Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Indo-Italian Joint Research Programme on Seismic Vulnerability of Historical Centres in South India

Guido Magenes, Giorgio Macchi and Alberto Pavese
Department of Structural Mechanics (DMS), University of Pavia, Pavia, Italy

A. Meher Prasad, G.R. Dodagoudar, M.S. Mathews and Devdas Menon
Department of Civil Engineering, Indian Institute of Technology Madras (IITM), Chennai, India

Carlo Lai and Andrea Penna
European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Pavia, Italy

Arun Menon
European School for Advanced Studies in Reduction of Seismic Risk (ROSE), Pavia, Italy

ABSTRACT: The recent earthquakes of Bhuj in India (2001) and Umbria-Marche in Italy (1997) have shown how the two countries, represented by a rich, vulnerable architectural heritage built in seismically active environment, are confronted with a common problem. A project proposal submitted to the Governments of India and Italy jointly by the University of Pavia and the Indian Institute of Technology Madras has been approved as a significant bilateral project in the area of cultural heritage, conservation and restoration technologies. The project aims at implementation of a multidisciplinary methodology integrating aspects of seismic hazard, local site response, vulnerability and exposure of historical building stock and a monument, culminating in the estimation of the seismic risk at urban scale. This paper illustrates the objectives and the details of the components of the research programme as well as an update of the activities currently in progress.

1 INTRODUCTION

1.1 Motivation of research and objectives

Historical buildings and historical urban nuclei constitute an essential component of the cultural heritage of a nation. This precious legacy, in seismically active countries such as India and Italy, is exposed to the threat of earthquakes which can potentially destroy or damage in a few instants what men have built over centuries shaping their homes and urban environment according to their culture and civilization. The recent earthquakes of Bhuj in India (2001) and Umbria-Marche in Italy (1997) have demonstrated how the two countries, represented by a rich, vulnerable architectural heritage, are confronted with a common problem.

The project described in this paper envisages a two-pronged strategy. On the one hand, seismic risk assessment of a historical urban nucleus will be carried out. On the other, a detailed seismic vulnerability study of a monumental structure, representative of the architectural style predominant in the selected region, will be executed. The proposed methodology is being applied to a historical urban centre in Tamil Nadu in south India (Kanchipuram) as a pilot study which can subsequently be replicated.

The region under discussion was, in 2002, reclassified as being in Zone III of earthquake hazard from Zone II, with the implication that the maximum intensity (MSK 64) expected is VII (BIS-1893:2002). The seismicity of the region under study, from historical data and current observations, is certainly low. Nevertheless, it was the occurrence of devastating earthquakes (Killari'93, M 6.4 and Jabalpur'97, M 6.0) in the Stable Continental Region of Peninsular India in the last decade that prompted reclassification of the seismic zoning. It is in the face of this reality that the proposed project gains significance. The seismic resistance of neither the traditional building practices in this region, nor the conventional structural restoration procedures employed by the Archaeological Survey of India (ASI) in monuments under their authority, have really been established.

The project aims at the implementation of a multidisciplinary methodology integrating aspects of seismic hazard, local site response, vulnerability and exposure of building stock culminating in the estimation of the seismic risk at urban scale. The outcome of such an investigation would also prove useful to local authorities for the development of risk mitigation strategies and interventions for risk reduction in architectural heritage. Reliable predictions of damage scenarios will also be useful for post-earthquake emergency management.

The project proposal is being funded within the Indo-Italian Programme of Cooperation 2005-2007.

2 STATE OF THE ART OF RESEARCH

2.1 The Indian Earthquake Scenario

Indian seismicity is characterised by relatively high frequency of great earthquakes and low frequency of moderate earthquakes. Due to the infrequent nature of moderate earthquakes, the Indian seismic problem often does not receive the due attention.

The catalogue of the Indian Meteorological Department lists 1200 known seismic events that have occurred in the country. Of these, 8 are events of M $\geq$ 8.0, 43 of M 7.0-7.9, 312 of M 6.0-6.9 and the rest of M 5.0-5.9 (Arya, 2000). Recent destructive earthquakes in India such as the Killari 1993 (M 6.4), Jabalpur 1997 (M 6.0) and Bhuj 2001 (M_w 7.7) exposed the vulnerability of architectural heritage apart from inadequacies in the seismic risk reduction programmes (Rai et al., 2002). Seismic hazard (Iyengar and Ghosh, 2004) and seismic microzonation studies (Sharma et al., 2004) have recently been carried out for Delhi demonstrating ground motion amplification near the river Yamuna.

Figure 1 : Seismic hazard zonation for the State of Tamil Nadu (BIS-1893:2002, Source: BMTPC, India)

The seismic zonation of India was recently upgraded by the Bureau of Indian Standards (BIS, 1893-2002). Zones I and II were merged. New regions were included in Zone III such as the Chennai area in Tamil Nadu (see Fig. 1). Most of India lies in Zone III, where a maximum intensity of VII is expected. New Delhi lies in Zone IV whereas Mumbai in Zone III. The intensity as per the Comprehensive Intensity Scale (MSK 64) associated with the zones is VI (or less), VII, VIII and IX (or above) for Zones II, III, IV and V, respectively.

The current zonation is based on historical records of felt effects from which the maximum recorded or likely intensities at any point are deduced. The model fails to indicate recurrence patterns of large earthquakes in a region and in demarcating areas where large earthquakes have long return periods. There is also a recognized paucity of data in the Stable Continental Region of Peninsular India.

A recent study (Jaiswal 2005) compared seismic hazard estimates for different regions of Peninsular India using a probabilistic model against the code-based zonation. Spatial variability and reservoir-induced seismicity were found to be some of the important characteristics of seismic activity in Peninsular India. Most of Peninsular India faces greater seismic hazard compared to the level defined by the zonation. The ratio of MCE (Maximum Considered Earthquake) to DBE (Design Basis Earthquake) is dependent on seismotectonic conditions and cannot be a uniform value as prescribed by the code. This is the case especially for low to moderate seismicity. For a site in Zone III, the code provides a Zone Factor (estimate of effective peak ground acceleration) for MCE of 0.16g. The peak acceleration for the MCE obtained from the PSHA for Zone III is in the range of 0.092-0.18g (Jaiswal 2005).

2.2 Seismic vulnerability of built heritage and risk assessment

A study on the widespread damage sustained by architectural heritage in the Bhuj earthquake in 2001 (D'Ayala and Kansal 2004) highlighted the deficiencies of historical masonry structures in seismically active regions in India. Hence, there arises an urgent need for identifying highly vulnerable building stock and developing strategies to mitigate their seismic risk.

Vernacular architecture and non-engineered, traditional construction techniques are widespread not only in rural and semi-urban areas in India but they also constitute a majority of the dwellings in urban historical nuclei. Jain (2005) points out the need for research in quantifying the seismic resistance of traditional constructions and in developing contemporary versions citing examples of the Assam-type traditional housing in the north-eastern states and the *Dhajji–Dwari* constructions in Kashmir with excellent earthquake resistance.

At present a comprehensive earthquake protection mechanisms does not exist in India for heritage structures. Interventions are required at both regional policy and planning level and individual structure level for seismic strengthening. There is a need to evolve special guidelines/code provisions for seismic strengthening and restoration of heritage structures for long term protection.

The assessment of seismic risk, i.e. the expected loss in terms of damage to the built environment and human fatalities consequent to an earthquake encompasses a rather accurate study of the four following components:

1. The *seismic hazard* on a regional scale.
2. The *modification of ground motion* at the site.
3. The *vulnerability of the built environment* to damage in an earthquake.
4. The *exposure of the built environment*.

Recent investigations (HAZUS 1999, Giovinazzi and Lagomarsino 2003, Restrepo-Velez and Magenes 2004b) on suitable methodologies for seismic risk assessment of architectural heritage at urban level address the need and potential for rational, structural mechanics-based models. Coordinated projects carried out on historical centres and urban areas in Italy and Colombia are showing the advantages of such procedures and their potential transferability and adaptability to different regions (Restrepo-Velez and Magenes 2005).

3 PROJECT IMPLEMENTATION METHODOLOGY

The project aims at implementing a methodology for assessment of seismic risk in historical centres in India and a detailed vulnerability assessment of a monumental structure.

Seismic hazard maps in terms of probabilities of exceedance of specified levels of ground motion parameters would be produced on a GIS platform and refined using results of microzonation and local site response. Based on detailed on-site reconnaissance and systematic examination of the building stock in the historical centre, seismic vulnerability models would be developed which could then be coupled with the ground motion scenarios previously defined to arrive at damage scenarios due to seismic events.

The initial phase of the project focuses on the definition of the methodology incorporating multidisciplinary aspects following which, the methodology would be applied to the selected site. A systematic feedback procedure will ensure that the methodology is refined and adapted to the characteristics of the selected site.

3.1 Seismic vulnerability of the built environment

The first step in the assessment of the vulnerability of the built environment on an urban scale is a detailed definition of the construction typology at the site. Recent works (EERI-IAEE 2002) on the classification of construction typology for housing in India highlight the diversity in materials and technologies used in construction within the country.

Information related to the materials of construction, construction techniques and structural configurations adopted for buildings, geometric parameters and a few other parameters required to classify buildings according to their typology have to be collected. Once a broad-based classification of the construction typology is achieved, the survey of the data pertaining to individual buildings would essentially be achieved through field survey forms, an expedient tool that allows customizing the field survey to the objectives of the study. The forms gather data related to the building's usage, maintenance conditions, cultural/architectural value, site morphology, building geometry, structural typology, plan irregularities, floor area, storey heights, characteristics of perimeter walls, etc., in a systematic manner for every building within the designated area. The form envisages the definition of the quality of information assignable to each parameter surveyed to account for uncertainty.

Georeferencing the data collected on a GIS platform would allow the creation and representation of damage scenarios.

Two different approaches for the damage vulnerability of structures under earthquake loading would be followed. The two approaches entail different definitions of the seismic input, namely, macroseismic intensity and response spectra in terms of spectral acceleration and displacement. The application of two diverse methodologies for the vulnerability assessment gives the opportunity to verify the outputs of each method.

1. *Macroseismic Model:* This method is qualitative and based on a statistical correlation between observed damage and typology of construction. Every building is assigned a score as a function of its construction typology. The score assigned to a building is either increased or decreased based on the presence or absence of specific features in the structure, its relationship with adjoining structures and the interaction of the structure with the subsoil. This provides the vulnerability index of a given structure which, when expressed as a function of intensity identifies the grade of damage as defined by the European Macroseismic Scale (EMS98).
2. *Mechanical Models:* The mechanical model is based on the definition of the non-linear seismic response of the structure in terms of its capacity curve. The capacity of the structure is represented by a force-displacement curve that is obtained by a non-linear static (pushover) analysis using simplified mechanics-based structural models (Calvi 1999, Glaister and Pinho 2003, Restrepo-Velez and Magenes 2004b), and is then converted to an equivalent s.d.o.f. capacity curve. The demands of the earthquake ground motion are defined by response spectra. The intersection of the capacity spectrum and the demand spectrum provides an estimate of the displacement demand. The displacement demand on the structure can be estimated for specific limit states, such as limited or severe damage and collapse.

The building stock of the historical centre will be assessed by the above methodologies, with the exception of monuments notable for their cultural heritage and important civic structures such as hospitals, fire stations, city councils, etc. which host critical functions in an emergency. These need a specific detailed modelling, due to their peculiar characteristics.

An innovative dimension of the research would be in using and refining mechanical models for vulnerability assessment. The models should be based on comparisons with the experiences from damage scenarios in recent seismic events and analyses of refined models. In masonry constructions, damage/collapse mechanisms are associated to in-plane or out-of-plane response. In case of out-of-plane response, characterised by overturning of whole or of portions of walls, static methods form the basis of the formulations. The static capacity of the structure can be expressed by a "*seismic collapse multiplier*". Among others, D'Ayala and Speranza, 2003, have shown how such a parameter can be usefully employed to correlate vulnerability to the mechanical behaviour of structural macroelements. However, the static capacity alone may underestimate the real seismic capacity, since under dynamic loading, once the structure develops its mechanism, it can withstand considerable displacement without collapse.

Systematic reformulation of these models by means of parametric analyses on suitable reference models, taking into to account geometric and constitutive non-linearity and representation of seismic excitation by other parameters related to velocity, displacements, duration and energy is an area of possible investigation. There is a strong need for comparisons of numerical and experimental results (static and dynamic) in line with recent work at the University of Pavia (Restrepo-Velez and Magenes 2004a). Recently developed models (Magenes and Della Fontana, 1998, Galasco et al. 2003) for non-linear static and dynamic analyses considering in-plane response of masonry form a solid basis for the evaluation of response of structural/architectural macro-elements and buildings.

3.2 Definition of seismic hazard

In addition to the definition of construction typology and vulnerability models, assessment of the seismic vulnerability of the building stock depends on two complementary yet indispensable themes: definition of the seismic hazard in terms of ground motion on a regional scale and the identification of local site effects that may modify the ground motion.

The seismic hazard on a regional scale is usually defined by a probabilistic approach and expressed as the probability of exceedance of a specified level of a ground motion parameter such as the peak horizontal ground acceleration or by a degree of macroseismic intensity that can be exceeded in a specified interval of time.

The design ground motion at the outcropping bed rock of a specified site would be defined based on the macrozonation. The seismic hazard would finally be represented in terms of horizontal and vertical response spectra as well as spectrum-compatible accelerograms in accordance with codes such as the Eurocode 8 (CEN 2005). Accelerograms could be selected from standard strong motion databases satisfying the criteria of being compatible with seismogenetic setting in terms of magnitudes and epicentral distances so that the accelerograms reflect realistic scenarios for the site under consideration and recorded on rock sites.

3.3 Local site effects and microzonation

Local site effects refer to those phenomena that tend to modify the design ground motion on rock outcropping obtained either from a macrozonation map or from a regional scale seismic hazard assessment. The estimation of the modification of ground motion due to local characteristics is known as *microzonation*. This term, however, also includes the so called “*induced effects*” such as slope instability, soil liquefaction and near-field effects.

Geological and geotechnical characteristics of the site exert a strong influence on the nature of the ground shaking experienced by structures and this is reflected by the response spectrum. Also, near-fault effects may alter the spectral ordinates at intermediate and longer periods.

Some specific issues in microzonation that are of interest in this study are listed hereunder:

1. Assessment of the non-linear effects of the soil, essentially the susceptibility of the soil to liquefaction or densification under cyclic loading;
2. Evaluation of the effects of surface and sub-surface topographic irregularities (such as ridges, peaks, etc.) and alluvial basin geometry on the ground motion (amplification and deamplification effects) using 2D and 3D analyses.

The solution of the issues discussed above would require collection of geophysical data for an accurate reconstruction of the subsoil geometry by identification of stratigraphic units and geophysical characterisation of longitudinal and transverse wave velocities including attenuation properties. Field and laboratory data on dynamic characteristics of the soil would be required to quantify soil stability under cyclic loading at low and high strain levels.

Microzonation for local ground response would be achieved by a Grade-1 or Grade-2 level of approach (ISSMGE 1999) where the zonation is achieved largely on the basis of compilation and interpretation of existing information from historical documents, published reports and available databases and a minimum level of field investigation.

3.4 Seismic risk, damage scenarios and loss estimation

Seismic risk maps and damage scenarios would be produced from the seismic vulnerability models of the built environment by integrating with the outputs of the seismic hazard assessment. In the event of an earthquake, the consequences suffered by building stocks can be estimated from the damage scenario. As an important by-product, damage to population (in terms of numbers of human lives lost, persons injured and rendered homeless) and it's social and economic impact could be estimated through statistical correlations between damages suffered by buildings and their disuse and loss in terms of human lives (Coburn and Spence 1992).

4 CURRENT STATUS

4.1 Site for project implementation

The historical town of Kanchipuram in the south Indian state of Tamil Nadu was chosen as the site for this pilot study following a visit to the area by the research teams in November 2005.

Kanchipuram district is situated on the northern end of the east coast of Tamil Nadu along the Bay of Bengal. It lies between 11° 00'-12° 00' N latitudes and 77° 28'-78° 50' E longitudes. The district has a geographical area of 443,210 hectares and the city of Kanchipuram is the District Capital. The town is situated on the banks of river *Vegavathi*, 76 km from the State Capital Chennai with a population of 144,955 persons (NIC).

Kanchipuram was the capital of the Early Cholas in the 2nd c. BC and a Pallava capital between the 6th-8th centuries following which Kanchipuram was administered by the Vijayanagar rulers, Muhammadan kings, and the British. Ancient Kanchipuram, known as the "city of thousand temples", is one of the seven most sacred Hindu pilgrim centres of India. Today, apart from its ancient temples, this town is identified for its thriving silk handloom industry.

According to the current seismic zonation, Kanchipuram falls in Zone III of seismic hazard where a maximum intensity of VII (MSK 64) is expected. The town has never been the epicentre of earthquakes in the past.

4.2 Traditional residential agglomerates

Aggregates of traditional dwellings in the proximity of religious monuments protected by the ASI and the Tamil Nadu Department of Archaeology have been identified in the town. In the past, these traditional dwellings were established as ordered settlements with a temple or a palace as the nucleus, linked with straight roads cutting at right angles. They have survived urbanisation due to their proximity to protected heritage structures. No new construction activity is allowed within a radius of 100m from an ASI protected monument and any construction activity in the area between 100-300m radii from such a temple requires express approval from the ASI. There is a height restriction of 9m for any new construction in the town.
Two distinct categories of dwellings can be identified as shown in Fig. 2:

1. Single-storied, traditional mud houses with sloped timber roof support and clay tiled roofing. Dwelling units are built adjacent to each other typically sharing a side wall. The houses may be built using burnt bricks and mud mortar also.
2. Single or double-storied, traditional brick masonry street houses. The roof is a sloped timber construction with clay tiling or flat, constructed using timber joists, rafters, and burnt clay bricks, tiles and lime plaster.

Houses are built on raised plinths. The units are usually rectangular with a narrow external façade with the main entrance and extend inwards longitudinally. Some of the characteristic features of these traditional houses are a garden in the backyard, small open-to-sky internal courtyards, and semi-private colonnaded front entrance known as the "*thinnai*".

Estimation of the collapse load for such a structural configuration and typology is one of the primary objectives of the study.

Figure 2 : Two typologies of traditional housing close to temple precincts in Kanchipuram.

Figure 3 : 58.5 metres high southern *Gopura* of the 16th century Ekambaranathar Temple in Kanchipuram.

4.3 Monumental structure

Besides the traditional housing aggregates, a protected monument has been selected for detailed structural investigation to estimate the seismic vulnerability. Identification of a monumental structure representative of the prevailing temple architecture of south-eastern India was an important criterion for the choice.

The 16th c. AD Shiva temple in Kanchipuram, Ekambaranathar Temple, has been provisionally chosen for the investigation. The temple was originally built by the Pallavas and later reconstructed by the Chola and Vijaynagara kings. The temple follows the architectural style of the Vijayanagara dynasty and is built in granite and brick masonry. The temple is famous for its 58.5m high southern entrance gateway known as a "*gopura*" shown in Fig. 3. The "*gopura*" is eleven storied. It has a truncated tapering prismatic shape with a central gateway at the ground level and internal staircase leading to upper levels. The "*gopura*" has a trabeated structural system. Investigation of the seismic response of such a structural configuration would be a unique and instructive task.

The modelling and analysis of the historical masonry structure would be achieved through structural component models by finite element method (Menon et al. 2003) and limit analysis by identifying the relevant collapse mechanisms. Choice of a linear or non-linear approach to finite element modelling would depend on the quantity and quality of data on geometry and material properties of the monument.

5 CONCLUDING REMARKS

This article aims at illustrating the motivation, objectives, methodology and current status of activities of a recently approved joint research project between the University of Pavia and IIT Madras on seismic vulnerability of historical centres in south India. It is believed that the project will contribute towards establishing a robust methodology for seismic risk assessment of historical centres in India.

ACKNOWLEDGEMENTS

The authors would like to acknowledge their gratitude to the officials of the MAE, Government of Italy and the DST, Government of India for the support extended to this collaborative programme. We record our thanks also to Mr. T. Sathyamurthy, Superintending Archaeologist, Chennai Circle, ASI for his valuable assistance in the project.

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