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Autor: Chiarugi, Andrea / Foraboschi, Paolo

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Maintenance of the Ponte Vecchio Historical Bridge in Florence
Restauration et entretien du pont historique Ponte Vecchio à Florence
Erneuerung der historischen Ponte-Vecchio-Brücke in Florenz

Andrea CHIARUGI
Professor
University degli Studi di Firenze
Firenze, Italy

Andrea Chiarugi, born 1937, received his civil engineering degree at the University of Bologna, Italy. He is Prof. in the Civil Engineering Department of the University of Florence, Italy.

Paolo FORABOSCHI
Dr. Eng.
Universita degli Studi di Bologna
Bologna, Italy

Paolo Foraboschi, born 1959, received his civil engineering degree at the Univ. of Bologna, and his Ph.D. at the University of Florence, Italy. He has now a fellowship at the University of Bologna.

SUMMARY
This paper presents a new maintenance procedure, proposed for existing buildings. It consists of the arrangement of a mechanical survey for historical bridges, i.e., old masonry bridges. The procedure is applied to "Ponte Vecchio", in Florence, one of the main Italian monuments. The bridge presents a great crack pattern and masonry is damaged. A nonlinear finite element model was updated referring to the crack pattern and the experimental natural frequencies. The safety of the bridge was assessed together with its residual strength.

RÉSUMÉ
Cet article présente une nouvelle procédure de contrôle pour des ouvrages existants. Elle consiste en une adaptation du contrôle mécanique pour des ponts historiques, par exemple les vieux ponts en maçonnerie. La procédure a été appliquée au Ponte Vecchio de Florence, l'un des plus importants monuments italiens. Le pont présente un réseau de fissures et les pierres sont très endommagées. Un modèle aux éléments finis non-linéaires a été réalisé en se référant au réseau de fissures et aux fréquences naturelles expérimentales. La sûreté et la résistance du pont ont été déterminées.

ZUSAMMENFASSUNG
Eine neue Entwicklung der Kontrolle bestehender Gebäude wird dargestellt. Sie wird als mechanische Aufnahme bezeichnet. Das neue Verfahren wird an den Ponte Vecchio, eines der wichtigsten italienischen Denkmäler, angewandt. Die Brücke zeigt eine grosse Rissverteilung und das Mauerwerk ist beschädigt. Ein nichtlineares Finite Elemente Modell wurde angepasst, um die Rissbildung zu berücksichtigen. Hierzu, wurde ein inverses Problem gelöst, so dass das wirkliche Verhalten der Brückenstruktur ermittelt werden konnte.

1. INTRODUCTION: MAINTAINANCE OF HISTORICAL BRIDGES

Most historical bridges are used in the infrastrucures. Thus, the load carrying capacity required, at the present time to historical bridges may be substantially larger than in the past. Moreover, the floods of most rivers are increased in centuries, since the urban areas are increased in number and extension. As a result of the larger loads, the damage rate has increased in time. Therefore, nowadays structural degeneration of historical bridges grows faster than in the past centuries. For the aformentioned reasons, the maintainance of historical bridges is a fundamental topic for structural engineering. The safety margins have to be periodically assessed with respect to both loadings and structural state existing at the moment at which the structural analysis is conducted. It follows that the bridges that are proved to be any longer safe must be rehabilitated, i.e. retrofitted.

In the case of existing buildings, the analized structures can be tested, wheras this is obviously not possible in the case of building yet to be built. Thus, observations provided by specific in situ tests of the analized building, hereafter named monitoring resuls, can be used to identify the structural behavior. Nevertheless, special procedures are necessary in order to gain profit from monitoring prospect, since ordinary structural analysis does not include a-posteriori information.

Aiming at analizing existing buildings on the basis of monitoring results, the authors had proposed a special procedure, named *mechanical survey* [1, 2]. All existing buildings can be treated within the framework of mechanical survey. Nevertheless, the special arrangements of the procedure need to be correlated to the type of building that is analized. This paper is concerned with the development of mechanical survey procedure in order to deal with historical bridges, i.e. with existing masonry bridges. The proposed procedure is applied to the *Ponte Vecchio*, in Florence.

2. DESCRIPTION OF THE STRUCTURE

Due to architectural worth and artistic value as well as historical significance, the masonry bridge named *Ponte Vecchio* (Fig. 1) represents one of the main Italian monuments. Despite this, it has never been studied extensively in the past.

2.1 Geometry of *Ponte Vecchio*

As seen from Fig. 1, the structure consists of: 1) three circular arches covering a 60 degree angle, respectively with span of: 26.35 m; 28.85; and 26.25, along with thickness of: 1.0 m; 1.05 m; and 1.0 m; 2) two piers; 3) the abutments (i.e. two bridge-seats). Longitudinal retaining walls at the sides of the arches contain spandrel fill. The spandrel fill results in a flat extrados of the deck.

2.2 Structural problems of the bridge

The present investigation was prompted by: 1) the visible and accentuated crack pattern; 2) the considerable level of damage of the structural material, especially of the masonry mortar joints; 3) and the total absence of any structural investigation on the bridge. The main focus of the present study was to assess the safety of the bridge. If an insufficient safety margin had resulted, the study was expected to point out how the bridge should be retrofitted.

3. MECHANICAL SURVEY OF THE BRIDGE

Motivated by the need to better comprehend the behavior of the bridge, as well as to assess the present strength and stiffness, a *mechanical survey* procedure was carried out [1, 2].

3.1 Mechanical survey: review of the procedure

The procedure of mechanical survey is based on the comparison between monitoring data (i.e. observed response quantities) and correspondent mathematical model predictions. A physical interpretative model, hereafter named *virtual model*, allows use to be made of all a priori information derived from the geometric survey as well as the theory of structures. Thus a well-detailed description of the structural response can be guaranteed by the virtual model. Uncertainties regarding structural modeling can be restricted to the values of N parameters, denoted as the N-dimensional vector $\{\lambda\}$. Let the M-dimensional vector $\{\zeta\}$ denotes the results of M measurements, $M > N$, $\vartheta(\{\lambda\})$ denotes the mathematical model posed as a function of the N unknown parameters $\{\lambda\}$, i.e. M nonlinear, continuously differentiable functions of $\{\lambda\}$. The following relation between $\{\zeta\}$ and $\{\vartheta\}$ is assumed

$$\{\zeta\} = \{\vartheta(\{\lambda\})\} + \{\rho\} \tag{1}$$

where $\{\rho\}$ is a stochastic M-dimensional vector noise (assumed additive, independent on $\{\lambda\}$ and Gaussian). The procedure updates the initial estimate of parameters $\{\upsilon_\mu\}$ in order to optimize the differences between the predicted overall response and the monitoring data. The best estimation was found in the minimum of the following objective function $\Theta(\{\lambda\})$:

$$\Theta(\{\lambda\}) = \left\| \{\{\zeta\} - \{\vartheta(\{\lambda\})\}\} \right\|_{[\Delta]} + \left\| \{\{\lambda\} - \{\upsilon_\mu\}\} \right\|_{[\chi]} \tag{2}$$

in which $[\Delta] = [\Xi]^{-1}$ where the M·M matrix $[\Xi]$ denotes the covariance matrix of the noise $\{\rho\}$, and $[\chi] = [\Psi]^{-1}$ where the N·N matrix $[\Psi]$ denotes the covariance matrix of the initial estimate of parameters $\{\upsilon_\mu\}$, and where $\|\{\alpha\}\|_{[\beta]}$ is taked to denote $\{\alpha\}^T \bullet [\beta] \bullet \{\alpha\}$.

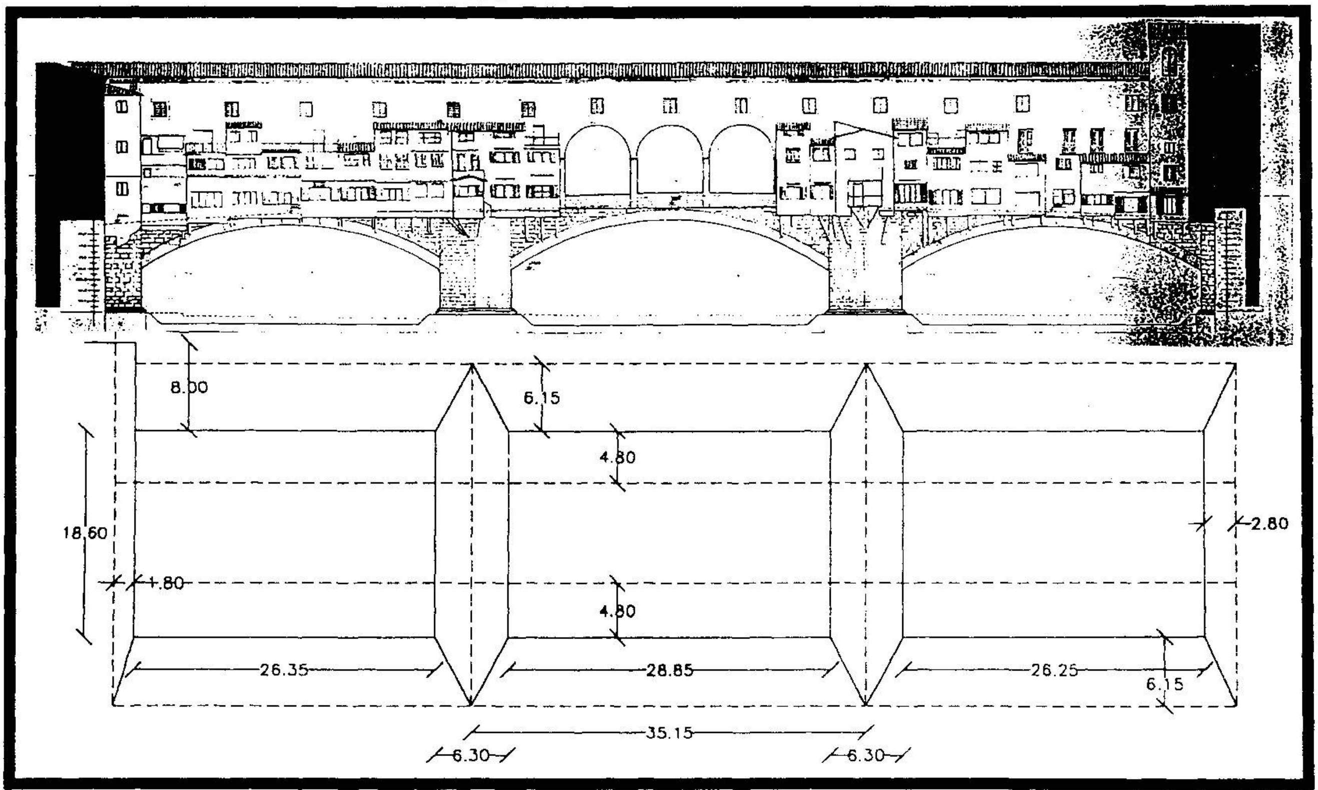


Fig. 1. Architectonic survey of the *Ponte Vecchio*, located in Florence, ITALY.

3.2 Historical information

Historical information about the bridge is necessary in order to obtain the virtual model. To this objective an extensive historical review of the bridge was carried out.

Ponte Vecchio was built to substitute the brigde that the 1333-river-Arno-flood destroyed. It should be noted that the thickness to span ratio is about 1/27, that corresponds to a low value and that the angle formed by the springing section to the horizontal is 30 degrees, that corresponds to an extremely large value. The heigth to span ratio is nearly 1/6, never built so little before.

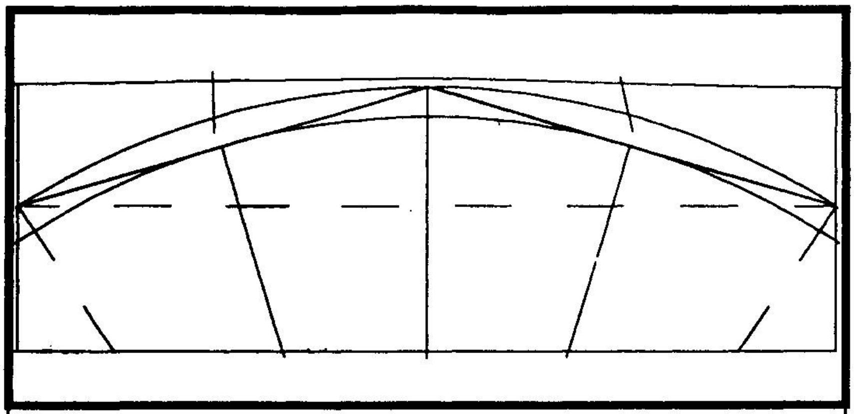


Fig. 2. Geometric rule used for the design

The reason of the dimensions was found in the rule explained in Fig. 2. Such a rule is attributed to Leonardo da Vinci, yet this study proved that the rule was known at least a century and an half before. Accordingly, it was possible to reduce both the hight of the crown to the springing, and the thickness. Nevertheless, this rule is not theoretically supported.

The bridge has been subjected to deep transformations. The shops have continuously grown in size. Moreover a gallery was built on the shops. As a result, the dead weights considerably increased. Arches and piers have never been modified, whereas piles (i.e. foundations columns) and diaphrams were built to support the existing foundations. In doing so, the bridge was upgraded so as to better withstand the periodical flood of the river Arno. As a result, the bridge was capable of resisting the flood of 1966, that corresponds to the largest flood of the river Arno.

3.3 Monitoring of the bridge

Maintainance of historical bridges requires: 1) the prediction of the structural response to vehicles and floods; 2) and the assessement of the present safety margins. Aiming at these two targets, two different monitoring strategies were carried out.

3.3.1 Mechanical survey for predictive analyses

Predictive analyses were conducted by tuning the virtual model according to Eq. (2) in which experimental modal parameters were used in $\{\zeta\}$. To obtain $\{\zeta\}$, a vibrodyne composed of 4 masses fixed at the edge of two disks rotating with opposite spin, ω, was used. The vibrodyne was located at the midspan of a lateral arch (point v) and the response of the structure was measured by severals accelerometers located at the level of the deck (points r). The excitation, $f_v(t)$, and the response, $q_r(t)$, can be written as (i denotes the imaginary unit)

$$f_v(t) = F(\omega)\cdot e^{i\cdot\omega\cdot t} \quad ; \quad q_r(t) = Q(\omega)\cdot e^{i\cdot[\omega\cdot t + \theta(t)]} \quad . \tag{3}$$

Let $H_{rv}(\omega)$ denotes the transfer function with respect to the vibrodyne in v. One obtains

$$H_{rv}(\omega) = \frac{Q\cdot e^{i\cdot(\omega\cdot t+\theta)}}{F\cdot e^{i\cdot\omega\cdot t}} = \frac{Q(\omega)}{F(\omega)}\cdot e^{i\theta(\omega)} \quad \rightarrow \quad H_{rv}(\omega) = \frac{Q}{F}\cdot[\cos(\theta) + i\cdot\sin(\theta)] \tag{4}$$

Using the readings from the instrumentations (e.g. accelerometers and vibrodyne), F, Q and θ were available as a function of ω. Thus, $H_{rv}(\omega)$ was numerically camputed. The natural frequencies of the structure were pointed out by the peaks of the imaginary part of the H_{jv} (1^{st} = 4.92 Hz), while the *j-th* element of the *k-th* modal shape, denoted with Φ_j^k, was yielded by the following expression

$$\Phi_j^k = \frac{I\langle H_{jv}^k(\omega_k)\rangle}{I\langle H_{vv}^k(\omega_k)\rangle} \cong \frac{I\langle H_{jv}(\omega_k)\rangle}{I\langle H_{vv}(\omega_k)\rangle} \tag{5}$$

3.3.2 Mechanical survey for safety assessement

In order to tune the model for safety assessement purposes, monitoring was composed of 3 parts: *1)* analysis of the structural materials; *2)* survey of the crack pattern; *3)* strain-temperature monitoring. The material analysis revealed a stone masonry along with the absence of mortar joints for a depth of 0.1 m at the the intrados. Thus, the thickness of the arches is now about 0.9 times the original ones.

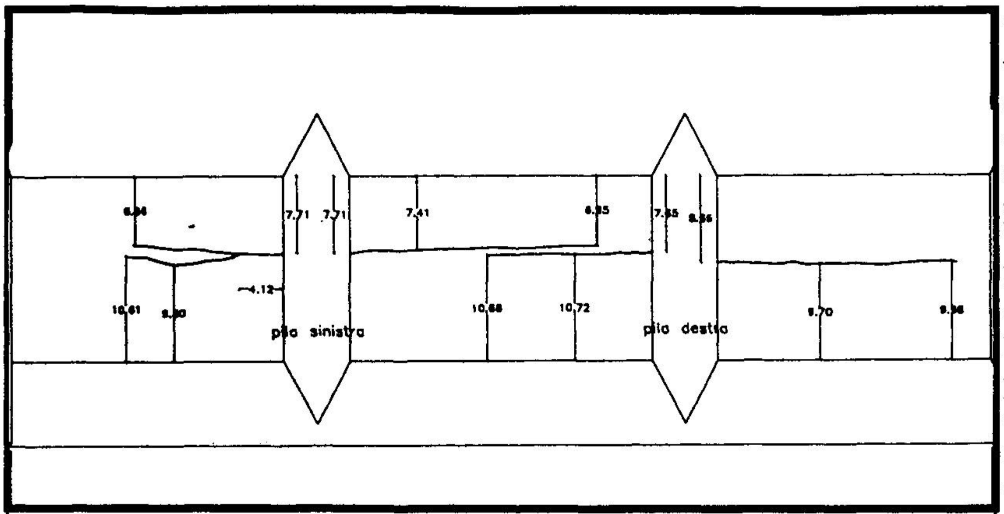


Fig. 3. Survey of the crack pattern

The crack pattern survey (Fig. 3) pointed out a longitudinal crack that split deck and piers into two parts. Thus, Ponte Vecchio resulted to be ideally composed of two ideal adjoining bridges. Strain-temperature monitoring correlated displacements of crack with temperature of air [3].

3.4 Virtual model

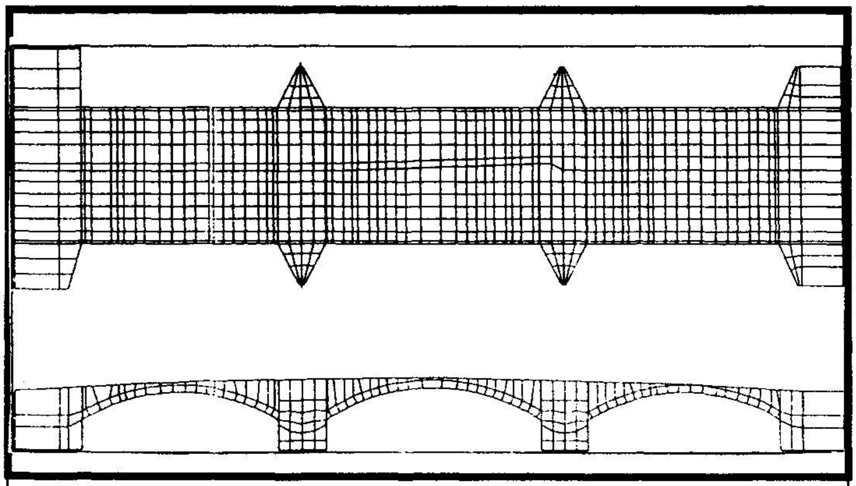


Fig. 4. Virtual model

A finite element model (Fig. 4) of the bridge was generated based on the geometrical survey. Brick element (eight-node element) was used. The virtual model exactly corresponds to the bridge in its first age. In fact, the shops were modelled with their original size, whereas the gallery was not modelled. The commercial program ANSYS version 4.4 installed in a 386 personal computer was used to perform the analysis.

4. ESTIMATION AND RESULTS

Two separate analyses were conducted, depending on the type of experimental data that are used.

4.1 Predictive analyses

The parameters were updated based on dynamic monitoring data, according to Eq. 2 [4]. The model tuned was used for simulating dynamic performances, including expected floods.

4.2 Safety margin

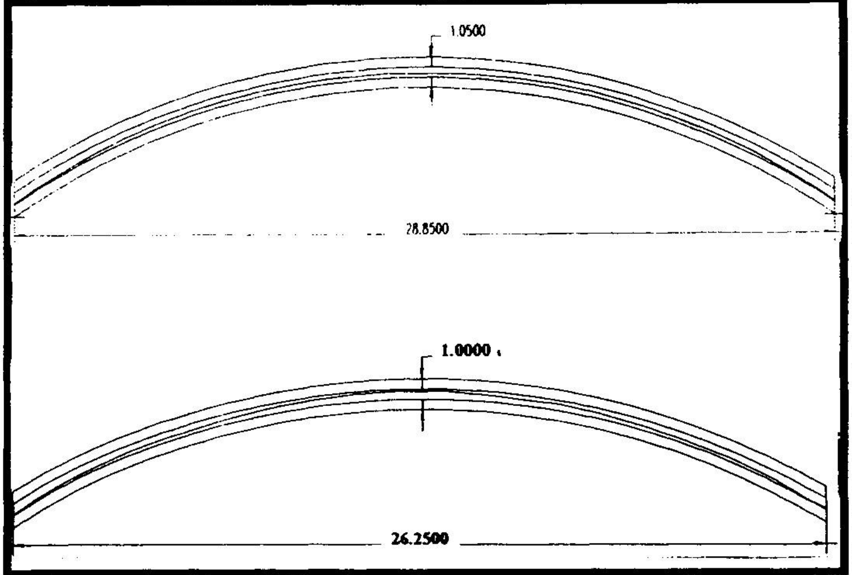
A new method was proposed for defining the safety margin of the bridge. A state-space description was used instead of a parameter-space one. Thus, a state-parameter vector was used for $\{\lambda\}$ in Eq. 2. To this objective, the following criteria were adopted for stresses and strains.

$$\sigma_3<\sigma_2<\sigma_1 < 0 \ ; \ [\varepsilon] = [\varepsilon]^e + [\varepsilon]^c \ ; \ \varepsilon_3^c<\varepsilon_2^c<\varepsilon_1^c > 0 \ ; [\sigma] \bullet [\varepsilon]^c = 0 \qquad (6)$$

in which σ_i and ε_i denote respectively principal stress and strain related to i-direction, apex "c" cracking strain, apex "e" elastic strain, $[\sigma]$ and $[\varepsilon]$ respectively the stress and strain tensors. A linear-elastic behavior is assumed. Denoting the elastic deformability tensor with [C], it follows:

$$[\varepsilon] = [C]\cdot[\sigma] + [\varepsilon]^c \tag{7}$$

The matrices $[\sigma]$ and $[\varepsilon]_c$ were assumed as the process state variables, and the measured matrix $[\varepsilon]^c_m$ as measurement noise vector. Gap elements (i.e. interfaces) were used to obtain $[\varepsilon]^c$.



Starting from the virtual model, the aformentioned process defined a new model that reproduced the crack pattern of the bridge in its first age. Then, the present dead loads were simulated and the process was repeated. In so doing, the new model reproduced the observed crack pattern. Thus, the mechanical history of the bridge was defined. The final model represents the bridge in the present state. Thus, it can be used to reliably assess the safety and the strength of the bridge in the present structural conditions.

Fig. 5. Lines of thrust in the present configuration: maximum compressive stress σ_{max} = 6,2 N/mm^2

5. FINAL REMARKS

The proposed procedure permits to establish strength and stiffness of existing bridges and to assess the safety. The application of the procedure to *Ponte Vecchio* has demonstrated that: 1) The crack pattern is stable; 2) The lines of thrust of the arches are in accordance with the *"middle third rule"* both in the present dead load configuration (Fig. 5) and in the original one. 3) The bridge - as obvious - was well designed; 3) Cracks do not reduce the load carrying capacity, since crack occurring modified the transversal behavior but not the longitudinal behavior of the structure. 4) The arches are capable of carrying the present dead loads; 5) The level reached by compressive stresses (6.2 N/mm^2) requires the rehabilitation of the damaged mortar joints. 6) The new foundations make the bridge capable of withstanding the expected floods. 7) The structural behavior of the bridge was predicted to not alter in the future, provided that damage of masonry is prevented.

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