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PERPETUATE Project: the Proposal of a Performance-based Approach to Earthquake Protection of Cultural Heritage

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Abstract The paper describes the methodology proposed in the PERPETUATE Project (funded by the Seventh Framework Programme – Theme ENV.2009.3.2.1.1). The methodology proposed in PERPETUATE uses a displacement-based approach for the vulnerability evaluation and design of interventions. The use of safety verification in terms of displacement, rather than strength, orients to new strengthening techniques and helps in the comprehension of interaction between structural elements and unmovable artistic assets. The procedure is based on the following fundamental steps: definition of performance limit states, specific for the cultural heritage assets (considering both structural and artistic assets); evaluation of seismic hazard and soil-foundation interactions; construction knowledge (non-destructive testing, material parameters, structural identification); development of structural models for the seismic analysis of masonry structures and artistic assets and design of interventions; application and validation of the methodology to case studies. Two main scales are considered: the seismic risk assessment at territorial scale and at the scale of single historic building or artistic assets. The final aim of the project is to develop European Guidelines for evaluation and mitigation of seismic risk to cultural heritage assets.

Keywords: Cultural heritage, earthquake protection, displacement-based approach

Introduction

PERPETUATE (www.perpetuate.eu) is a project funded by the Seventh Framework Programme (Theme ENV.2009.3.2.1.1) developed by a consortium which includes 6 Universities, 2 Public Institutions and 3 SMEs. In particular, 5 European Countries (France, Greece, Italy, Slovenia, United Kingdom) and 1 International Cooperation Partner Country (Algeria) are represented. The project will last from 2010 to 2012.

The driving ideas of the project are:

i) adoption of a performance-based approach for the evaluation of seismic safety of cultural assets and the design of strengthening interventions;

ii) identification of proper safety levels for cultural heritage, considering both conservation and safety issues;

iii) minimization of strengthening interventions through increasing knowledge and improving modelling tools.

The name of the project derives from the idea that preventive actions must be adopted in order to PERPETUATE the life of monuments in seismic areas, in due time, before an earthquake interrupts their life forever.

The final aim of PERPETUATE is the development of European Guidelines for evaluation and mitigation of seismic risk to cultural heritage assets. In particular, the Italian "Guidelines for the evaluation and mitigation of seismic risk to cultural heritage" (Guidelines for evaluation and mitigation of seismic risk to cultural heritage 2007) will be the framework for the drawing up of this document. Focusing the attention on masonry structures, the project will face the problem for both architectonic assets (historic buildings or parts of them) and artistic assets (frescos, stucco-works, statues, pinnacles). Both seismic risk assessment at territorial scale, oriented to plan mitigation policies, and assessment of single cultural heritage assets, oriented to design suitable interventions, will be considered.

PERPETUATE methodology adopts a displacement-based approach. The use of safety verification in terms of displacement, rather than strength, suggests new strengthening strategies and helps in the comprehension of the interaction between structural elements and unmovable artistic assets.

The procedure is based on the following fundamental steps: 1) definition of performance limit states, specific for the cultural heritage assets (both structural and artistic assets are considered); 2) evaluation of seismic hazard and soil-foundation interactions; 3) construction knowledge (non-destructive testing, material parameters, structural identification); 4) development of structural models for the seismic analysis of masonry structures and artistic assets and for the design of interventions; 5) application and validation of the methodology to case studies. Experimental campaigns (in situ and indoor), considering also shaking table tests, will be carried out in order to support the formulation and validate the models.

In the following, the innovative contents concerning each step will be described.

Definition of Performance Limit States for Cultural Heritage Assets

Many national and international technical rules and guidelines for the rehabilitation of existing buildings (FEMA 356 2000, ASCE Standard ASCE-SEI 41-06 2007, Eurocode 8 part I 2005, Eurocode 8 part III 2005, Italian Technical Code for the design of constructions 2008) have acknowledged the concepts of performance-based design. This approach allows the seismic design or upgrade of buildings with a realistic risk estimation (safety of life, occupancy, economic loss). Since earthquake is a rare enviromental action, it must defined through a probabilist approach (hazard scenario). Moreover, since it is impossible that ancient masonry costructions withstand without any damage to strong ground motions, the definition of proper performance levels is needed.

In FEMA documents (FEMA 356 2000), different rehabilitation objectives are identified, with various combinations of structural requirements and seismic action levels, divided into three categories (limited, basic safety, enhanced). In particular, four perfomance levels (operational performance, immediate occupancy, life safety, collapse prevention) are defined which precise exceedance probability values in 50 years (50%, 20%, 10% and 2% respectively) correspond to.

In European codes, the concept of performance-based design is also present. In case of new buildings (Eurocode 8 part I 2005), two performance conditions are described: the damage limitation state and the ultimate limit state. These limit states are related to two different hazard levels: those related to an earthquake having probability of exceedance of 50% and 10% in 50 years, respectively. They may be set (using FEMA terminology) among the "limited objectives"; in fact, in the U.S. documents, the "basic safety objective" is reached only if also the collapse in case of the earthquake having probability of exceedance of 2% in 50 years is avoided. In case of existing buildings(Eurocode 8 part III 2005) three performance levels are considered; they are related to damage limitation, significant damage and near collapse conditions, which correspond to probabilities of exceedance of 20%, 10% and 2% in 50 years, respectively.

Even in Italy, the recent seismic decree (Italian Technical Code for the design of constructions 2008) introduces performance-based design approach. In particular, in case of existing buildings, four performance levels are defined (corresponding to operational perfomance, damage limitation, life safety and collapse prevention conditions) which probabilities of exceedance are defined with reference to a reference life V_R value. If a reference life V_R of 50 years is considered, the values of 81%, 63%, 10% and 5% are obtained, respectively. In particular the reference life combines concepts associated to both the usable life (that is the time in which the building can be considered safe only assuring structural healt monitoring and proper maintenance) and the use (occasional, frequent or frequent with crowding). The concept of reference life has been recently introduced in a new updated version of the Italian Guidelines (Guidelines for evaluation and mitigation of seismic risk to cultural heritage 2007). The definition of a proper reference life is particularly important in case of cultural heritage assets since it is an efficient tool for timing mitigation strategies and balancing safety and conservation requirements keeping into account the cultural significance of assets

Moreover, with respect to the case of ordinary unreinforced masonry buildings, in case of cultural heritage assets, also the damage induced in artistic assets has to be taken into account by introducing proper performance levels related to(i.e. in case of frescos or decorative elements attached to masonry panels).

Need of preservation of cultural heritage and recent improvements in seismic codes impose to focus the attention on feasible procedures for safety assessment and design of possible interventions. Although the documents afore mentioned point out the need for a quantitative evaluation in case of historic buildings, they do not propose a specific methodology. The Italian Guidelines (Guidelines for evaluation and mitigation of seismic risk to cultural heritage 2007) partially try to overcome this lack; however, they simply outline a conceptual approach to this problem, lacking in the definition of operative models and in the identification of specific limit states for cultural heritage. Thus, the identification and definition of reliable measures of limit state are needed and represent an open issue for cultural heritage assets (e.g. in the case of artistic assets like as frescos, stucco-works).

In particular, among the seismic verification procedures proposed in the literature, the use of non linear static procedures, based on the evaluation of pushover curves (that is a force-displcement curve able to describe the overall inelastic response of the structure) is particularly encouraged. Perfomance levels (or limit states) may be defined on the pushover curve with reference to both structural elements and artistic assets. Once defined the earthquake hazard level, displacement demand may be then evaluated by referring to methods like as the Capacity Spectrum Method (as adopted in ATC-40 1996), using an acceleration–displacement response spectrum properly reduced. Fig. 1 summarizes, even in schematic way, this whole procedure.

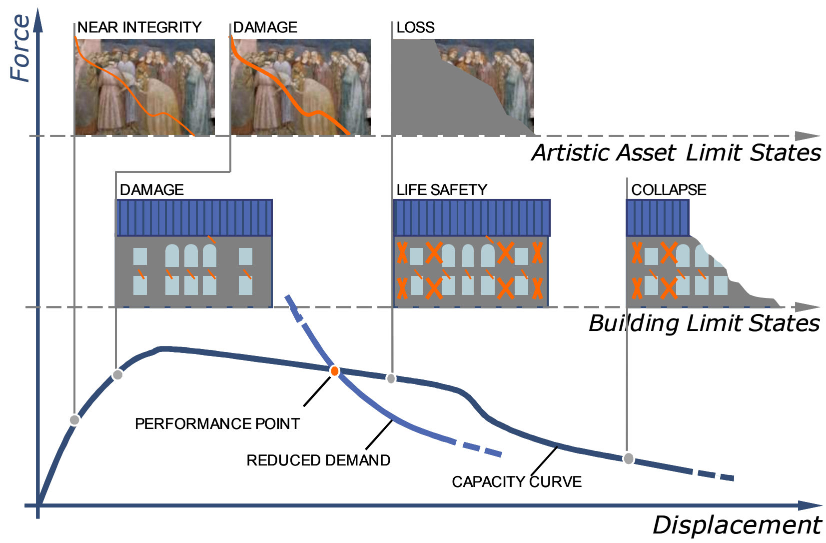

Figure 1: Displacement-based approach and performance levels definition on the pushover curve

In particular, in this context, PERPETUATE aims to define proper limit states for cultural heritage assets and the related reference seismic input, taking into account both human life safety and specific conservation requirements (aesthetics, serviceability, reparability). These limit states will be correlated to proper damage measures, specifically defined for the different cultural heritage assets, in order to allow safety verifications. As known, in case of masonry buildings damage measures are usually related to drift limits (shear deformation of masonry panels) or rotation limits (for out-of-plane mechanisms). In particular, at building scale, PERPETUATE intends to define damage measures for both single structural elements (i.e. piers, arches, vaults, domes) and the entire building; in this latter case, particular attention will be posed to the weigth associated to the different failure mechanisms which may occur (i.e. in plane and out-of-plane) and to the number of elements which are involved. Moreover, at artworks scale, the more original contributions are oriented to definition of damage measures for decorative elements and drift limits for frescos or stuccos. The experimental campaigns specifically addressed to this aim will constitute a fundamental support.

Evaluation of the Seismic Hazard of Soil-foundation Interactions

In order to evaluate the displacement demand through non linear static procedure, the pushover curve needs to be compared with the seismic demand, properly defined. Thus, probabilistic and deterministic methods to assess seismic hazard and ground motion characteristics have to be combined with specific models to account for local soil and site effects including topography, soil non-linearity, basin edge effects and other important parameters regarding "source" and "path" effects. A good knowledge about the complexity of surface geology and the complex nature of earthquake generation process has a crucial effect on the reliability of the hazard maps. In fact, numerous and substantial uncertainties characterise all steps of seismic hazard assessment, independently of the method used.

In this context, PERPETUATE aims to define Demand Spectra for different soil categories and seismic hazard appropriate for masonry historic buildings of various types. Indeed, it is well known that seismic input cannot be defined by a single parameter (e.g. peak ground acceleration, macroseismic intensity); in addition to acceleration-displacement response spectra (ADRS), other intensity measures will be evaluated (Arias intensity, Housner intensity, various duration measures, number of cycles of motion). The seismic input will be defined for longer return periods than those adopted by codes for new buildings because lower annual probabilities of exceedance are desired for cultural heritage assets. This input motion will be generally higher than code-defined input motions.

In particular, a comprehensive set of numerical, analytical and experimental studies to evaluate the role of the foundation compliance and associated soil-foundation interaction (SFI) and soil-foundation-structure interaction (SFSI) effects in the response of massive masonry structures (monuments, building aggregates in historical centres) and their vulnerability assessment will be provided. The aim is to develop an improved foundation model for the vulnerability assessment of classified masonry structures and monuments. The role of the foundation and SFSI effects will be studied both for seismic ground shaking and induced permanent ground deformations.

Construction Knowledge

The knowledge phase of an existing building (or artwork) plays a fundamental role in the assessment of its structural safety. Lacks in knowledge are usually considered as uncertainties affecting the modelling of the structure. Thus, a decreasing degree of knowledge imposes to consider increasing safety factors and, thus, lower conventional resistances. In general, this means that a maximization of the knowledge of the structure (in term of geometry, material properties) may lead to a minimization of the interventions to guarantee acceptable safety levels. For ordinary buildings, the choice knowledge/interventions is purely economic (ratio between knowledge and intervention costs). For cultural assets, this choice should take into account also conservation requirements, which impose, as far is possible, a minimization of the interventions. For the achievement of all these data, an effective on-site testing campaign by means of application of different test methodologies as a combination of DT (destructive tests), MDT (minor destructive tests) and NDT (non-destructive tests) needs to be performed. From the results of recently carried EU research project ONSITEFORMASONRY [8], where a comprehensive set of Guidelines and Recommendations for the application of different test methodologies in evaluation of the state of the structure and material was made, in PERPETUATE an extension will be made to optimize developed methodologies regarding achieved confidence factor and their cost effectiveness and to propose new methods for structural identification.

Structural Models for the Seismic Analysis and for the Design of Interventions

Starting from a literature review, the more suitable modelling strategies for the cultural heritage assets, both for the analysis of buildings or architectonic elements and for artistic assets, will be identify and classified. The displacement-based approach for the seismic analysis requires the development of nonlinear static procedures (pushover), in order to evaluate the capacity curve and identify the performance point. After a classification of different types of buildings, architectonic elements and artistic assets, reliable innovative mechanical models will be developed, capable to describe the non linear behaviour of the assets under seismic actions, till to their collapse. As known, the idealisation of the structure at the building scale may be performed considering: a) meshing of the material continuum (Finite Element Models); b) subdivision into significant structural elements (Structural Elements Models); c) predefined collapse mechanisms of rigid blocks. In the first two approaches, the pushover curve may be obtained by finite element incremental static analyses, while in the third one, an incremental equilibrium limit analysis (kinematic approach) may be adopted, by considering a set of varied displacement configurations. All these modelling strategies will be considered. Moreover, seismic verification procedures will be established overcoming some of the open issues present in literature related to their application to masonry historical structures (e.g. the evaluation of the sensitivity of the verification procedure in terms of target displacement in presence of flexible floors; the correlation of the displacement capacity of the structure to predefined limit states in the case of FEM models). In case of the analysis of out-of-plane local mechanisms, also the amplification of motion due to their position in the main building will be taken into account.

Operative procedures, practical tips and clarifying examples will be provided. Moreover the Soil Foundation Interaction results and the soil-foundation model will be included in the development of the general structural model.

Non linear models and modelling strategies developed will be used for the evaluation of effectiveness and reliability of the different interventions techniques, both traditional (like as insertion of tie-rods, new buttresses) and much more innovative. In particular, the performance-based approach will be adopted in order to assess the effect on the displacement capacity of the structure (performance approach vs. strength approach). It is important to broaden the knowledge on modelling historical structures with new, innovative modelling tools because modern codes are prepared mostly for new structures. In fact, applying the same models and safety factors proposed for new structures to historical structures is usually inappropriate and leads to invasive interventions, in order to assure seismic safety of historical buildings, which are in collision with conservation requirements. Moreover, particular attention will be paid to the modelling of the cultural assets at different scales, in order to evaluate the effect of interventions not only on the structure of the building but also on the unmovable cultural assets present in it.

Finally, in addition to models applicable at scale of the single assets, innovative methodologies for the vulnerability evaluation on a large number of assets (buildings and artworks) will be developed in order to develop mitigation strategies at territorial scale, defining priorities of interventions and providing criteria for the budget optimization. In particular, such methodologies will be based on quick surveys and will be focused on simplified mechanical models or statistical models (derived by damage assessment data, obtained by previous earthquakes).

Application and Validation of the Methodology to Case Studies

All the contributions obtained by the previous steps will be collected and coordinated in order to define an integrate methodology, to be validated and applicated to case study areas. An innovative contribution is the procedure for estimation of uncertainties, both aleatory (randomness) and epistemic (due to incomplete, vague or imprecise information). In particular, epistemic uncertainties in the field of earthquake risk assessment require the development of adequate tools, by the use of logic tree approach, in which expert judgement compensates for the incompleteness of existing information. The final result is a range of capacity curves associated with weights, and the choice of the fragility curve for the risk evaluation can be made by using the fuzzy set theory.

The validation and demonstration of the proposed methodology will consider relevant case studies, selected to be representative of two scales of analysis considered (the territorial one and that of the single asset), in particular: the Citadel of Algiers; the historical centre of Rhodes; the Cathedral St. Nicholas in Ljubljana; Santa Maria Paganica church and Ardinghelli palace in the historical centre of L'Aquila (Italy) hit by the earthquake on 6th april 2009; the St. Pardo Cathedral in Larino (Molise Region, Italy). In particular, the Citadel of Algiers and the historical centre of Rhodes (both in the UNESCO list of the World Cultural Heritage) are made up of a complex aggregation of historical buildings, which represent a cultural heritage asset as a whole but also contain a wide number of single important monuments. For this reason, they are both an optimal example for the application of the methodology at the two different scales: a) an overall evaluation inside the historical centre (singling out of the cultural heritage assets at higher risk; proposal of a cost-efficient and reliable mitigation strategy); b) a detailed evaluation of the most significant monuments and artistic assets (proposal of strengthening interventions or of a structural health monitoring protocol).

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