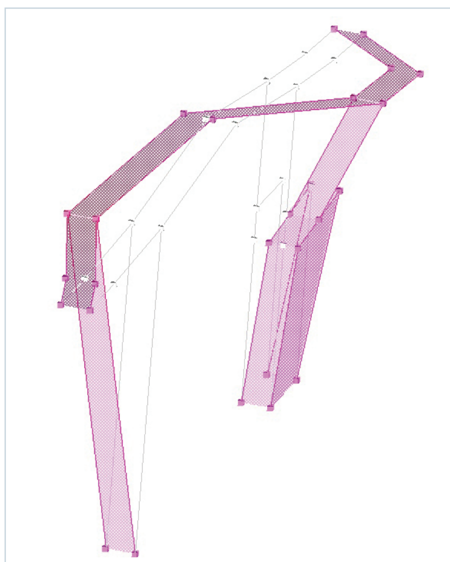
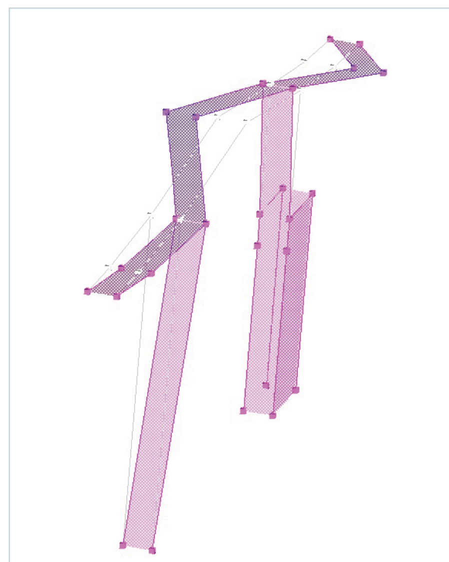




The stabilization is very good at the frequencies that have the higher peaks, starting from the lowest degrees of polynomial extraction. This evidence leads to a reliable estimation of the modal parameters, especially for frequency and damping. All frequencies correspond to certain modes of vibration in the horizontal plane of the bridge; in particular, they are all prevalent components in the Y direction (across the bridge deck), except mode 6, which is in the longitudinal direction. Vertical modes occur at very high frequency (> 20 Hz) and, therefore, the physical meaning, in view of a modal participation of the response, is irrelevant. The first mode is at a rather low frequency (corresponding to an oscillation period of 0.57 s) with a shape that is purely translational along the Y direction. This is consistent with the shape of the bridge in which the stacks are quite slender for out-of-plane bending compared to the stiffness of the arch for bending in its vertical plane. The stacks have a movement in phase opposition, with the main arch that moves in synchronous motion with the stack on the right bank. However, the stacks have different foundations and, as a result, the heights vary slightly.

The second flexural form of stacks corresponds to mode 8, visible only for the stack on the right bank as it is the only one instrumented along the stem. The discontinuity at the interface between materials of different texture is not found in the extracted mode shapes in which the points instrumented C, D (along with a vertical through point B positioned at the top) and L move in phase with each other. It follows that the stem of the stack is intact and the discontinuity only affects the surface with a good scarfing between the walls inside. The remaining modes involve stacks and decks with mode shapes more or less articulated and keystone movements in phase or in antiphase. There is a good consistency in damping with values virtually identical for all modes of vibration, all on the order of one percent.

The three figures below show the first three mode shapes with the main behavior in the lateral plane of deck and piers. The related frequencies are respectively 1.75 Hz, 3.07 Hz and 4.55 Hz

Conclusion

This survey was meant to provide a measure that identifies the state of the bridge so the status of conservation can be accurately compared in future investigations, especially to check for any damage due to possible new load scenarios, such as was the case with the flood of 2012. The monolithic ensemble was found to correspond to all the modes involved in the central stack, demonstrating the effectiveness of the static rehabilitation that recently took place.

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