Effects of Alternate Load Paths in damage evolution and identification in architectural heritage

Original
Effects of Alternate Load Paths in damage evolution and identification in architectural heritage / De Biagi, Valerio; Bernardino, Chiaia. - STAMPA. - (2014), pp. 807-814. ((Intervento presentato al convegno Le vie dei Mercanti _ XII Forum Internazionale di Studi tenutosi a Aversa, Capri nel Giugno 2014.

Publisher:
La Scuola di Pitagora Editrice

Published
DOI:

Effects of Alternate Load Paths in damage evolution and identification in architectural heritage

Valerio DE BIAGI,[1] **Bernardino M. CHIAIA**[2]

(1) Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy
E-mail: valerio.debiagi@polito.it
(2) bernardino.chiaia@polito.it

Abstract

The conservation of architectural heritage encompasses various aspects of technical sciences. In large buildings, made and further modified in different stages with different materials and techniques, it is difficult to measure the “health” of its structure in a simple way. The monitoring through displacement gauges represents one of the less costly solutions for estimating the evolution of damage in an existing structure: evidence of damage is represented by an increase of displacements. Anyway, due to the nonlinear behavior of large constructions, it is possible that displacements are measured only when the damage is at an advanced stage. In this sense, urgent measures have to be taken for ensure the stability of the construction. A preliminary study of the monitoring system and a good calibration of the threshold displacement values is required in order to limit the uncertainty about the true damage evolution stage. At the end, a full example illustrating the strategy to adopt in monitoring an historical construction is proposed.

Keywords: Structural monitoring, progressive damage

1. Introduction

Architectural conservation has a crucial role in the modern era. The history of any country is in some sense defined by its architecture. The actual trends are focused on preservation of historical architectures and monuments.

Weaver [1] noted that architectural conservation of historic urban sites is the most important evidence of the past life style. The idea of preservation deals with issues of prolonging the life and integrity of architectural character and integrity, such as form and style, and its constituent materials, such as stone, brick, glass, metal, and wood. What exactly is architectural conservation has been defined by Stubbs and Makas [2]: architectural conservation constitutes actions and interests that address the repair, restoration, maintenance and display of historic buildings and sites or measures taken to keep the existing state of a heritage resource from destruction or change. Therefore, actions preventing decay and prolonging life are needed. This includes maintenance, repair, consolidation, and reinforcement.

The international community as a whole and, in particular, the international scientific community have a very important duty: protect the integrity of cultural heritage sites from the destructive effects of natural and man-made hazards. The most prominent factors affecting cultural heritage structures are the environment, pollution, and tourism [3-5]. Some sites with recognized cultural value have been already deteriorated, partially destroyed, or are in imminent danger due to the effects of various “stresses” as earthquakes, volcanic eruptions, floods, land subsidence, pollution and acid rains.

Engineers can help architects and all the people involved in the conservation of such objects through innovative techniques. As said, continuous deterioration plays one of the most relevant hazards for historical constructions. One strategy for assessing such continuous processes is represented by the installation of sensors able to detect unusual increments in displacements in the structure. These can be related to progressive damage. Unfortunately, various problems occur. Preliminary to any discussion, the behavior of structures made by connected entities has to be highlighted (Section 2).

Then, solutions to the emerging problems are presented. These are based on the idea of force paths in the structure. An example of what has been theoretically presented is reported in Section 4. General conclusions are, then, illustrated in Section 5.

2. Behavior of damaged structures

The response of connected structures to damage can be extremely variable. Usually, such structures are characterized by the presence of multiple load paths. In other words, once a set of loads is assigned to the elevation part of the construction, the ways the forces are transferred to the foundations is extremely variable. The presence of multiple load paths is essentially linked to the static indeterminacy of the scheme, for which equilibrium equations are not sufficient for finding the forces in the elements. Thinking about robustness, intended as the capacity of a structure not to be too sensitive to local damage, whatever the source of damage, the presence of multiple load paths is considered a powerful strategy for preventing large deformations due to local damages and, thus, for ensuring the robustness of the structure. In parallel, the robustness of the structure may be a good indicator on the possibility that the structure exhibits large or smaller displacements before the collapse. In these terms, it is important to assess whether a structure is robust or not. To discuss on the behavior of frame structures under localized damage and on the difficulty in assessing the progression of the damage, consider the structure represented in Figure 1, taken from [6].

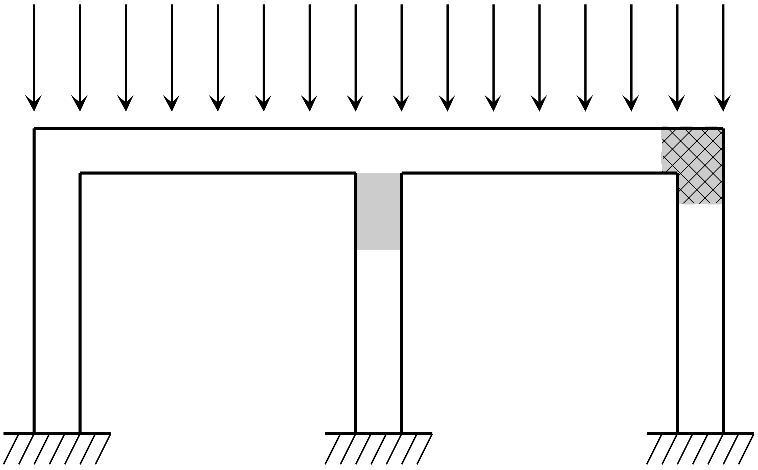

Fig. 1: A three columns – one storey concrete frame. Two different damages are supposed to act, alternatively on the structure. The damage acting on the top right joint (indicated as grey shaded transversal black hatchings represents the first situation. Otherwise, the plain grey area represents the second damage situation, from [6].

The example relates to a three column-one storey frame on which a uniform load acts on the horizontal deep beam. Since the system is symmetric, the bending moment in the central vertical element is null. Therefore, only an axial force acts on this vertical element. Idealizing the system as made by five monodimensional elements, say “beam elements” in a finite element software (two for the top beam and the remaining three for the columns), the degrees of static indeterminacy are 6. In this sense, as briefly explained, there are various load paths.

A main question follows: what happens if one column is progressively damaged? Since the system is statically indeterminate, the damage does not turn the equilibrated system into a mechanism. In particular, as soon as the degrees of static indeterminacy of the undamaged scheme are larger than one, the damaged scheme is still statically indeterminate (and presents more than one load path). In other words, damaging progressively one column, the remaining is able to sustain the external actions, i.e. to transfer the loads from the elevation to the foundation.

Suppose now to monitor the vertical displacement at the two mid- spans of the top beam. In the case in which the damage interests the top right joint, the resisting bending moment at that point reduces and, thus, the bending of the top beam increases, i.e. the mid-span of the right beam moves down. On the contrary, if the damage interests the cross- section of the central column, which is only subjected to axial force, the stiffness reduction is smaller. This is essentially due to the fact that the flexural stiffness is several orders of magnitude higher to the respect to the axial one. Hence, the damage progresses and the system apparently behaves as undamaged. The collapse may occur in two distinct situations: (i) if compressive strength in the central column is exceeded and the element breaks in compression, (ii) if flexural strength is not sufficient for the additional horizontal force acting on the structure and generating bending in the columns [6].

As a result of what presented above, as much as there are alternatives in the ways the loads are transferred from the elevation to the foundations, the effects of damage can be various. There is the possibility that the monitoring of some cinematic quantities (say displacement or rotation) at the wrong point does not give any evidence of progressive damage [6].

This fact has been highlighted by De Biagi [7] in evaluating the variation of deformation work after a localized progressive damage. He generated topologically similar structures with different stiffnesses distribution. In theory, since the topology is constant in the analysis, the number of load paths does not change. Anyway, the different distribution of stiffnesses, i.e. the cross-section of the elements varies, causes the behavior of the structure to be different, once a load is applied on it. That is, if one considers the scheme into which the load path, i.e. the way the forces are transferred from the elevation to the foundation, is unique the suppression of elements belonging to the most effective (and unique) load path entails large increases in the work of deformation. In parallel, the removal of elements not belonging to the most effective load path, does not involve an increase in work of deformation. On the contrary, if the stiffnesses distribution is such that is not possible to identify the dominant load path, the effects of progressive damage on deformation work are extremely reduced.

2.1 Models for damage evolution

Damage phenomena on constructions are various and uniform approaches are difficult. Although the choice of a function for structural damage is a challenging task [8], specific approaches are possible only once damage causes are clearly identified. In order to assess structural robustness with respect to a progressive deterioration of the structural components, the damage on the structure acts at the material level. As reported in Lemaître and Chaboche [9], the phenomenon can be modelled by softening of material strength and/or stiffness. In this sense, the decrement of stiffness is governed by a reduction of material elastic modulus, from its nominal value to zero in the undamaged and totally damaged cases, respectively.

3. Monitoring for damage through displacements

The damage can be considered as an unplanned variation of the properties or of the geometry of one or more parts of a structure, which entails a weakening and, usually, negative consequences. The methods usually used in the evaluation of damage on a structure consider its static or dynamic response, or both. Previous researches shown that the former is more sensitive to damage than the latter [10] and stressed the fact that the instrumental equipment for static measures is economic and easy to install [11].

As stated in the previous section, because of the redundancy in the structural schemes, the interpretation of deflection, rotations and strains is not straightforward for a direct evaluation of the health of the structure [12]. The main problems in the usage of static data rise when the damage acts on an element that has no or fairly little contribution to structural deformation under a certain load case.

The response of the structure, under its elastic phase, is a function of the distribution of stiffnesses and the position and magnitude of the external loads. In structures with high degree of static indeterminacy, e.g. frames, the overall behavior is determined by the contribution of all the elements belonging to the scheme. For example, in a three stories frame subjected to vertical loads and horizontal wind forces, the actions at the foot of one of the columns are highly dependent upon the way the stiffnesses are distributed on the whole structure, rather than on the neighborhood of the column under consideration.

3.1 Instrumentation for displacement measurements

The best way to assess the displacements of a large construction is represented by a topographical survey. Marks are placed on the building at precise points and the position of the measuring instrumentation is clearly defined in the neighborhood of the construction (which may be considered fixed). At precise time steps, the relative position of the reference points (materialized on the construction with the marks) is measured by means of distance and angles. In order to evaluate the absolute displacement, the set of reference points has to include fixed points (say objects that cannot deform or move around the construction). The displacement of the measuring points is estimated by subtracting the positions of two consecutive surveys.

In order to get the measurement quicker, it is possible to idealize a fixed measuring gird. Concrete pillars can support topographical instruments and keeping the alignments unchanged for many steps. One of the major advantages of the possibility to fix the position at the initial time is represented by the automatic survey. The system is able to recognize the correct position and performs automatic searching within the angular range set by the operator. In addition, the metallic marks can be substituted with crystal prisms and the procedure can be further accelerated.

4. Example: monitoring the main facade of Roman Theatre of Aosta (IT)

The effectiveness of the considerations made in the previous sections are now applied to a real example of piece of architecture.

4.1 Historical aspects

The considered construction is the Roman Theatre in Aosta, Northwestern Italy. It was built in the late reign of Augustus, some decades after the foundation of the city (25 BC), as testified by the presence of pre-existing structures in the area. There was also an amphitheatre, built during the reign of Claudius, located nearby. The theatre occupies three blocks annexed to the ancient city walls, along the Roman main road (the decumanus maximus, next to the Porta Praetoria. The structure occupied an area of 81 x 64 m, and could contain up to 3 500/4 000 spectators.

What remains today include the southern facade, standing at 22 m. The theatre is made of large parallelepipeds of “puddinga” a local sandstone with large grains. It was covered by slabs of limestone. The cavea was enclosed in a rectangular-shaped wall including the remaining southern part. This was reinforced by buttresses each 5.5 m from the other, and included by four orders of arcades, which lightened its structure. It has been supposed that the theatre once had an upper cover, making it a teatrum tectum.

The orchestra had a diameter of 10 m. The scene, of which only the foundations remain, was decorated by Corinthian columns and statues, and was covered with marble slabs [13].

The first archeological analyses were made in the first half of 19th Century by Promis. At the beginning of 20th Century, the facade was still covered by medieval houses and part of the area was totally covered by debris. During Fascism, the architectural shape was highlighted through the demolition of superfluous constructions and with excavations, see Figure 2. Many problems due to humidity and low temperature emerged after this intervention. The building was later restored in 2009, see Figure 3.

Fig. 2: Roman Theatre of Aosta in the Therties during the first intervention works. The houses built around the historical monument were demolished, source Wikipedia [13].

Fig. 3: The Roman Theatre of Aosta nowadays, source Regione Autonoma Valle d'Aosta.

4.2 Damage analysis

In the following, the structure of the main facade of the Roman Theatre of Aosta is subjected to a progressive damage. As explained in Section 2.1, the damage model takes into account the reduction of Young's modulus of the material constituting the construction through the parameter *d*. Young's modulus of the undamaged "puddinga" is set equal to 10 GPa.

The damage parameter varies from 0 to 1 for undamaged and totally damaged (i.e. removed) element, respectively.

A frame-equivalent scheme discretizes the masonry facade. A node is set at each connection. Beams connect the nodes. The model is composed by 49 nodes and 76 beams. The cross section dimension of each beam is determined from the sizes of the real masonry structure. The self-weight of the construction is inserted in the numerical model through nodal loads. The frame-equivalent scheme has been determined from rotated and scaled pictures, see Figure 4.

Fig. 4: The main facade of the Roman Theatre of Aosta, source Regione Autonoma Valle d'Aosta.

Since progressive damage velocity is extremely reduced, each damage situation can be considered as a static case. Each simulation consider the damage progressing on just one element. The vertical and horizontal displacements of a control point are monitored as much as the damage evolves on the structure. The control point is at the top of the construction, as indicated by red diamond in Figure 5. The initial displacement, in case of undamaged element, is subtracted from the set of measurements as long as the damage evolves. This gives the possibility to measure relative displacements, instead of giving absolute values that may be prone to various measure errors. In this sense, in the undamaged situation, the monitored value is null.

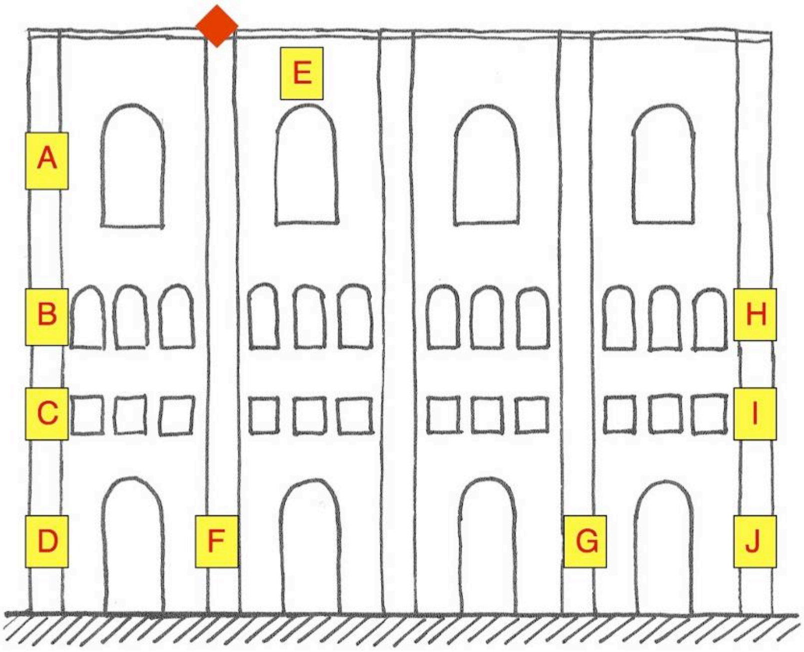

Fig. 5: Localization of the control point (red diamond) and the damaged elements

The vertical displacement due to damage evolution is proposed in Figure 6. Here we show that there are damages that imply larger displacements at the control point, and others not.

The vertical displacement at the control point (red diamond in Figure 5) is plotted as a function of the damage on elements of the frame-equivalent structure. As can be seen in Figure 6, there is evidence of progressive damage only in a limited set of cases. For example, as much as damage progresses on element F, i.e. one of the main columns of the masonry facade, the displacement increases rapidly. Effects of damages on vertical elements are various. Despite the fact that a damage on the columns close to the measurement point induces larger vertical displacements, this does not appear in the case of damage on distant columns.

The horizontal displacement at the control point is plotted as a function of the damage on elements of the frame-equivalent structure. As can be seen in Figure 7, the response of the structure to damage is variable. The main effects are shown in case of damage on elements D and J. This causes large horizontal displacements after the damage reaches a prescribed value. Damage on horizontal beams, say element E, does not cause an increase of horizontal displacement.

Few considerations can be drawn:

- the proposed calculations showed that damages close to the monitored point do not always imply increase in the recorded data. Remembering the damage on element E, no horizontal and vertical displacements are measured, while the damage acts. This is due to the lack of external horizontal forces acting on the structure.
- the evolution of damage and the evolution of displacements are not linear. That is, I record a large increase in the measurements as much as Young's Modulus of the damaged element is close to zero. This affects my estimates on the real health state of the structure.

5. Conclusions

It has been shown that, in frame systems, the response of the system is governed not only by the evolution of damage, intended as a localized reduction of Young's elastic modulus, but also by the connectedness of the elements. This implies non-linear response of the system when damage occurs on one of its parts.

This fact is important in structural monitoring. The local measure of displacements can give wrong interpretation of the real progressive phenomenon. As clearly visible in Figures 6 and 7, the response of the system does not increase to the final value as much as the damage evolves. This is due to the connectedness of the system and its capacity to redistribute the loads.

An example on a real historical construction shows this property of such structures. The best strategy we propose is to subject the structure to other sort of external loadings (say by mean of tendons) in order to activate other load paths in the structure and highlight all the possible damages.

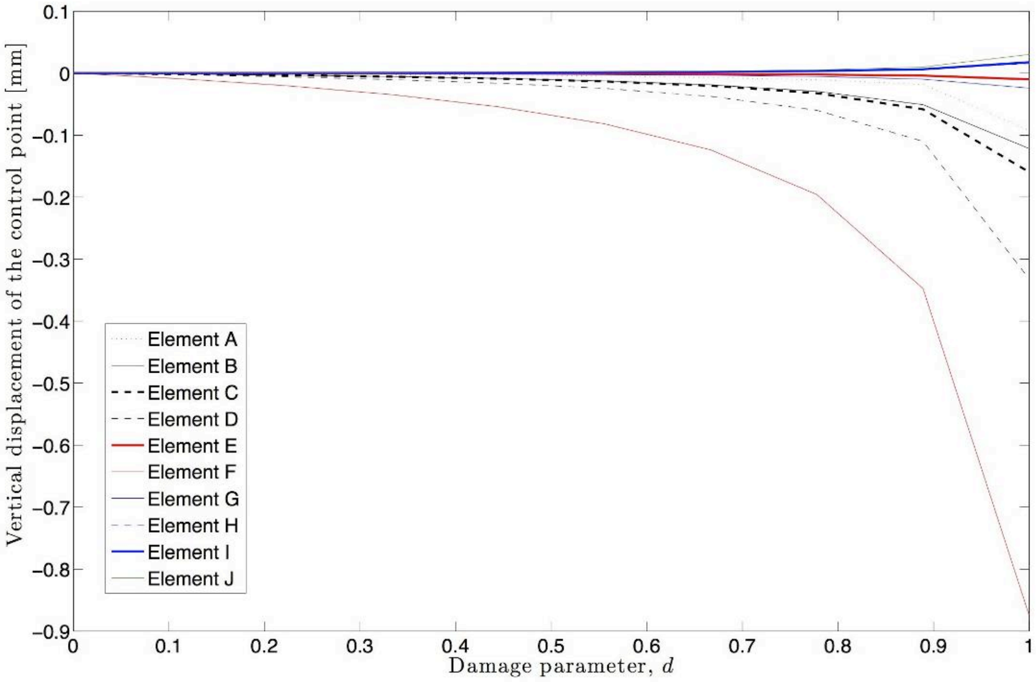

Fig. 6: Vertical displacement at the control point as a function of the damage on vertical and horizontal elements of the frame-equivalent structure.

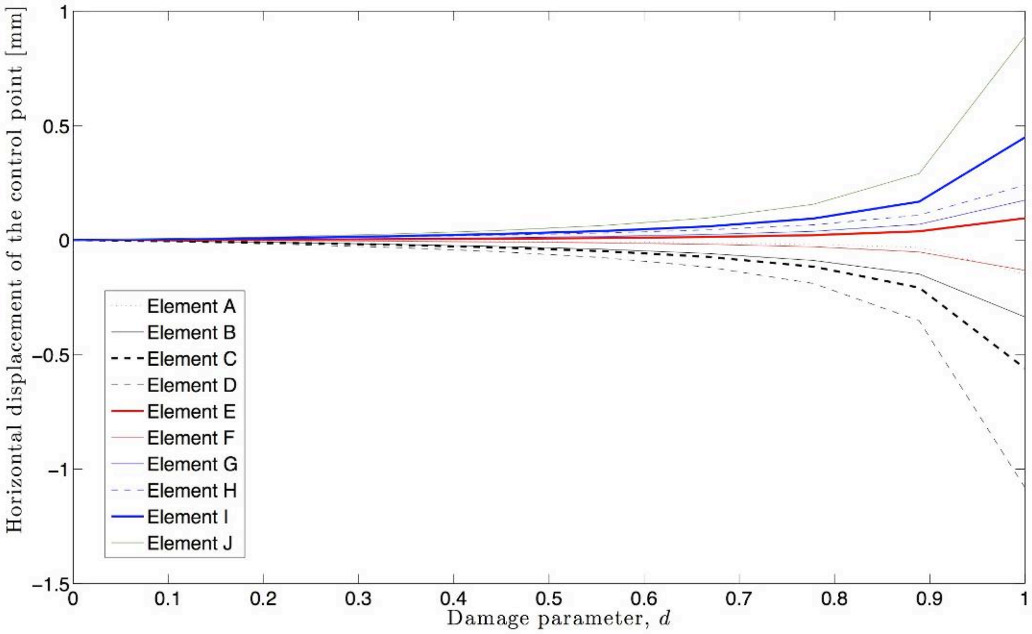

Fig. 7: horizontal displacement at the control point as a function of the damage on vertical and horizontal elements of the frame-equivalent structure.

Bibliographical References

[1] WEAVER, Martin. *Conserving Buildings: A Manual of Techniques and Materials*. New York: John Wiley & Sons, 1997. ISBN: 978-0-471-50944-8

[2] STUBBS, John, MAKAS, Emily. *Architectural Conservation in Europe and the Americas: national experience and practice*. New York: John Wiley & Sons, 2011. ISBN: 978-0-470-60385-7

[3] BENARIE, Michel. Air pollution and conservation. Safeguarding our architectural heritage. In ROSVALL, J., ALEBY, S. edited by ROSVALL, J. and ALEBY, S., Elsevier, Amsterdam, 1991.

[4] BAER, Norbert Sebastian, SNETHLAGE, Rolf. *Saving our architectural heritage: the conservation of historic stone structures: report of the Dahlem Workshop on Saving Our Architectural Heritage: the Conservation of Historic Stone Structures*, Berlin. John Wiley & Son Ltd, 1997.

[5] STUBBS, John (2009). *Time Honored: A Global View of Architectural Conservation*. ISBN 0470260491, Wiley; 1 edition

[6] CENNAMO, Claudia, CHIAIA, Bernardino, DE BIAGI, Valerio, PLACIDI, Luca. Monitoring and compartmentalized structures. *Zeitschrift für Angewandte Mathematik und Mechanik*, 2014. DOI 10.1002/zamm.201300091

[7] DE BIAGI, Valerio. *Complexity and robustness of structures against extreme events*. PhD dissertation, Politecnico di Torino, 2013.

[8] PETRYNA, Yuri, KRATZIG, Wilfried. Compliance-based structural damage measure and its sensitivity to uncertainties. *Computers Structures*, 2005. Volume 83, pp. 1113-1133.

[9] LEMAITRE, Jean, CHABOCHE, Jean Louis, 1994. Mechanics of Solid Materials. Cambridge University Press.

[10] HJELMSTAD, Keith D., SHIN, Soobong. Damage detection and assessment of structures from static response. *Journal of Engineering Mechanics*, 1997, Volume 123, pp. 568-576.

[11] WANG, Xu, HU, Ning, FUKUNAGA, Hisao, YAO, Zhenhan. Structural damage identification using static test data and changes in frequencies. *Engineering Structures*, 2001, Volume 23, pp. 610-621.

[12] HOUSNER, George W., BERGMAN, Lawrence A., CAUGHLEY, Thomas K., CHASSIAK-OS, Anastassios G., CLAUS, Richard O., MASRI, Sami F., SKELTON, Robert E., SOONG, Tsuteh, YAO, James. Structural control: past, present, and future. *Journal of engineering mechanics,* 1997*.* Volume 123, pp. 897-971.

[13] http://en.wikipedia.org/wiki/Roman_Theatre,_Aosta