Engineering Structures 160 (2018) 34–43

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Bridging performance based seismic design with restricted interventions on cultural heritage structures

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ARTICLE INFO

Keywords:
Historic structures
Monuments
Seismic risk
Interventions
Safety levels
Nominal life

ABSTRACT

There is lack of a common approach to assess seismic risk of historic structures and monuments. The challenge of balancing safety with maintenance of architectural and artistic features of historic structures remains a pressing issue. In many cases limitations, stemming from the implementation of interventions on historic structures and monuments that do not comply with internationally accepted guidelines do not allow for heritage structures to fulfill the performance level of new constructions for the required probability within a specific conventional life that is usually defined by seismic codes.

Earthquake protection of cultural heritage structures can be realized through a preventive knowledge of the seismic risk in order to plan mitigation strategies and schedule the necessary strengthening measures to reduce vulnerability. Strengthening of cultural heritage structures in order to meet the requirements of contemporary seismic codes often requires invasive interventions that may not be applied because of relevant limitations.

This work presents a methodology that leads to interventions balancing the demands of security to seismic hazard with respect for the cultural and archaeological characteristics of the structure. Following the proposed methodology rehabilitation measures are designed for a specific performance level that is associated to a certain nominal life, after which the structure should be re-evaluated. Utilizing attenuation equations, it arrives at a simple to apply procedure and diagrams that can be used to evaluate and design interventions to heritage structures. The application of the method is demonstrated with a historic structure in north-eastern Greece. The analysis shows that after the application of all acceptable interventions the strengthened structure could not fulfill the performance level of a new structure. The proposed methodology allows the determination of the nominal life of the applicable interventions after which structural integrity should be re-examined.

1. Research aims

Selecting interventions that fulfill demands steaming from cultural, aesthetical, architectural and seismic risk is a well known challenge to civil engineers, architects, archeologists and curators. The issue always attracts the interest of engineers and cultural heritage authorities after earthquake events that have caused damage to monuments.

This work addresses this pressing issue presenting a methodology that bridges earthquake protection and safety allowing at the same time the selection of interventions that respect the aesthetic and architectural features of the monument.

2. Introduction

An increased interest regarding the maintenance of cultural heritage structures has been observed during the last decades in seismic prone regions following the occurrence of significant earthquake events, including Greece, Italy and Turkey, e.g., [1,2]. The necessity to protect structures of cultural significance has emerged by the fact that many of them have been constructed with no seismic regulations while, in many cases, they have already suffered damage from past seismic activity.

Also, recent advances in engineering seismology have significantly increased our knowledge regarding seismic hazard, especially at small distances from active faults, in the so-called near-fault region. Within this area the strong ground motion significantly differs compared to the motion at great distances from the causative fault [3]. These characteristics, also called near-source phenomena, are now considered responsible for the extensive damage that is mainly observed at the epicentral region of earthquakes [4,5]. Near-fault effects have not yet been included appropriately in international provisions for seismic design because of the relatively recent and ongoing international research; thus, there is an urgent need to assess the adequacy of existing methods of seismic design in light of new scientific results regarding the nature of strong ground motion in the near-source area [6,7]. These

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https://doi.org/10.1016/j.engstruct.2018.01.022
Received 3 August 2017; Received in revised form 4 December 2017; Accepted 9 January 2018
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Nomenclature

A	performance level of "Damage Limitation" according to Eurocode 8
a_{gR}	reference peak ground acceleration on stiff soil
a_{gRL}	reference peak ground acceleration on stiff soil for which a structure reaches a desired performance level
B	performance level of "Significant Damage" according to Eurocode 8
CASIM	Greek Code for the Assessment and Interventions on Masonry Structures
C	performance level of "Near Collapse" according to Eurocode 8
Ci	parameter for the classification of monuments into three categories (i = 1, 2, 3)
CSI	Greek Code for Structural Interventions
C_U	importance factor
DEM	Discrete Element Method
EC8	Eurocode 8
FEM	Finite Element Method
$H(a_{gR})$	annual rate of exceedance
k	exponent relating nominal life of intervention for different importance classes (see Eq. (5))
PBA	performance based assessment
P_R	probability of exceedance
SHM	structural health monitoring
SLA	performance level of structural members/parts and even contents of artistic value according to the Italian code DR 226/02/2011
SLC	performance level of "Near Collapse" according to the Italian code DR 226/02/2011
SLD	performance level of "Damage Limitation" according to the Italian code DR 226/02/2011
SLO	performance level of almost "no-damage" according to the Italian code DR 226/02/2011
SLV	performance level of "Significant Damage" according to the Italian code DR 226/02/2011
T_L	conventional life
T_{RL}	average return period
T_Δ	nominal life of intervention
$T_{\Delta R}$	reference nominal life of intervention
V_N	nominal life of a structure
V_R	reference duration ($V_R = V_N \times C_U$)
Z_i	parameter for the definition of three seismic hazard zones (i = 1, 2, 3)
γ_I	importance factor

new concepts for seismic hazard suggest an increased difficulty for restoration studies of both conventional and cultural heritage structures.

Advances regarding use of computational methods, real-time monitoring, in-situ and laboratory testing, as well as use of new materials provide new means towards the effort of maintenance and restoration of historic structures and monuments. Nowadays, elaborated analysis with the Finite Element Method, FEM, or the Discrete Element Method, DEM, that require large computational effort may be performed more easily than a decade ago, e.g., [8–11]. Also, a significant improvement has been made on linear and non-linear analysis with simplified models, such as equivalent frame and strut-tie models, e.g., [12]. An extended discussion on applications of these different computational tools to restore monuments may be found in [13]. The applicability of monitoring technology allows for non-invasive assessment of monuments for both static and seismic actions. The estimation of basic dynamic characteristics, such as natural periods, mode shapes and damping by measuring environmentally-induced vibrations is one of the techniques that become operative in the last years, e.g., [14]. A more permanent application of monitoring to monuments with modal updating techniques to evaluate damage and to plan maintenance and structural rehabilitation also gains the interest of engineers, e.g., [15].

The selection of a proper retrofit scheme for cultural heritage structures is a combination of art and coordinated methodology. For this reason, it is difficult to distinguish individual strategies; however, innovative means are available today in terms of retrofit techniques, especially for historic structures made of unreinforced masonry, including: (a) material stabilization with metal-based inserts including dowels and rods; (b) floor and roof connection upgrades with network of ties [16]; fixing of the outer layer façade [17]; post-tensioning with rods [18]; use of fiber reinforced polymers, FRPs [19]; construction of new structural members compatible with the already existing [16]; application of base isolation [20]. The availability of innovative materials, including fiber reinforced composites that are available, may provide solutions in difficult retrofit and strengthening problems regarding monuments. The application of these materials in monumental structures allows a less invasive modification in the inertia and/or stiffness characteristics of the overall structure, which may be mandatory with standard retrofit materials [21–24].

Despite the significant progress achieved in all the areas mentioned above the preservation and restoration of heritage structures presents difficulties that are not common for conventional structures. These difficulties mainly arise from the fact that, according to the widely adopted national standards and international regulations for the conservation and restoration of monuments, such as the Athens Charter [25], the Venice Charter [26] and the Amsterdam Charter [27], only a limited number of interventions that are non-invasive and reversible may be applied. More limitations arise from aesthetic and archaeological criteria. However, these less invasive interventions rarely provide durability compatible with the one required for non preserved structures according to modern concepts for earthquake hazard. Therefore, while the intervention on a monument would be desirable to warrant behavior for a period longer than for a conventional structure, this is rarely achieved because of the aforementioned limitations. The restoration of a monument under these constraints remains a challenging engineering issue that requires balance between safety and feasibility of implementation based on the legislative documents that apply in this area, e.g., [28].

In the present study a new methodology is proposed that allows balancing between structural integrity and limitations in the application of interventions on cultural heritage structures. The method suggests the introduction of the notion of "nominal life of intervention, T_Δ", that is, the duration within which a certain quality of performance, "a performance level", is complied given that the acceptable and feasible interventions are applied. Practically the method specifies a shorter duration (T_Δ) of the interventions as compared to what is acceptable for a non preserved structure; however, requesting a re-assessment of the heritage structure after the T_Δ duration expires. A similar discussion is currently open for a large part of the existing infrastructure, including buildings and bridges that have reached their design life and may not fully comply with the safety requirements of current codes, e.g., [29].

The concept of a reduced nominal life of an intervention as a means to allow immediate less invasive interventions has been proposed by the national code of Italy for the restoration of monuments [28]. The present paper addresses the major concepts of the relevant Italian code and proposes proper modifications in order to be applied to: (a) other countries where site-specific spectra are not available; (b) in the vicinity of a single fault that controls the seismicity of the area. Also, some critical aspects regarding the restoration of monuments between different provisions are discussed.

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