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SEISMIC VULNERABILITY ASSESSMENT OF HERITAGE SITES IN INDIA.

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Abstract

The total collapse of Dharhara tower in the April 2015 Gorkha Nepal earthquake of magnitude of 7.8 has once again exposed vulnerability of heritage buildings. Architectural heritage is often under constant threat from natural disasters like hurricanes, floods, earthquakes, landslides, volcanoes, and fires, which may cause irreversible damages. It has been observed that heritage sites are further damaged by inadequate emergency interventions which are not sensitive to cultural heritage as urgent responses on occurrence of a disaster is needed. India has observed large number of destructive earthquakes occurred in last 4-5 decades damaging architectural heritage and highlighted the need to redefine the retrofitting strategies for heritage sites located in high seismic risk regions. UNESCO has taken efforts with their mission to Gujarat, India, for the conservation of earthquake-damaged cultural properties in year 2001 followed by preliminary survey of damaged heritage sites by the Indian National Trust for Artistic and Cultural Heritage (INTACH). The identification and listing of cultural heritage properties in other parts of the country which are supposed to be affected by an earthquake is the need in the present context in addition to preparing a comprehensive action plan for disaster mitigation as top most priority. There is an urgent need to understand the seismic behavior of historical construction and to assess the benefits of different techniques which can be used for reinforcing these structures. Present paper analyses the behavior of historic buildings under seismic loading. Vulnerability of historic structures with reference to their seismicity and structural and architectural characteristics located in various seismic zones on India is examined. Specifically the vulnerability of UNESCO listed monuments in India is discussed. It provides an insight on some of the methods for assessing seismic vulnerability as well as retrofitting techniques of historical constructions and their use on occurrence of an earthquake. It is stressed that Adequate timely measures can minimize the effects of aftershocks; avoid hurried demolition made under extreme pressure. The aim is to minimize damages to architectural heritage in future for posterity.

Keywords: Heritage, India, Historical, Retrofitting, Monuments.

1. Introduction

The April 2015 Gorkha Nepal earthquake of magnitude of 7.8 claimed more than 900 lives, destruction to built environment and once again exposed vulnerability of heritage buildings. Dharhara Tower the 19th century nine-storey minaret, a UNESCO World Heritage site raged to rubbles damaging iconic cultural heritage. The tower was Built in 1832 which was extensively damaged in 1934 by 8.3-magnitude earthquake. It was rebuilt and opened to the public but in recent 7.9 magnitude earthquake of 2015 it was totally collapsed claiming about 200 precious lives. Other UESCO listed heritage includes the Durbar Squares of Hanuman Dhoka (Kathmandu), Patan and Bhaktapur, the Buddhist stupas of Swayambhu &Bauddhanath and the Hindu temples of Pashupati &Changu Narayan. Most of historic buildings in India are designed on the effects of gravity loads with little attention to provide adequate lateral resistance and ductility , when subjected to seismic loading. They are generally have unreinforced bearing walls provide limited resistance against lateral loading and a high potential of discontinuity at corners or connection to the roof. Many buildings which are reinforced concrete building suffer with discontinued flexural reinforcements, no transverse reinforcement in beam-column joint zones and minimal confinement in columns.In such circumstances retrofit process becomes complicated which include local modification of components, minimizing structural irregularities (in mass and stiffness), structural stiffening, structural strengthening, mass reduction and high tech measures like seismic isolation to improve the structural performance and comply with current building codes

In many countries inventories of immoveable cultural heritage has been made and registered primarily without systematic geographical positioning, besides it does not have technical description of the materials and structures applied, information about its current state regarding their vulnerability to natural disasters. Many guidelines and action plans are in place issued by government bodies which are legal documents in many countries but they do not address logistics of dealing with disasters particularly for cultural heritage sites.

1. Damages to Historic Structures in Past

History of earthquake damages to monumental structures is evident from beginning of civilization. The Great Temple at Abu Simbel damaged by an earthquake in 1265 BC., as well as damage to the Colosseum, Rome is some of the glaring examples . Many countries across the globe have repeatedly faced massive damages to architectural heritage in past which are located in seismically active zones. Istanbul is located on the North Anatolian Fault, one of the largest active faults in the world have rocked with more than 30 earthquakes of 7 or more magnitude on Richter scale in past 2000 years. The 31-m diameter dome of Hagia Sofia in Istanbul was the largest at that time, which was collapsed in 558 by pushing the walls outward following an earthquake.

The structure was retrofitted by the great architect Sinan with addition of support walls later in the 16th century, and the structural system was further strengthened during the 19th and 20th centuries. The Basilica Cathedral of Arequipa constructed in 1540 AD was destroyed by a massive earthquake in 1583 and was rebuilt in 1590 by city authorities. It was again damaged by another earthquake in 1604 after that a new cathedral was completed in 1656. It had faced minor damage occurred from earthquakes in 1666, 1668, 1687, 1784 and severely damaged in the year 1868. Recently 7.4 magnitude, Izmit earthquake, occurred in 1999 earthquake claimed 18,000 lives and damages to the historic monuments. Many libraries and museums such as the Museum of Turkish and Islamic Arts, the Topkapi Palace Museum, Beyazit Library, Suleymaniye Library, the Dolmabahce Palace Museum and the Istanbul Painting and Sculpture Museum were damaged in this event [1].
In Italy the city of L'Aquila and region have faced large scale damages to monuments particularly in Abruzzo which was an important trade route in Roman times housing many medieval period buildings. Benedictine churches, medieval Gothic church covered with unique frescos located in Fossa, Abruzzo's largest Romanesque church, the 13th-century Basilica di Santa Maria di Collemaggio are some of such architectural heritage which were subjected to damages in past [2].

2. Damage Mechanism with Reference to Historic Structures

Natural disasters generate loads which in many cases act against the usual gravity loads (e.g. uplifting and suction), horizontal forces (horizontal movement, moisture expansion of most building materials) or dynamic forces (flow, shocks, impacts). Most of the design standards and recommendations do not consider this aspect besides architects and engineers are not well informed and educated to design and implement protective or mitigation measures. Any decision about future strategies and measures to protect cultural heritage against the effects of natural disasters must be justified by a reasonably reliable knowledge of the cultural heritage stock at risk.

Architectural and structural characteristics of monuments from earthquake point of view depend largely on the availability of resources and material as well as knowledge and aptitude of the designer at the time of construction. In historic buildings structural components are generally hidden as a result they do not get the necessary attention or protection they deserve. Because of deterioration architectural components lose their strength, stiffness and deformation capacity to efficiently carry gravity and other external loads including earthquakes. In historic structures damage generally triggered or exacerbated by many factors that contribute to deterioration, failure and potential collapse on earthquake occurrence. [3, 4]. Some of such factors are as below :

- Surface or rain water runoff.
- Soil settlement and relative movement of foundation.
- Deficiencies in the load carrying structural system.

- Insufficient material strength.
- In adequate detailing

3. Assessment of Seismic Vulnerability of Architectural Heritage

Many rational methods have been developed for structural analysis of monumental structures in past two decades [5]. The seismic vulnerability of historic structures can be assessed by quantitative estimation of the damage level of the structural system. Panagiotis suggested an analytical cubic polynomial method for structural analysis which estimate and describe the damage of masonry elements [6]. This is based on a computer programme in which Finite Element Analysis results and the mechanical characteristics of masonry material are used as input data which result in coloured graphic images of the failure for each individual element within the structure as the output. This is further analysed to develop fragility curves which demonstrate the probability of a building to be damaged beyond a specified damage stage for various level of ground shaking.

Heritage buildings located in urban areas suffer from soil settlements, traffic vibrations, air pollution as well as they are not subject to continuous maintenance this makes them more vulnerable to earthquake damages. To safeguard heritage structure a multidisciplinary approach is needed which include risk analysis, in situ survey and monitoring, numerical analyses and the design and application of innovative strengthening strategies.

- Identification of appropriate preventive measure.
- Determination of structural efficiency of structure with optimal modelling strategy.
- Cost-benefit analysis.

In this process it is important to identify the properties like dissipation, ductility, properties of material as well as the identification of dynamic properties of monuments which are to be addressed adequately in strengthening interventions.

4. Structural Analysis of Architectural Heritage

A quasi-static method to determine the dynamic effects of seismic loading on heritage structures were used in the early 1980's while dynamic analysis now can be done using dynamic analysis software. Broadly five methods are adopted for structural analysis as follows:

- Equivalent static analysis
- Response spectrum analysis
- Linear dynamic analysis
- Nonlinear static analysis
- Nonlinear dynamic analysis

4.1 Numerical Modelling : Earthquake performance of monuments can be analysed by Linear Static, Modal and Time-History Analysis based on output, variance in time period and frequency with the change in different modes. Based on this correlation between deflection v/s time-period and pseudo-acceleration v/s time-period can be identified. Model analysis is aimed to find out the effect on frequency as the mode shape changes. Increased frequency exhibits mode shape changes as well as stiffness changes. In such a structure joints are rigid and the structure behaves like a one structure. Research established suitability of mechanical models for a comprehensive three dimensional (3D) non-linear behaviour of the masonry [7]. Masonry exhibit nonlinear behaviour with negligible tensile strength as a result numerical modelling becomes difficult as experimental characterization of the mechanical properties of structural elements cannot be done completely besides the complex geometry adds to the level of difficulty. In such circumstances numerical modelling found suitable because it facilitate more flexibility in addressing architectural configuration and decorative features responses. It can be done in two ways:

- Finite Element Modelling
- Applied Element Modelling

4.2 Pushover Analysis : In this method structure is subjected to gravity load as well as a monotonic displacement-controlled lateral load pattern which continuously increases through elastic and inelastic behaviour until an ultimate condition is reached. These methods can be used to analyze likely performance of heritage structures on earthquake occurrence. Majority of Indian monuments are vulnerable to earthquake damages because of their complex configuration, presence of soft story, open spaces, inadequate connections between structural components and predominant use of masonry. Because of this phenomenon it is very difficult to analyze static and dynamic behaviour of the monuments. Research conducted using finite Element Analysis, Pushover analysis, Fragility Analysis at different ground motions resulted in the identification of the most vulnerable parts of historic monuments [8] which can prove instrumental for retrofitting interventions

5. Earthquake Retrofitting

A number of retrofitting techniques are available which are widely used for historic structures such as conventional techniques like use of braces, jacketing and advanced techniques like base isolation, energy dissipation devices or use of Fibre Reinforced Polymers(FRP) or Shape Memory Alloys. Selection of suitable techniques is a critical task which involve assessment of seismic vulnerability where economic considerations, technical knowhow and invasiveness are major issues. Use of seismic isolation or energy dissipation in buildings aimed at reducing earthquake induced forces. Base isolation decouples the movement of foundation from the movement of ground by filtering the horizontal components of earthquake which is highly dangerous as far as damage to the structures is concerned. This method is suitable for earthquake retrofitting of historic structures but it is expensive as well as it needs lots of excavation which is not possible in many instances. Another technique is energy dissipation which is achieved with the use of suitable devices generally referred as "dampers".

5.1 Energy Dissipation Devices

Passive energy control and dissipation techniques presents effective seismic protection solutions for monumental structures as they limit the extent of strongly invasive consolidation interventions with increased capacity against inertia forces induced by earthquakes. The energy dissipation devices are to be placed at key points of the structure, where relative displacements between members allow some energy to be dissipated by means of viscous and/or hysteretic effect [9]. They are generally fixed at the wall-to-floor interface of masonry buildings, where relative motion can occur to avoid risk disintegration of structure. They are found better than Base Isolation as this technique do not require requires heavy interventions like base cut, new foundation structure, etc. In addition they have other advantages like they are economical, no need of external energy, stability, and they can work against strong winds. Masonry structures are stiff in nature and need large energy dissipation which is activated with small displacements. Most commonly used dampers are Elastic Plastic Dampers (EPD's), Viscous Dampers (VD's), Viscous Elastic Dampers (VED's) and Friction Dampers (FD's). Fluid viscous dampers which are velocity-dependent systems provide maximum damping effect against lateral movements is found suitable for retrofitting of historic structures specially minarets. Effective use of such devices can be seen in the S. Giovanni Battista Church in Carife-Italy [10] and in the New Library of Federico II University which reportedly is the very first cases of seismic upgrading of historical constructions.

5.2 Shape Memory Alloy Devices: Shape memory alloys (SMADs) are metallic materials which possess unique properties to achieve the reversible transformation between two crystalline phases, Austenite and Martensite Superelasticity which result in an elastic (reversible) response to an applied stress, caused by this phase transformation. The SMAD allows the disconnected structural components to join which are likely to face large reflective displacement on occurrence of an earthquake. Many historic buildings were successfully retrofitted using SMAD's such as Cathedral of Santa Maria at L'Aquila, Basilica of St. Francis, Assisi in Italy [11]

6. Architectural Heritage and Seismic Environment in India

India has observed large number of destructive earthquakes occurred in last 4-5 decades damaging architectural heritage and highlighted the need to redefine the retrofitting strategies for heritage sites located in high seismic risk regions. UNESCO has taken efforts with their mission to Gujarat, India, for the conservation of earthquake-damaged cultural properties in year 2001 followed by preliminary survey of damaged heritage sites by the Indian National Trust for Artistic and Cultural Heritage (INTACH). The identification and listing of cultural heritage properties in other parts of the country which are supposed to be affected by an earthquake is the need in the present context in addition to preparing a comprehensive action plan for disaster mitigation as top most priority [12]. As far as earthquake impacts are concerned, there is no world statistical information available regarding the damage inflicted to the stock of historical constructions.

The United Nations Educational, Scientific and Cultural Organization (UNESCO) have recognized 32 world heritage sites in India [13] which are located in four seismic zones as per the latest version of the seismic zoning map of India . This map assigns four levels of seismicity in terms of zone factors [14] . Out of 32 sites 2 are located in very high risk zone, 11 in high risk 13 in moderate and 6 in low risk zone (table 1) location of heritage sites is shown in Fig.1.

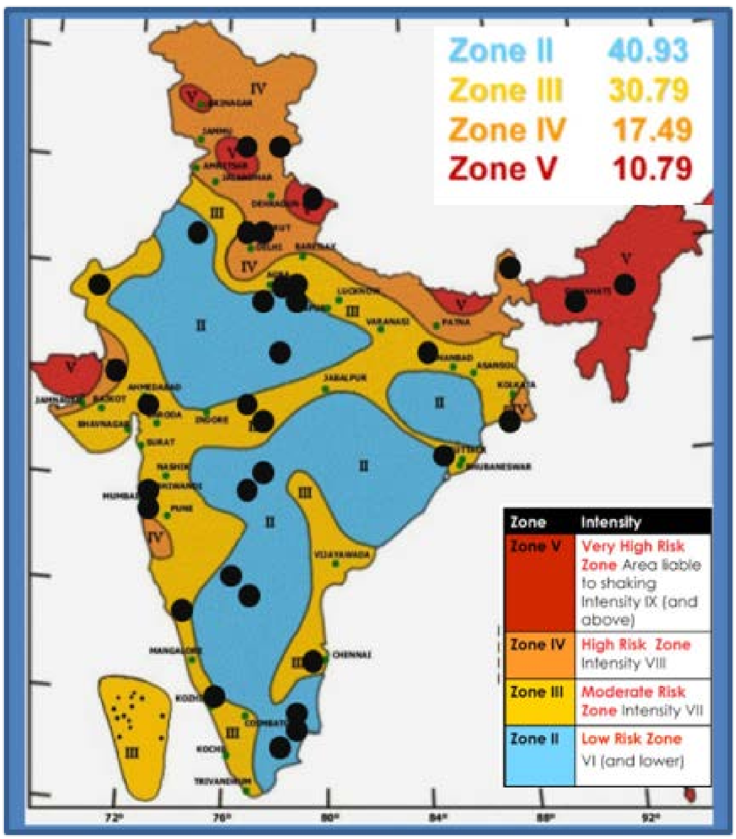


Table 1: Seismic Risk to Heritage Sites.

	NAME	REGION	S		NAME	REGION	S
01	Kaziranga Wildlife Sanctuary,	Assam		17	Chhatrapati Shivaji Terminus	Maharashtra	
02	Manas Wildlife Sanctuary,	Assam		18	Sun Temple, Konârak	Orissa	
03	Mahabodhi Temple Complex	Bihar		19	Keoladeo National Park	Rajasthan	
04	Humayun's Tomb,	Delhi		20	Jantar Mantar, Jaipur	Rajasthan	
05	Qutb Minar and its Monuments	Delhi		21	Great Living Chola Temples	Tamil Nadu	
06	Red Fort Complex	Delhi		22	fMonuments at Mahabalipuram	.Tamil Nadu	
07	Churches and Convents	Goa		23	Agra Fort, Uttar Pradesh	Uttar Pradesh	
08	Champaner Archaeological Park,	Gujarat		24	Fatehpur Sikri, Uttar Pradesh	Uttar Pradesh	
09	Group of Monuments at Hampi	Karnataka		25	Taj Mahal, Uttar Pradesh	Uttar Pradesh	
10	Monuments at Pattadakal	Karnataka		26	Mountain Railways of India	W. B. T.N. H.P.	
11	Buddhist Monuments at Sanchi,	Madhya Pradesh		27	Nanda Devi and Valley of Flowers	Uttarakhand	
12	Rock Shelters of Bhimbetka,	Madhya Pradesh		28	Sundarbans National Park	West Bengal	
13	Khajuraho Group of Monuments,	Madhya Pradesh		29	Western Ghats	Nilgiri , Sahyadri	
14	Ajanta Caves	Maharashtra		30	Hill Forts of Rajasthan	Rajasthan	
15	Ellora Caves	Maharashtra		31	Rani ki vav	Patan, Gujarat	
16	Elephanta Caves	Maharashtra		32	Great Himalayan National Park	Himachal Pradesh	

Very High Risk Zone	High Risk Zone	Moderate Risk Zone	Low Risk Zone

Source: Author

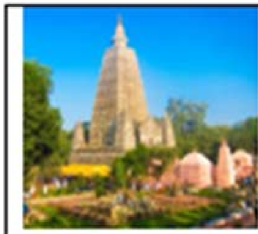
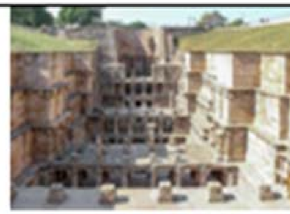
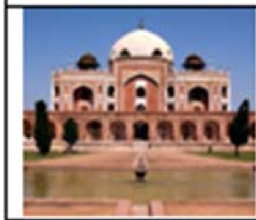
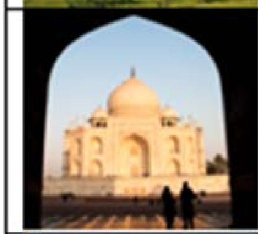
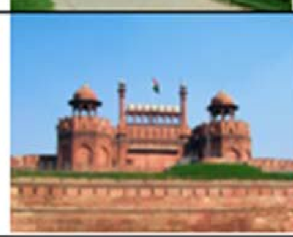
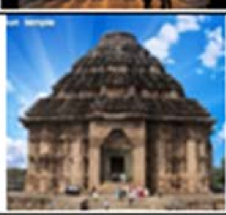
Vulnerabiity of Architectural Heritage in India

Many historic structure in India were made of stone this is one of the reasons why they survive many natural hazards and different harsh weather and environmental conditions. Failure in stone and brick walls is attributed to poor quality mortar including mud or low quality lime which considerably reduces the strength and stiffness of the wall. Use of timber as one of the structural materials is another reason as it is more susceptible to humidity and temperature variations and because of poor maintenance; they may decay and lose their load carrying capacity at a much faster rate. Geographic location and use of structures also contribute to damage. It has been observed that the use or occupancy of the structure is changed and created larger unexpected loads. In many instances loading from continuous traffic on adjoining roads lead to vibrations and excessive loads on foundations. The gradual deterioration of materials or the load carrying structural system can be prevented as the damage progresses and becomes visible. There is a need to evaluate the capacity of existing historical structures and to retrofit them before an earthquake strikes.

Research established the vulnerability of historic buildings built with masonry which are located in zone 3 or 4 and are likely to expose to an earthquake of 7 magnitudes or above. Masonry structures capacity to sustain an earthquake depends on the physical properties, mineralogical and chemical composition of material of construction which generally suffers from continued deterioration because of aging and lack of adequate maintenance. Most of old buildings constructed in 1917-18 are constructed of burnt clay bricks in lime or surkhi mortar which has very low tensile strength and shear force resistance. Most of such structures suffer from inadequate connection between parts which results in separation of massive walls from rigid columns. Each building components tends to work independently proportional to the mass and the natural stiffness which prevents the force distribution proportional to the mass. Damage to tall and slender elements like minarets and other decorative features attributed to amplified effects and low bearing capacity and shear failure of walls or the upper parts of the structure due to the poor quality of mortar and least shear force resistance [15].

Retrofitting methods need to be used considering the quality of built stock with reference to architectural heritage of India a large part of which consists of very flexible buildings, in majority of which walls are not adequately connected to each other. Location of heritage premises, buildings at highly congested areas in city core is another reason for their suitability and unsuitability of techniques like seismic base isolation for earthquake retrofitting interventions. Indian architectural heritage includes numerous structures, sites each having a unique character and consequently seismic strength. A study of Architectural heritage is conducted aimed at their idetification with reference to seismicity of the area and their structural capacity to withstand an earthquake in located in New Delhi, Uttrakhand, Uttarpradesh, Assam and Gujrat. Some of the identified heritage buildings and sites which are located in high to medium earthquake risk zone are presented in the table 2.

Table 2. Seismic Risk to Heritage Sites

	Mahabodhi Temple, Bodh Gaya, Bihar. PERIOD: 3rd century BC, 5th and 6th century AD and 19th century UNESCO DATA: 1056 rev, 2002, i, ii, iii, iv, vi		Rani ki vav(The Queen's Stepwell) Patan, Gujarat. PERIOD: 11th century AD UNESCO DATA: 2014
	Humayun's Tomb, Delhi PERIOD : 1570 UNESCO DATA: 232, 1993, (ii), (iv)		Jantar Mantar, Jaipur, Rajasthan PERIOD :1727 and 1734 UNESCO DATA: 1338; 2010; (iii)(iv)
	Qutb Minar and its Monuments, Delhi PERIOD : Late 12th century UNESCO DATA: 233, 1993, (iv)		Agra Fort, Uttar Pradesh PERIOD :16th century UNESCO DATA: 251; 1983; iii
	Taj Mahal, Uttar Pradesh. PERIOD :17th century UNESCO DATA: 252; 1983;i		Red Fort Complex PERIOD :1648 UNESCO DATA: 231rev, 2007, (ii), (iii), (vi)
	Sun Temple, Konârak Puri District,Orissa. PERIOD :13th-century UNESCO DATA: 246; 1984;(i)(iii)(vi)		Fatehpur Sikri, Uttar Pradesh PERIOD : 16th century UNESCO DATA: 255; 1986; ii,iii,iv

Very High Risk Zone | High Risk Zone | Moderate Risk Zone

Source: Author, adopted from .wikipedia.org

Source: Author, adopted from .wikipedia.org

The Archaeological Survey of India, under the Ministry of Culture, is the premier organization for the archaeological researches and protection of the cultural heritage of the country has prepared a list of monuments containing 174 sites of historic significance in Delhi, 70 in Bihar, 742 in Uttar Pradesh, 44 in Uttrakhand 202 in Gujrat . The INTACH Delhi Chapter has published a list of 1200 buildings containing detail of the structure, which includes the ownership details, significance of the building, condition of the structure etc. The heritage sites were selected from selected four states based n their historic importance. Each of the studied heritage sites/structures were analysed in order to find out their vulnearbility. The criteia for vunerability analysis inculded the seismicity of the area, age , use of building material and technology for construction, Plan density, Presence of soft week story, building configuration, past and current use, presence of architectural decorative features, building location and adjoining featurs. The buildings studied were rated on 5 point likart scale for each of the attribute ranging from highly vulnerable to safe. An inventory is prepared based on the vulnerability analysis for above mentioned states. In addition to the listed world heritage sites country possess numerous monuments of regional and local importance which are to be analysed for seismic performance and consequently adequate seismic retrofitting interventions.

Conclusion

The majority of the historic buildings in India are made of masonry elements, composed of stone, bricks and mortar which have a poor response to earthquakes. A detailed comprehension of the structural behaviour under static and dynamic (earthquake) loading is the key for a successful intervention which is aimed at providing capacity to withstand future actions with the minimum possible damages. Analysing historic structure is a challenging task because of multiple reasons like complex geometry, the variability of the traditional material's properties and different techniques used in construction as well as the lack of knowledge on the existing damage from the actions, which affect the monuments throughout their lifetime.

The uniqueness of each monument do not allow to individuate an a priori reliable, well defined analytical and interpretative strategy as a result an univocal safety assessment procedure cannot be defined.

The characteristics of structure from a historical, constructive-geometric and mechanical point of view intervenes the evaluation of the seismic safety for the implementation of strengthening interventions. For heritage buildings it is very difficult to find data about the original conception of the structure as well as the alterations, modifications which may occurred during the life time (due to anthropic interventions, materials ageing, external actions); moreover, the execution of a complete investigation campaign can be excessively invasive. To encounter the threat of earthquake occurrence the country needs attention towards the retrofitting of historic structures at topmost priority. Considering the frequent occurrence of earthquakes in last two three decades in India structural longevity will become a requirement, not just a goal, for historic buildings, regardless of their current condition or location. Attempts are therefore necessary to provide at 'code of practice' for the assessment, analysis and strengthening aspects of the seismic rehabilitation of historic structures

Historic buildings require structural strengthening to minimize destruction under future seismic activity without any perturbation to their authenticity as far as their architectural expression is concerned. A balance has to be achieved between the need for safety and integrity, and the need for preservation of the original structure and tissue with minimal intervention. Each structure has to be analyzed identifying the original constructional aspects, their evolution in time under the action of all aging ingredients, both from nature and from repairing, including the earthquake impacts. Adequate intervention for conservation efforts needs information about the building/site with reference to their vulnerabilty on occurrence of an earthquke. The inventory prepared based on vulnerability analysis of selected structures/sites is supposed to prove instrumental for conservation architects in idle phase of earthquake occurrece as well as may assist in emergency phase on occurrence of such an event.

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