In Italian schools of architecture, restoration would from its very beginning be a defining discipline that clearly distinguished between the skills required of an architect and those possessed by a civil engineer. Now, in such a transitional world as our own, what role should be played by the teaching of restoration? This issue of how, within a rapidly changing present, such a discipline might define the professional function and figure of the architect is a matter in which a range of factors come into play. Obviously, one of these is the architectural schools themselves, but one must also bear in mind the policies adopted in the management of territorial resources and the very nature of the multiform globalised society within which one is striving to assert the role, value – and very future – of our built heritage.
This is why it may be useful here to compare Italian and European schools of architectural restoration, looking at their past experiences, the analytical and interpretative approaches they have adopted, and their goals for the future. In one respect, this volume aims to compare the discipline of restoration as taught and practised in countries in which one can see a clear cultural and geographical proximity to Italy.
However, at the same time, it also contains contributions whose goal is to establish a dialogue with other disciplines and centres of research that pursue a shared goal: knowledge, understanding and protection of our built heritage.

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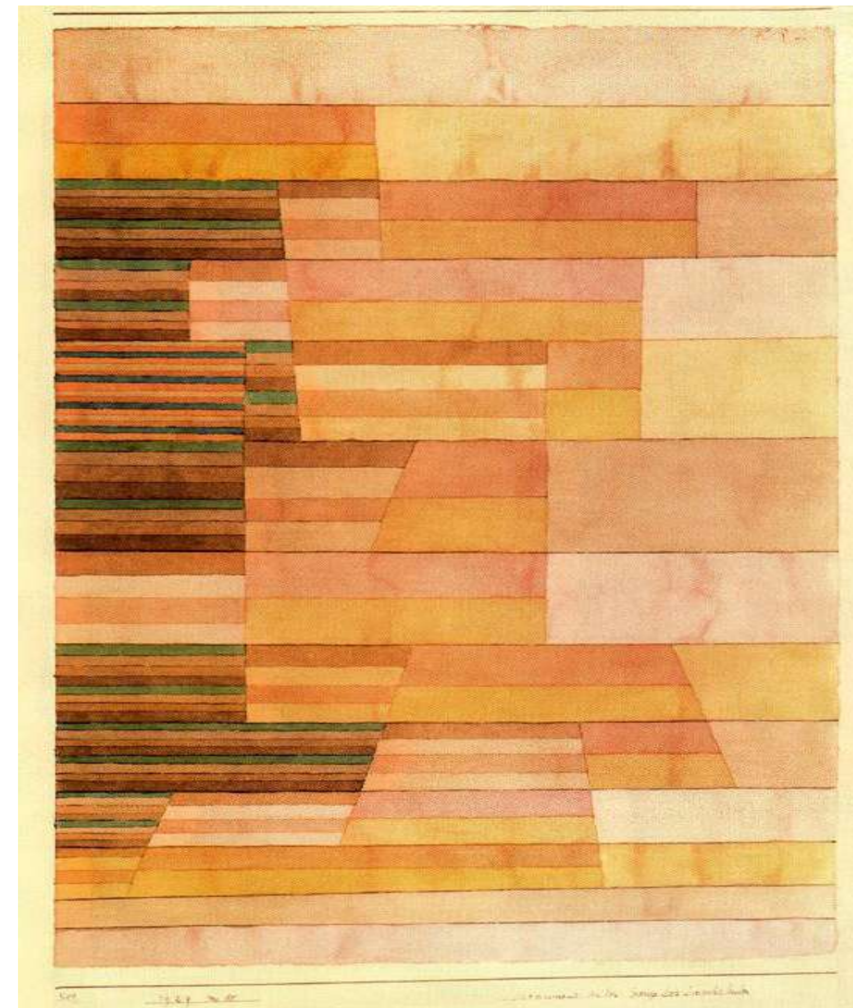

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Contents

The Role of Structural Engineering and Geotechnics in the Conservation of Historical Monuments. The case study of the of the Sanctuary of Vicoforte with its large elliptical dome

Mario Alberto Chiorino

Introduction

The protection of architectural heritage requires the contribution of different sciences. The paper discusses the significant and progressively increasing role of structural and geotechnical disciplines in the strategies for conservation and restoration of historical constructions and monumental buildings. Attention is paid to the gradually increasing recognition of the importance of this role within international debate[1], and corresponding reflection in principles and guidelines successively incorporated in charters and documents formulated at national and international level. A process that was accentuated in recent years, in connection in particular with the perspective of establishing scientifically based global strategies for the evaluation and mitigation of the seismic risk of some of the most relevant architectural heritage patrimonies located in seismic active areas, as e.g. Italy and India[2].

In the end, attention is focused on a relevant case study apt to demonstrate how these disciplines can contribute to the processes of reliability analyses of structurally complex and challenging important monuments. Reference is made to the Sanctuary of Vicoforte, a monumental building of great historical, architectural, and structural significance, characterized by one of the largest masonry domes in the world, and by far the largest elliptical one. Mention is made of the strategies adopted for structural modelling and analyses in the static domain, for the reliability assessments under gravity loads, as well as to the analyses in the dynamic domain, for both model updating processes and the evaluation of the seismic risk of this outstanding historical construction.

Fig. 1. Interior view of the dome of the Vicoforte Basilica

1. D.F. D'Ayala, M. Forsyth, *What is Conservation Engineering?,* in M. Forsyth (ed.), *Structures & Construction in Historic Building Conservation*, Wiley-Blackwell, Oxford 2007.
2. R. Cecchi, M. Calvi (coords.), S. Lagomardino (ed.), *Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle Norme Tecniche per le Costruzioni* (Guidelines for the evaluation and reduction of seismic risk of cultural heritage with reference to the Technical Code for Constructions; in Italian), July 2006; 1st official edition: Dirett. Pres. Cons. Min. 12.10.2007, Gazzetta Ufficiale 29.01.2008 n. 24; 2nd official edition: Dirett. Pres. Cons. Min. 09.02.2011, Gazzetta Ufficiale 26.02.2011, n. 47, Supplemento ordinario n. 54. EU-India Economic Cross Cultural Programme: Improving the Seismic Resistance of Cultural Heritage Buildings, *Guidelines for the Conservation of Historical Masonry Structures in Seismic Areas,* Universidade do Minho, Universidad Politécnica de Catalunya, Central Building Research Institute (India), Università di Padova, 2006.

Historical aspects

Roots and early development of the contribution of mechanical and engineering sciences to conservation and restoration of historical monuments can be detected in the entire construction history of past centuries. The description of this intriguing and exciting itinerary falls beyond the limits of this paper; reference can be made to specialized literature in the history of mechanics and construction science[3]. One preeminent episode was the early application, although with errors and limits, of the kinematic and the static approach of modern limit analysis to the checks of safety conditions of St. Peter's dome in Rome, by, respectively, the Three Mathematicians[4] and by Poleni[5], preliminary and in parallel to the strengthening intervention operated by Poleni and Vanvitelli in 1743-1748.

Principles and guidelines gradually incorporated in charters and documents

In a search for a more recent historical perspective of the progressively rising interaction and mutual fertilization between, on one side, the art, culture and science of conservation and restoration and, on the other side, the engineering sciences and techniques, in the frame of a broad vision of the polytechnic culture, one can first explore basic principles and conceptual guidance rules that were debated at the turn of 19th century in the national and international ambient of congresses and societies of architects and engineers. As an example, the First Italian Restoration Charter developed – with the preeminent role of Italian architect Camillo Boito (1836-1914) – within the 3rd Congress of Italian Architects and Engineers in 1883[6] after having established as basic principle the respect of authenticity of monuments of architectural heritage, takes into consideration the problems arising from the need of improving their structural reliability. At this respect, it recommends a proper strategy based, on one side, on minimum interventions, and, on the other side, in case of necessary additions, on an easy possibility to distinguish them from the original parts.

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3. See e.g. E. Benvenuto, *La scienza delle costruzioni e il suo sviluppo storico* (Structural mechanics and its historical development; in Italian), Sansoni, Firenze 1981.
4. T. Le Seur, F. Jacquier, R.G. Boscovich, *Parere di tre mattematici sopra i danni che si sono trovati nella cupola di S. Pietro, Sul fine dell'Anno 1742, dato per ordine di Nostro Signore Benedetto XIV* (Opinion of three mathematicians on the damages observed in St. Peter's dome at the end of the year 1742, given by order of Our Lord Benedict XIV; in Italian), Rome, Fratelli Palearini. Also in: *Scritture concernenti i danni della cupola di San Pietro di Roma e i loro rimedi* (Writings on the damages of St. Peter's dome and related remedial measures), Occhi, Venezia 1742. T. Le Seur, F. Jacquier, G.R. Boscovich, *Riflessioni de' padri Tommaso Le Seur, Francesco Jacquier dell'Ordine de' Minimi, e Ruggiero Giuseppe Boscovich della Compagnia di Gesù, sopra alcune difficoltà spettanti i danni, e Risarcimenti della Cupola di S. Pietro Proposte nella Congregazione tenutasi al Quirinale a' 20 Gennaro MDCCXLII1. E sopra alcune nuove Ispezzioni fatte dopo la medesima Congregazione* (Reflections of …on some difficulties concerning damages and remedial actions in St. Peter's presented in the Congregation held at the Quirinale on January 20th 1743. And on some new surveys made after the same congregation; in Italian), Rome 1743.
5. G. Poleni, *Memorie istoriche della gran cupola del Tempio Vaticano, e de' i danni di essa, e de'ristoramenti loro,divise in libri cinque, alla Santità di Nostro Signore Papa Benedetto XIV* (Historical notes on the large dome of Vatican Temple, and on its damages, and their restoration,subdivided in five books, to the Holiness of Our Lord Benedict XIV; in Italian), Stamperia del Seminario, Padova 1748.
6. C. Boito (ed.), *Prima Carta Italiana del Restauro* (First Italian Charter for Restoration; in Italian), 3rd Congress of Italian Architects and Engineers, Rome 1883.

The Athens Charter for the Restoration of Historic Monuments, adopted at the First International Congress of Architects and Technicians of Historic Monuments, Athens 1931[7] represents the main document in this domain developed in the first half of 20th century, establishing basic principles and guidelines. In its main introductory resolutions it clearly states, for the first time, the principle that "modern techniques and materials may be used in restoration work", while recommending in subsequent item IV Restoration of Monuments a "judicious use of all the resources at the disposal of modern technique and more especially of reinforced concrete" (a somehow ambiguous and perhaps excessive evidence given to this new technique, whose use is expected today to be considered with proper caution, in particular when rehabilitation interventions are intended to reduce the seismic risk of masonry and stone constructions of historical architectural heritage, due to possible undesirable increases in mass and rigidity in some parts of these constructions[8]).
The Athens Charter also recommends at its item VI that "before any consolidation or partial restoration is undertaken, a thorough analysis should be made of the defects and the nature of the decay of these monuments", recognizing that each case needs to be treated individually: an anticipated recommendation of modern integrated approach and methodological consistency, which, as discussed in the sequel, currently specify an appropriate sequence of consecutive steps similar to those used in medicine, where therapy must be preceded by proper anamnesis and diagnosis[9].
The Italian Charter of Restoration, established in 1932 by "Consiglio Superiore delle Antichità e Belle Arti"[10], is largely inspired by the Athens Charter of 1931. After having stated that "restoration (…) results from a combination of science, art and technique", the Charter recommends to pay the deepest attention to maintenance and rehabilitation works in order to re-establish proper strength and durability for the monuments. Further in the text the following other guiding criteria are recommended:

- "in what concerns the additions that will be required to obtain the strengthening (…) the criterion to be followed should be, besides that of limiting these interventions to the possible minimum, also that of conceiving them in the simplest possible way and in accordance with the original structural conception";
- in the aim of improving structural safety and reliability of a monument "the most advanced modern techniques may be used, whenever the use of techniques similar to the ancient ones appears inadequate for this scope", and structural conservation procedures must be based on "strictly scientific approaches".

In the first decades of the second half of past century, the major cultural event, in the progressive development at the international level of advanced policies for conservation and restoration of cultural heritage, is represented by the 2nd International

7. *Athens Charter for the Restoration of Historic Monuments*, adopted at the First International Congress of Architects and Technicians of Historic Monuments, Athens 1931. http://www.icomos.org/en/charters-and-texts/179-articles-en-francais/ressources/charters-and-standards/167-the-athens-charter-for-the-restoration-of-historic-monuments.
8. See references in note 2.
9. See ICOMOS-ISCARSAH, *Recommendations for the Analysis and Restoration of Historical Structures – Principles and Guidelines*, 2003 (http://iscarsah.org/documents/), and EU-India 2006.
10. *Carta Italiana del Restauro* (Italian Charter for Restoration; in Italian), Consiglio Superiore per le antichità e belle arti, 1932. http://www.sbapge.liguria.beniculturali.it/index.php?it/178/carta-italiana-del-restauro-1932

Congress of Restoration held in Venice in 1964[11], which gathered architects and technicians of historic monuments from all over the world. The main outputs of this congress were the establishment of ICOMOS International Council on Monuments and Sites[12], and the drafting of the International Charter for the Conservation and Restoration of Monuments and Sites[13].

In what concerns ICOMOS, it must be noted that its mission underlines the contribution of sciences to the conservation process, stating that "it is the only global non-government organisation of this kind, which is dedicated to promoting the application of theory, methodology, and scientific techniques to the conservation of the architectural and archaeological heritage"[14].

As for the Venice Charter, Piero Gazzola, Chairman of the organizing committee of the Congress and principal author with Raymond Lemaire of the Charter, declares in the Foreword to the records of the congress that "above all, it is to be recognized that the most important positive result by far of this assembly has been the formulation of the international code for restoration: not simply a cultural episode but a text of historical importance (…). In fact, from now on, the Charter of Venice will be in the entire world the official code in the field of the conservation of cultural properties"[15].

Reaffirming some of the principles already stated in previous charters[16] the Venice Charter declares at its Article 2 – "The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage", and at its Article 10 – "Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience".

If we go through the ponderous volume of the proceedings of the Venice Congress[17] we may notice that some of the debated subjects show the progressive increase of the influence of the role of structural engineering and geotechnics in the conservation of historical monuments. Just to quote a few, we may indicate the discussion on the reconstruction, repair and preservation of monuments at Skopje destroyed or heavily damaged by the catastrophic earthquake of July 1963; the use of advanced techniques like strengthening through the application of active prestressing by steel tendons in the restoration of structures of architectural heritage; the debated problem of the detecting of adequate solutions for improving the progressively worsening stability, at the time, of the leaning Tower of Pisa, and the related structural and geotechnical issues[18].

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11. ICOMOS International Council of Monuments and Sites – Conseil International des Monuments et des Sites, *Il monumento per l'uomo – Le monument pour l'homme – The monument for the man*, Records of the II International Congress of Restoration Venezia, 25-31 Maggio 1964, Marsilio Editori, Padova 1971.
12. *Resolution Concerning the Creation of an International Non-Governmental Organisation for Monuments and Sites*, 1964, in ICOMOS 1971, pp. LXXII- LXXIV.
13. *International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter)*, 1964, in ICOMOS 1971, pp. LXIX-LXXII, http://www.icomos.org/charters/venice_e.pdf
14. http://www.icomos.org/en/.
15. P. Gazzola, *Foreword*, in ICOMOS 1971, pp. XXVII – XXX.
16. P. Gazzola, R. Pane, *Proposte per una Carta Internazionale del Restauro* (Proposal for an International Charter of Restoration; in Italian with English Summary), in ICOMOS 1971, pp. 14-19.
17. ICOMOS 1971.
18. C. Cestelli Guidi, *Prolegomeni al problema della stabilità della Torre di Pisa* (Prolegomena to the problem of stability of the Tower of Pisa; in Italian with English Summary), in ICOMOS 1971, pp. 506-512.

ISCARSAH Principles and Guidelines

A turning point in the establishment of a specific ambient for debating the role of structural and geotechnical disciplines in the restoration of architectural heritage was the founding in 1996 by ICOMOS of ISCARSAH, the International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage, as a worldwide forum and network for all those involved in the field. After a few years of debate, ISCARSAH authored the ICOMOS Charter Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage, ratified by ICOMOS in 2003, which were followed by Guidelines to be used in tandem with the Principles as global recommendations in this domain[19].

These two fundamental documents still represent the main international reference for selecting proper strategies for conservation and structural restoration interventions. In the past decade they also represented the conceptual frame for the establishment by the scientific community of advanced guidance criteria and strategies, which are discussed in the sequel, for the more specific and increasingly relevant challenge of the evaluation and reduction of the seismic risk of architectural heritage.

The main concepts incorporated in the ISCARSAH Principles are the following:

- "Conservation, reinforcement and restoration of architectural heritage requires a multi-disciplinary approach";
- "The peculiarity of heritage structures, with their complex history, requires the organisation of studies and analyses in steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the condition survey, identification of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions".

With respect to diagnosis the Principles state that it "is based on historical information and qualitative and quantitative approaches" and that "the quantitative approach requires material and structural tests, monitoring and structural analysis."

In what concerns remedial measures and controls, an articulated framework is indicated for a virtuous approach evidencing, among other aspects, the needs to "address root causes rather than symptoms", to base conservation and reinforcement measures on adequate "safety evaluation and an understanding of the historical and cultural significance of the structure", and to "keep intervention to the minimum necessary to guarantee safety and durability and with the least damage to heritage values".

It is also specified that "the choice between «traditional» and «innovative» techniques should be determined on a case-by-case basis, with preference given to those that are least invasive and most compatible with heritage values, consistent with the need for safety and durability". And it is remarked that "at times the difficulty of evaluating both the safety levels and the possible benefits of interventions may suggest «an observational method», i.e. an incremental approach, beginning with a minimum level of intervention, with the possible adoption of subsequent supplementary or corrective measures".

Finally, the Principles insist on the concepts of a) *reversibility*, recommending that " where possible, any measures adopted should be «reversible», so that they can be re-

19. ICOMOS-ISCARSAH, 2003.

moved and replaced with more suitable measures if new knowledge is acquired" and that "where they are not completely reversible, interventions should not compromise later interventions"; and b) *compatibility*, requiring that "the characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established".
The related Guidelines represent an extended organic global document intended to assist in establishing a rational approach and related proper strategies for the analysis, conservation and structural restoration of architectural heritage. The successive topics of: 1) General Criteria, 2) Acquisition of data: Information and Investigation, 3) The structural behaviour, 4) Diagnosis and safety evaluation, and 5) Structural damage, materials decay and remedial measures, are discussed in detail providing valuable guidance criteria. The crucial role of modern structural analysis is underlined in what concerns item 4), evidencing, among other aspects, that "the essence of the problem is the identification of meaningful models that adequately depict both the structure and the associated phenomena with all their complexity making it possible to apply the theories at our disposal". A proper evidence to the important role of mathematical interpretative models, and to the currently fully recognized fundamental role of model identification and updating techniques as further and more precisely stated in the sequel of the text: "Mathematical models are the common tools used in structural analysis. Models describing the original structure, if appropriately calibrated, allow comparison of the theoretical damage produced by different kinds of action with the damage actually surveyed, providing a useful tool for identifying the causes of such damage. Mathematical models of both the damaged and the reinforced structure will help to evaluate present safety levels and to assess the benefits of proposed interventions".

Guidelines for evaluation and mitigation of seismic risk to cultural heritage

One major occasion for a more intense recognition of the role of structural engineering and geotechnics in the conservation of historical monuments has been provided by the development, especially in the last more than one decade, of extended debate at international level on conservation strategies for architectural heritage in seismic prone areas, and the consequent editing in recent years of relevant guidance documents in the field aimed to contribute to mitigate the risk associated with the seismic vulnerability of this heritage. Such actions were undertaken in particular in consideration of major losses suffered along past century and in the first years of new century the by extended portions and important masterpieces of architectural heritage in some regions characterized at the same time by the presence of outstanding multi-century patrimony of this heritage and significant seismic action, like, for example and especially, Italy and India.
The Italian Code of cultural heritage and landscape[20], edited in 2004, at its article 29, Conservation, already recognizes the basic strategic concept that "in the case of

20. *Codice dei beni culturali e del paesaggio, ai sensi dell'articolo 10 della legge 6 luglio 2002, n. 137* (Code for cultural heritage and landscape; in Italian), Decreto Legislativo 22 gennaio 2004, n. 42, Gazzetta Ufficiale 24.02.2004, n. 45, Supplemento Ordinario n. 28 (see also further amendments 2004-2011).

historical buildings situated in regions with a declared seismic risk, the restoration must include structural improvement", for the reduction of this risk.
In the wake of this new progressive awareness of the importance of preserving cultural heritage, with particular regards to historical constructions and monuments, from seismic risk, one important and valuable document resulting from intense interdisciplinary debate is represented by the Italian Guidelines for evaluation and mitigation of seismic risk to cultural heritage[21]. Drafted by a panel of academic and professional experts of, on one side, the art and science of restoration, and, on the other side, structural and geotechnical engineering, these Guidelines were first established in 2006, and subsequently reedited and updated in agreement with development and progressive evolution of the national Technical Code for constructions and inherent prescriptions on analyses and safety and reliability checks with respect to seismic actions.
At the international level, an important reference document is represented by the coeval Guidelines for the Conservation of Historical Masonry Structures in Seismic Areas, published in 2006 in the frame of EU-India Economic Cross Cultural Programme[22], together with two other guidance documents on, respectively, monitoring and strengthening strategies.
More recently, at the European level, the text of the European Guidelines for the seismic preservation of cultural heritage assets was delivered within the research program PERPETUATE (Performance-based approach to the earthquake protection of cultural heritage in European and Mediterranean countries) supported by the European Commission[23]. The parallel research project NIKER (New integrated knowledge-based approaches to the protection of cultural heritage from earthquake-induced risk), also funded by the European Commission, aims at developing an integrated methodology for the systemic improvement of the seismic behaviour of cultural heritage assets[24].
A detailed examination of the contents of all the above documents is out of the scope of this report. Suffice to say that, combining the most advanced outputs of current research in the fields of seismic engineering and of structural mechanics (with special regards to traditional construction techniques and materials, like e.g. stone and brick masonry and wood[25]) with the requirements of conservation and restoration, pursuing the complex and debated target of reconciling safety and conservation requirements, the guidance

21. See reference in note 2.
22. See reference in note 2.
23. C. Modena, S. Lagomarsino, F. da Porto, S. Cattari, *Earthquake protection of masonry historical constructions: overview of results from Niker and Perpetuate European projects*, in J. Jasieńko (ed.) *SAHC 2012, 8th International Conference on Structural Analysis of Historical Constructions*, Wroclaw, Poland, October 15-17, 2012, DWE, Wroclaw 2012, pp. 2851-2860. S. Lagomarsino, S. Cattari, C. Calderini, *European Guidelines for the seismic preservation* of *cultural heritage assets*, in "Deliverable D41", PERPETUATE, 2012. D. F. D'Ayala, S. Lagomarsino, *Performance-based assessment of cultural heritage assets: outcomes of the European FP7 PERPETUATE project*, in «Bulletin of Earthquake Engineering», Volume 13, Issue 1, January 2015, pp. 5-12. S. Lagomarsino, S. Cattari, *PERPETUATE guidelines for seismic performance-based assessment of cultural heritage masonry structures*, in «Bulletin of Earthquake Engineering», Volume 13, Issue 1, January 2015, pp. 13-47. See also http://www.perpetuate.eu/.
24. C. Modena, S. Lagomarsino, F. da Porto, S. Cattari 2012; F. da Porto, B. Silva, F. Lorenzoni, P. Girardello, M.R. Valluzzi, C. Modena, *New integrated knowledge based approaches to the protection of cultural heritage from earthquake-induced risk*, in "Structural Engineering World Congress SEWC 2011", Villa Erba, Italy 2011, April 4-6. See also http://www.niker.eu/.
25. While the ICOMOS and ISCARSAH Principles and Guidelines are referred to all types of historical structures of the architectural heritage, including modern buildings in iron, steel and reinforced concrete that are now recognised as being of historic importance, all other mentioned guidelines principally refer to historical masonry constructions.

concepts and criteria developed in all these documents address the following sequential aspects: the definition of performance limit states specific for the cultural heritage assets, the definition of the seismic input with proper attention to site amplification effects, the knowledge of the historical construction under consideration, the techniques for the analysis of the seismic response and evaluation of seismic safety through adequate modelling and, lastly, the definition of proper strategies for rehabilitation.

In what concerns structural models for the evaluation of seismic safety, besides discussing both different possible approaches for seismic analysis methods and seismic assessment levels, attention is dedicated, in particular by Italian Guidelines, to simplified evaluation models by structural types. These models are apt for a first level qualitative analysis for seismic safety assessment of the entire architectural heritage at a regional scale.

In consideration of the particular seismic vulnerability of the important architectural heritage represented in Italy by churches[26] (being characterized, especially in the case of monumental ones, by challenging structural architecture encompassing wide internal spaces, large arches and vaults, important façades with free standing tympanums, and, in quite a few cases, daring dome and drum configurations) a specific focus is placed on this type of structures. A certain number of typical damage mechanisms associated to various macro elements, which exhibit an almost independent behaviour, are presented in detail in the Italian Guidelines.

In the most recent of the above documents, like e.g. PERPETUATE European Guidelines, a few advanced conceptual guidance criteria are accentuated. "The first driving idea is that the protection of cultural heritage needs an improvement in methods of analysis and assessment procedures rather than in intervention techniques. The second is that a verification approach in terms of displacement capacity rather than in term of strength is more reliable and effective for heritage buildings and that flexibility; ductility and lightness are positive factors for their seismic behaviour. The third idea is that a reliable assessment procedure of heritage buildings requires the assessment of both architectonic and artistic assets contained in them"[27].

Outstanding recent case studies emphasizing the role of structural engineering and geotechnics in the conservation of historical monuments

In recent years, a few outstanding cases of structural restoration interventions were successfully performed with a fundamental contribution of structural engineering and geotechnics, in the frame of an intentional multidisciplinary approach.

26. Surveys of vulnerability and damage assessment performed at regional levels after seismic events taking into consideration the entire heritage of both churches (including the simplest and less monumental) and of residential palaces show that in some cases the seismic vulnerability of palaces may result statistically higher, due to lack of maintenance, or improper rehabilitation and strengthening interventions by private owners. See S. Podestà, C. Romano, L. Scandolo, *Molise, Valutazione della sicurezza sismica a livello territoriale* (Molise, Evaluation of seismic safety at territorial level; in Italian). www.beniculturali.it/mibac/multimedia/MiBAC/documents/1295445079370_4) Esempi(6).pdf.
27. http://www.perpetuate.eu/.

A most eminent case, among others, was the intervention, after decades of debate, for the safeguard of the celebrated monument of the leaning Tower of Pisa. An extraordinary and unique intervention that was based on the use of the most advanced scientific knowledge and techniques both in the field of geotechnics and structural mechanics, performed with the specific intent of adopting the less invasive approaches in the full respect of the historical artistic and architectural values of the monument, and the ethics of restoration. Developed with a deep understanding of the strict connections between progressive leaning, risk of structural collapse and materials decay, the final intervention – which was based on controlled ground extraction (under-excavation) from foundation layers, and active reversible intervention for local strengthening of the construction after a thorough mechanical analysis and investigation of the structure of the Tower – was the result not only of an intense debate but also, and especially, of a synthesis and integration between different cultures[28].
Other outstanding cases of structural analysis, monitoring, and in some cases of strengthening and rehabilitation interventions, of important historical constructions are related to other celebrated monuments like, to quote just a few among many others, the Cathedral of Mexico City (where advanced monitoring and modeling was performed, with respect to soil settlements and seismic risk, and the under-excavation remedial measure was first tested to counteract differential settlements[29]); the dome of Santa Maria del Fiore in Florence[30], as well as other notable monuments around the world.

Advanced debate, research and education ambients

In the last two decades, an intense activity was developed at national and international level for the establishment of proper ambients for advanced debate, synthesis of research, and education on the role to be played by structural engineering and geotechnics in a multidisciplinary approach to the conservation architectural heritage. One main forum for discussion of research achievements and for the analysis of notable case studies is represented by the series of SAHC international conferences on “Structural Analysis of Historical Constructions”. The first two editions were held in Barcelona in 1995 and 1998, followed by biennial editions in Europe and other locations in the world; the last venue was Mexico City in 2014, and the next one is scheduled in 2016 in Leuven, Belgium.

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28. S. Settis, M. D’Elia, M. Jamiolkowski, G. Macchi, F. Veniale, G. Viggiani (eds.), *La Torre restituita. Gli studi e gli interventi che hanno consentito la stabilizzazione della Torre di Pisa* (The recovered Tower. Studies and interventions that have led to the stabilization of the Tower of Pisa; in Italian), Vol.I-III, Ist. Poligrafico e Zecca dello Stato, Coll. Bollettino d’Arte,Volume Speciale. Roma 2005.
29. R. Meli, A.R. Sánchez, *Rehabilitation of the Mexico City Cathedral*, in «Structural Engineering International», 9 (2), 1997, pp. 101-106. D. Rivera, R. Meli, R. Sánchez, B. Orozco, *Evaluation of the measured seismic response of the Mexico City Cathedral*, in «Earthquake Engineering & Structural Dynamics», Volume 37, Issue 10, 2008, pp. 1249–1268. V. Hernández, E. Santoyo, J. Hernández, *Geotechnical behavior of the Cathedral after 10 years of the intervention of subsoil*, in F. Peña & M. Chávez (ed.), *Proceedings of SAHC 2014, 9th International Conference on Structural Analysis of Historical Constructions*, Mexico City, Mexico, 14-17, October 2014.
30. G. Bartoli, M. Betti, C. Borri, *Numerical Modeling of the Structural Behavior of Brunelleschi’s Dome of Santa Maria del Fiore*, in “International Journal of Architectural Heritage: Conservation, Analysis, and Restoration”, Vol. 9 N° 4, 2015, pp. 408-429.

At the scientific literature level, one of the corresponding principal vehicles for research dissemination and debate in the field is currently represented by the "International Journal of Architectural Heritage".
High level research and education multidisciplinary programs, merging advanced technical and scientific achievements in structural mechanics and geotechnics with the science, culture and ethics of conservation and restoration, have been established in various universities and academic institutions, in Italy and elsewhere, and within international networks of these institutions (see e.g. SAHC Advanced Masters in Structural Analysis of Monuments and Historical Constructions[31] and, in the more specific domain of protection of cultural heritage from earthquake-induced risk, the above mentioned European programs NIKER and PERPERTUATE).

The case study of the of the Sanctuary of Vicoforte with its large elliptical dome

In this last part brief reference is made to a relevant case study concerning the contribution of structural engineering and geotechnics to the conservation of the Basilica "Regina Montis Regalis", also known as Sanctuary of Vicoforte, in northwest Italy. The Basilica is a monument of great historical and architectural significance, owing its fame primarily to its big masonry elliptical dome (axes 37.23 m x 24.89 m), the largest of this shape the world over, and one of the largest domes as a whole (fig. 2).
Since the earliest stages of construction, started in 1596 on the basis of a project by architect Ascanio Vittozzi (1583–1615), the large and massive oval building of the Basilica was adversely affected by important absolute and differential settlements of foundations, due to an unfortunate selection of the site, which is characterized by an inclined (from east-northeast to west-southwest) marlstone bed-rock surmounted by soft clay-silt layers of increasing depth (only the north-east part of the foundations of the Basilica reach the marl bed-rock; see fig. 3). Construction was slowed down and almost stopped along the 17th century, while in the early 18th century works were resumed and entrusted to architect Francesco Gallo (1672–1750), who demolished the previously built part of the drum, levelled its base, and erected a new slender and transparent drum with closely spaced window openings. The construction of the shallow baroque ribbed masonry dome, with wide circular openings at its base and contained by a system of iron tension rings located within the masonry at three different levels in this same region, was started in 1731 and the Basilica was inaugurated in 1735.
The dome-drum system suffered since the beginning from significant structural problems, related in part to the additional settlements induced by the new built masses, and, to a large extent, to the daring structural configuration of the system itself. During the years following the construction stage an extended system of wide cracks developed along the meridians of the dome and the drum (fig. 3), progressively transforming the structural system into an ensemble, typical of these masonry

31. http://www.msc-sahc.org/.

architectural configurations, of slender masonry slices, separated by meridian plans and converging to the top of the dome. The significant lateral thrusts exerted by these loosely arch shaped structural elements, insufficiently opposed by the iron tension rings, was evidenced by significant shear-type diagonal cracks in the vertical walls of the eight slender buttressing vertical elements located at the perimeter of the drum and the dome, part of them incorporating the ascending stairs.

In 1983, concerns over these severe settlement and cracking phenomena affecting the structure prompted the decision to undertake inspection, monitoring, and strengthening interventions. After a survey and investigation campaign designed to acquire detailed data on the conditions of the foundations, the geotechnical aspects of the site, the mechanical parameters of the masonry, the crack widths and distribution, and the geometry of the dome and of the monument as a whole, a strengthening system was put in place (1985–1987). It consisted of 56 active high strength steel tie-bars placed within holes drilled in the masonry at the top of the drum along 14 tangents around the perimeter, and slightly tensioned by jacks. The 14 segments of this perimeter strengthening system are connected each other by steel frames. A monitoring system was set up to survey crack propagation, deformations of the structure as well as stresses in the tie-bars (re-tensioned in 1997)[32]. Although the strengthening intervention was of an undoubtedly invasive type, proper design choices were adopted to conceal its structural components. From the structural point of view, the intervention proved to be effective to contain lateral thrusts and to govern the tendency of cracks to further expand. Along the last more than one decade a new intense survey, investigation and research program was established on the geometry of the construction, its constitutive aspects, the physic-mechanical characteristics of the materials, and the modelling and analysis of the structural responses in the static domain under the action of gravity loads and foundation settlements.

In recent years, concerns about the safety of the monument with respect to seismic events – in the context of the new strategies discussed in previous paragraphs for the evaluation and reduction of seismic risk of architectural heritage developed at national and international level – prompted the decision to develop a new wide scope investigation program. This was done in the frame of an agreement with Italian Ministry for Cultural Heritage aimed at testing the practicality of the specific Italian Guidelines on this subject[33] in the case of outstanding monuments, selecting the Basilica at Vicoforte as a case study for this evaluation.

32. M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino, *Modeling strategies for the world's largest elliptical dome at Vicoforte,* in «International Journal of Architectural Heritage: Conservation, Analysis, and Restoration» Vol. 2 N° 3, July-September 2008, pp. 274-303.

33. See reference in note 2.

The results, at the date, of the program are documented in detail in a series of recent papers[34] and briefly summarized in the following.

– Limit analysis of the dome-drum system under gravity loads

Plastic limit analysis provides a conceptually simple and robust method to estimate the safety of masonry structures introducing the simplifying assumption that considers masonry as a rigid material with no resistance to tensile stresses and adopting the static and/or kinematic approach based on the use, respectively, of the static or kinematic theorems. As such, it has been long applied to the two-dimensional analysis of masonry structures or structural elements for expeditious evaluations of safety levels.

A concise approximate estimation of the safety conditions of the dome-drum system of the Sanctuary of Vicoforte under gravity loads was performed according to these procedures, applying both the static and kinematic approach to investigate, within an ideal planar problem, the stability of the masonry slices (as defined above and corresponding to an assumption of full cracking of the dome-drum system along its meridional plans) located along the major and minor axis[35]. Both approaches demonstrate the lack of stability of dome-drum system in the absence of circular tension stiffening, confirming the central role conferred to the original iron rings to guarantee this stability, and prompting a positive evaluation of the strengthening intervention performed in 1985-1987 through the application of the high strength tensioned steel tie-bars and of their subsequent re-tensioning operated in 1997, as appropriate safeguard measures. The stabilizing contribution of the original iron tension rings was taken into account in the safety evaluations on the basis of the kinematic approach – in which safety is evaluated in terms of the absolute value ratio between resisting and pushing virtual works *Wr* and *Wp* – introducing the assumption of complete plasticization of the rings, so that each point of the rings is considered subjected to

34. M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino, 2008. M.A. Chiorino, R. Ceravolo, A. Spadafora, L. Zanotti Fragonara, G. Abbiati, *Dynamic Characterization of Complex Masonry Structures: The Sanctuary of Vicoforte*, in «International Journal of Architectural Heritage: Conservation, Analysis, and Restoration», Vol. 5 N° 3, 2011, pp. 296-314. M.A. Chiorino, C. Casalegno, *Survey and structural modeling for the reliability assessment of the world's largest elliptical dome at Vicoforte*, Keynote lecture, Proceedings of "Domes in the World" International Congress, Florence, Italy, March 19-23, 2012, CD. M.A. Chiorino, R. Ceravolo, C.G. Lai, C. Casalegno, *Survey, seismic input and structural modeling of the "Regina Montis Regalis" Basilica and large elliptical dome at Vicoforte, northern Italy*, in J. Jasieńko (ed.), *SAHC 2012, 8th International Conference on Structural Analysis of Historical Constructions,* Wroclaw, Poland, October 15 – 17, 2012, DWE, Wroclaw 2012, pp.1432-1440. C.G. Lai, M. Corigliano, H. Sánchez, L. Scandella, *Definition of seismic input at the "Regina Montis Regalis" Basilica of Vicoforte*, *Northern Italy*, IUSS Press Pavia 2009. L. Scandella, C. G. Lai, D. Spallarossa, M. Corigliano, *Ground shaking scenarios at the town of Vicoforte, Italy*, in "Soil Dynamics and Earthquake Engineering", Elsevier, 31, 2011, pp. 757-772. G. Ventura, M. Coppola, C. Calderini, M.A. Chiorino, *Three-Dimensional Limit Analysis of the Vicoforte Elliptical Dome*, in «International Journal of Architectural Heritage: Conservation, Analysis, and Restoration», Vol. 8 N° 5, 2014, pp. 649-669. C. Casalegno, R. Ceravolo, M.A. Chiorino, M.L. Pecorelli, L. Zanotti Fragonara, *Soil-Structure Modeling and Updating of the "Regina Monte Regalis" Basilica at Vicoforte, Italy*, in F. Peña, M. Chávez (eds.), *SAHC 2014, 9th International Conference on Structural Analysis of Historical Constructions*, Mexico City, Mexico, 14–17, October 2014.

35. A. Reffo, *Applicazioni dell'analisi limite alla verifica delle grandi cupole in muratura: la cupola del Santuario di Vicoforte* (Application of limit analysis to the reliability assessments of large masonry domes: the dome of the Sanctuary of Vicoforte; in Italian), School of Architecture, Politecnico di Torino Master's thesis, 2002. M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino 2008.

Fig. 2. (left) External view of the Basilica and (right) the interior of the dome.

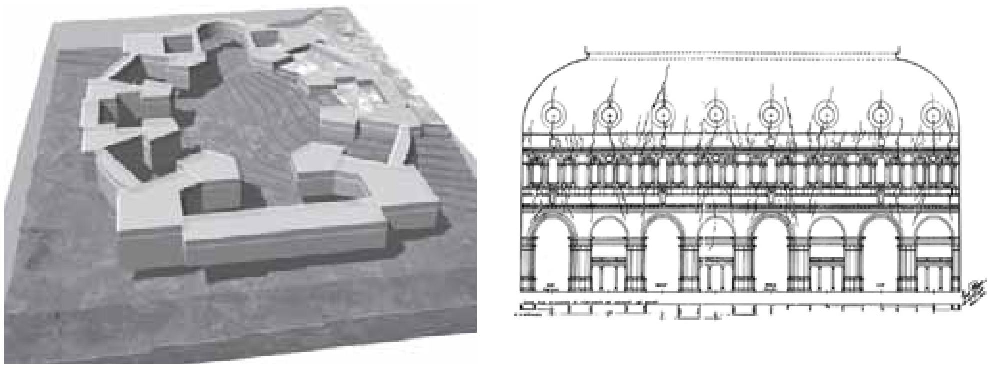

Fig. 3. (left) Axonometric view of the foundations (evidencing the inclined marlstone bed-rock, and (right) cracking pattern of the dome and the drum recorded before strengthening intervention.

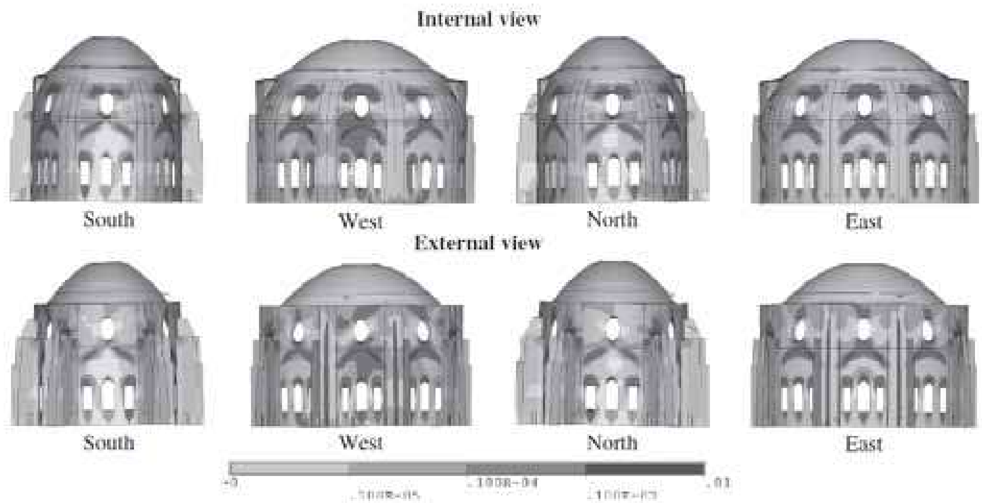

Fig. 4. Non-linear analysis under gravity loads with settlements; principal inelastic strains.

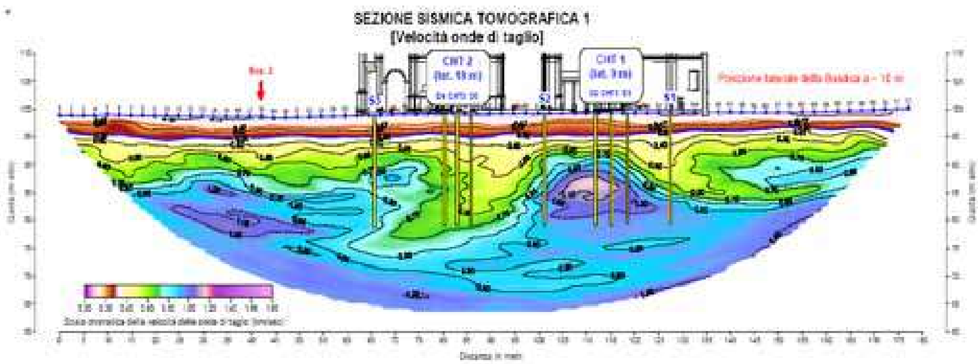

Fig. 5. Seismic tomography for S-waves carried out at the site of the Basilica at Vicoforte (G.G. Lai et al. 2009)

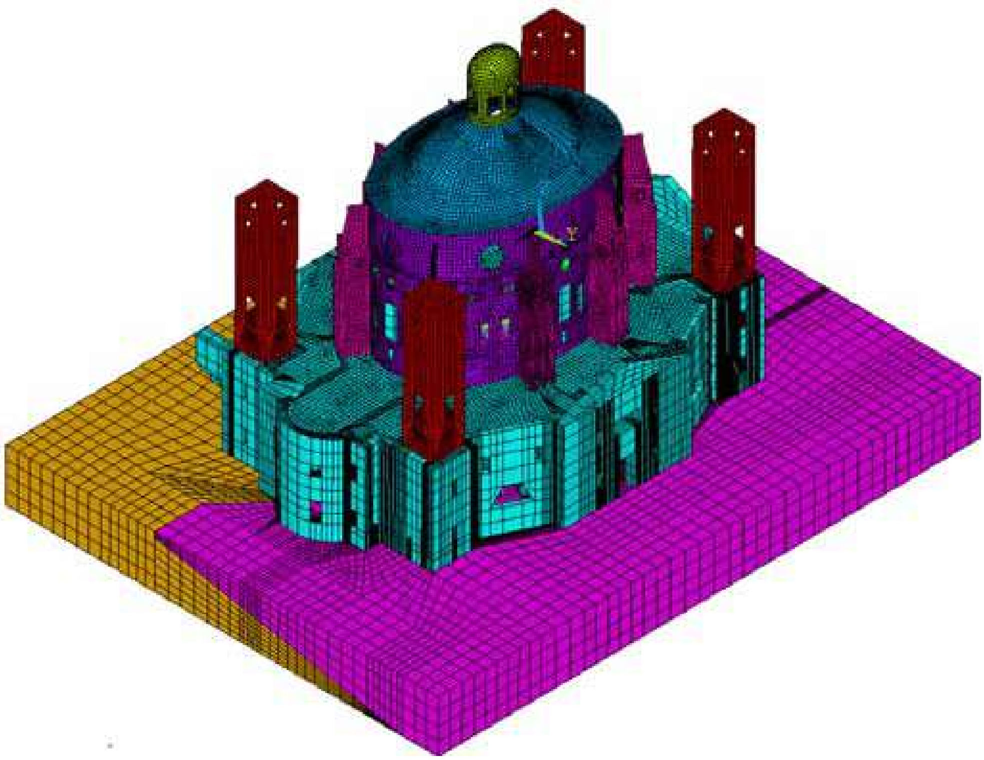

Fig. 6. The finite element model inclusive of the foundation soil layers (clay-silt in purple and marlstone in light brown). The other colours identify the different material used for the different macro-elements within the model. (C. Casalegno et al. 2014)

a tensile stress equal to the iron yielding strength, and adding the plastic dissipation work of the rings to the sum of the resisting works *Wr*.

A kinematic limit analysis of the entire dome-drum system was also attempted considering the system subdivided into sixteen separate interacting slices.[36] The safety factors *Wr/Wp* were first determined for each separate slice as functions of the position α of the intermediate hinge of their respective collapse mechanisms, adopting the same procedures as above, and without considering, in a first step, the stabilizing contribution of the original tension rings. In this case stability was found, for each one of the four symmetric sectors of the dome, only for the two intermediate slices benefiting of the stabilizing contribution of external buttresses, while the lack of stability was confirmed for the two slices corresponding to the maximum and minimum diameters of the dome.

A tentative approximate evaluation of the global safety factor of the dome-drum system considered as a spatial structure – with account for the interaction between the sixteen separate slices (four slices for each sector), while still ignoring the contribution of the tension rings – was then performed. This was done by adding, for each one of the four symmetric sectors of the dome-drum system, the contributions of each slice to *Wr* and *Wp*, and then determining the minimum value of the ratio between these sums as a function of four variables (the positions α of the intermediate hinge for each slice), obtaining an approximate global safety estimation for the entire dome-drum system $(Wr/Wp)_{\text{dome-drum}} = 1.27$.

Finally, the stability of the dome was analyzed considering the contribution of the original iron tension rings by adding, as previously indicated, the plastic dissipation work of the rings to the sum of the resisting works *Wr*. Significant increases in the safety coefficients were consequently obtained, both in the verification of the stability of the single slices, confirming the result trends of the above mentioned previous evaluations, and in the estimation of the global safety of the dome-drum system, obtaining an approximate indicative evaluation of the global safety coefficient $(Wr/Wp)_{\text{dome-drum}} = 3.03$.

Further controls were then performed to ensure that the three tension rings, located at different levels, can exhibit simultaneously plastic dissipation work for the assumed mechanisms, checking that the difference between the maximum and minimum strain in the three rings is less than the extension of the plastic plateau being assumed for the iron material[37], and attention was paid also to the influence of possible non-uniform strain and stress distribution along the iron rings, due to friction and adherence to the masonry.

A lower indicative value of the global safety coefficient $(Wr/Wp)_{\text{dome-drum}} = 2.08$ is obtained if reference is made to the more restrictive assumption of not taking advantage of the plastic resources of the iron tension rings and the ratio between resisting and pushing works is evaluated for a deformed configuration of the collapse mechanism that brings the most strained ring at initial yielding.

36. G. Ventura, M. Coppola, C. Calderini, M.A. Chiorino 2014.

37. Experimental checks in terms of stress-strain diagrams on the original iron material still to be performed. Refer to the original paper for further details.

In what concerns the results of all above mentioned evaluations, attention should be paid more to the order of magnitude and general trends of safety levels, than to specific values of safety coefficients, as determined in particular e.g. through the kinematic approach. These values may in fact be debatable, as they depend, among other things, on the way in which – in the definition of the reference ideal planar slices adopted in the computational procedures – the presence of window openings is accounted for, on the simplified assumptions introduced to account for the interaction between the separate slices in the approximate evaluation of the global safety factor of the dome-drum system considered as a spatial structure, and on the perhaps too schematic and non conservative assumption introduced for the restraint conditions at the base dome-drum system (a fixed hinge, without horizontal displacements) to model the effective, although significant, containing action exerted by the underlying parts of the monumental structure.

- Non-linear FEM analyses with shell elements of the dome-drum system under gravity loads and with account for settlements

This approach, aimed at a more refined and realistic analysis of the mechanical response of the dome-drum system and at an interpretation of its historical damage prior to the strengthening intervention, incorporates within a finite element method (FEM) analysis a non-linear anisotropic damage constitutive model for the masonry capturing the principal non linear aspects of its behaviour[38]. This constitutive model, which considers the different in-plane damage mechanisms affecting both the mortar joints and the blocks (both friction and cohesive mechanisms), was implemented in non-linear 4-node shell elements with transverse shear strain capability. The constitutive equations were implemented in a general-purpose finite element code[39]. The original iron rings are modelled by nonlinear link elements for which a Von Mises strength criterion is adopted.

Two types of analysis were performed. In the first one, only the weight of the dome-drum system, plus the lantern, was considered. In the second, the effects of the differential settlements of the foundations, as determined from the optical leveling performed at the base of the drum, were also considered, and applied as vertical imposed displacements to the nodes at the base of the drum[40].

The results of this second analysis shown in figure 4 evidence the regions of more intense masonry damage, which is responsible for the development of cracks. In particular, the west side of the dome-drum system, characterized by higher values of the differential settlements, appears more damaged than the east side, which corresponds to the cracking pattern recorded before the strengthening intervention (fig. 4).

Based on the same computational instrument incorporating the non-linear anisotropic damage constitutive model for the masonry, an incremental FEM analysis under gravity loads was also performed[41] for estimating the multiplier of the self weight

38. C. Calderini, S. Lagomarsino, *A continuum model for in-plane anisotropic inelastic behaviour of masonry*, in «Journal of Structural Engineering», ASCE, 134(2), 2008, pp. 209-220.
39. ANSYS 2003.
40. M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino 2008. M.A. Chiorino, C. Casalegno 2012.
41. G. Ventura, M. Coppola, C. Calderini, M.A. Chiorino 2014.

at collapse, for the sake of comparison to the results, in terms of safety levels, obtained through the limit analysis approaches described in the preceding section. As expected, further larger values of the safety margins were detected[42], with respect also to the evaluations based on the global kinematic limit analyses of the entire dome-drum system. This confirms that the simplest two dimensional limit analyses performed on single slices of the dome-drum system give in any case conservative safety evaluation results compared to all other more refined approaches, providing the lowest values for the estimated safety margins.
Therefore, even if accurate modelling procedures by most recent techniques appear as valuable tools for more refined evaluations of the safety margins, intended also to contribute to develop proper rehabilitation strategies aiming at limiting at best any possible required intervention on the architectural heritage, the simplest stages of limit analysis methodology discussed in the previous section seem to be able of giving useful first indicative estimates of the global safety coefficient of a complex monumental structure like the dome-drum system of the Basilica.

- Evaluation of seismic risk

Although Vicoforte is located in an area of moderate seismicity with respect to the whole Italian region (third level out of four groups ordered according to decreasing intensity), albeit not far from more active areas, the seismic risk of the Basilica deserves to be accurately investigated, and, where needed, proper strategies should be explored for its possible reduction.
This is due to the consideration, on one side, of the great historical, architectural and structural significance of the monument, and, on the other side, of its apparent vulnerability to seismic excitations, related in particular to the daring configuration of its dome-drum structural system. In fact, while these macro-elements are characterized in general by a high seismic vulnerability, as demonstrated by relevant damage or full destruction suffered in many cases on the occasion of significant seismic events in past and recent years (with special regards to Italy and its important architectural heritage of religious buildings), in the specific case of this important monument the very special configuration of its slender and transparent dome-drum system – where the dome is particularly shallow – magnifies this vulnerability.
A further consideration concerns the influence on the seismic response of the unfavourable geotechnical situation of the specific site, with special regard to possible amplification effects on the seismic input induced by the soft subsoil layers.
The first steps of this new investigation and research process regarded the definition of the seismic input at the site where the Basilica is located and the dynamic characterization of the structure. Work is still in progress in what concerns the use of these results in the subsequent phases of structural dynamic analysis of the monument, and of evaluation and, the case being, mitigation of its seismic risk.

42. Two different assumptions were introduced in what concerns the restraint conditions at the base of the drum, i.e. *a)* free horizontal displacements of all nodes at the base, and *b)* inhibited horizontal displacements. This second assumption, for which higher values of the multiplier of the self weight at collapse were detected, is closer to reality by considering the stiffness of the underlying structures.

1) Definition of seismic input at the base of the monument

The research was articulated in two phases. The first phase was devoted to the execution of the site-specific Probabilistic Seismic Hazard Analysis (PSHA) and the Deterministic Seismic Hazard Analysis (DSHA), both under the assumption of stiff ground and level topographic condition. The DSHA was adopted to define the worst shaking scenario which would occur in the future, compatibly with the tectonic and seismic setting of the region. The probabilistic approach provided more severe ground shaking scenarios with respect to deterministic methods. Nevertheless, PSHA and DSHA are both important as they provide complementary information to the predicted hazard.

The second part of the research treated the investigation of the seismic site response through 1D stochastic and 2D deterministic approach, in order to evaluate possible amplification effects due to localized lithostratigrafic characteristics at the site. To this aim, a 3D subsoil model was constructed integrating the results of advanced geotechnical investigation campaigns including seismic tomography (fig. 5). Finally, as an output of the study, dynamic impedances at the foundations of the Basilica were computed to be used in soil structure interaction analysis[43].

2) Dynamic characterization of the structure

The characterization of dynamic behaviour is an essential part of structural monitoring and damage control, especially in the case of complex monumental masonry buildings. Although they cannot be directly correlated with a specific safety level, dynamic investigations contribute to the updating of valid models for the reliability assessment stage of these types of structures and the optimization of prospective strengthening interventions, and they are indispensable instruments for the formulation of accurate forecasts as to their seismic behaviour.

A data acquisition campaign was performed in 2008 using tri-axial geophones and piezoelectric accelerometers. Instruments were positioned according to different acquisition setups and different sampling frequencies were used in order to arrive at a global identification of the structure. Wind, vehicle traffic and bells served as sources of excitation.

The next step was a model updating and identification process assisted by a finite element model constructed using the ANSYS computation code. In a first stage, the structure of the monument was assumed to be clamped at the base, disregarding soil-structure interaction[44]. In a second stage, this aspect was given proper attention incorporating in the finite element model the foundation soil layers and the foundation structures of the monumental building (fig. 6). In this case, the dynamic characterisation of the building allowed the identification and classification of 10 vibration modes and the calibration of a FE model that takes into account soil-structure interaction and dynamic effects[45].

43. C.G. Lai, M. Corigliano, H. Sánchez, L. Scandella 2009; L. Scandella, C. G. Lai, D. Spallarossa, M. Corigliano 2011.
44. M.A. Chiorino, R. Ceravolo, A. Spadafora, L. Zanotti Fragonara, G. Abbiati 2011; M.A. Chiorino, R. Ceravolo, C.G. Lai, C. Casalegno 2012.
45. C. Casalegno, R. Ceravolo, M.A. Chiorino, M.L. Pecorelli, L. Zanotti Fragonara 2014.

Conclusions

The paper discussed the significant and progressively increasing role of structural and geotechnical disciplines in the strategies for conservation and rehabilitation of architectural heritage, analyzing first the gradual recognition of this role within principles and guidelines incorporated in charters and documents formulated at national and international level, in particular in recent years.
Specific attention was then paid to the contribution of these disciplines to the analyses of historical constructions and monumental buildings in the static domain for reliability assessments under gravity loads, as well as to the analyses in the dynamic domain for both model updating processes and the evaluation of the seismic risk. Reference was made to the case study of the Santuario di Vicoforte, a monumental building of great historical, architectural, and structural significance, characterized by one of the largest masonry domes in the world, and by far the largest elliptical one.
The paper presented the results, at the date, of a wide investigation and research program, intended to propose the case study of Vicoforte as a reference case at national and international level for the structural conservation of important monuments, with specific attention to their protection from seismic hazards.

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Abstract

The Role of Structural Engineering and Geotechnics in the Conservation of Historical Monuments. The case study of the of the Sanctuary of Vicoforte with its large elliptical dome

Mario Alberto Chiorino

The conservation of architectural heritage requires the contribution of different sciences. The paper discusses the significant and progressively increasing role of structural and geotechnical disciplines in the strategies for conservation and rehabilitation of historical constructions and monumental buildings, as recognized also by principles and guidelines gradually incorporated in charters and documents formulated at national and international level, in particular in recent years. Specific attention is paid to the contribution of these disciplines to the analyses in the static domain for reliability assessments under gravity loads, as well as to the analyses in the dynamic domain for both model updating processes and the evaluation of the seismic risk. Reference is made to the case study of the Santuario di Vicoforte, a monumental building of great historical, architectural and structural significance, characterized by one of the largest masonry domes in the world, and by far the largest elliptical one. In the last two decades, this outstanding monument was selected as a reference case study, within a wide research/educational program implemented at the Politecnico di Torino, Italy, in cooperation with other scientific and academic institutions at national and international level, with the aim of developing advanced formats for a profitable contribution of structural and geotechnical disciplines to the conservation of the architectural heritage, with special attention to the protection from seismic hazards.