International Journal of Scientific & Engineering Research, Volume 6, Issue 2, February-2015
ISSN 2229-5518

Seismic Saftey Evaluation of Heritage Structures

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Abstract— This paper presents necessary considerations for seismic safety evaluation of Cultural Heritage structures by investigation of existing structural characteristics; identification of significant deficiencies to cater additional lateral force arose by the revision of codes. Thorough understanding of the existing construction, research into its limiting strength and deformation characteristics and performance objectives to evaluate performance of the structure during earthquake are discussed first followed by discussions on seismic deficiencies commonly found in buildings.

Key words— Structural Design, Structural shortcomings, Reinforced Concrete, Steel, Wood, Performance Objectives, Prescriptive Requirements, Seismic Demand, Seismic Capacity, Strength, Stiffness, Flexibility, Drift, Deformation, Load Paths.

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1 BACKGROUND

THE engineer for a new building has the opportunity to require inspection of important aspects of the construction and to confirm the quality of materials and workmanship incorporated. As a result, most structural characteristics important to seismic performance including ductility, strength, deformability, continuity, configuration and construction quality, can be controlled.

Seismic safety evaluation of existing structures presents a completely different problem. First, for most types of structures, up to very recently, there was no clear professional consensus on appropriate design criteria. That of course has changed substantially by publication of revised codes and performance based design guidelines such as the FEMA 273/274 and the ATC-40(l) guidelines.

The configuration and materials of construction are predetermined. The details and quality of construction are frequently unknown and because the structure has been in service for some time, deterioration and damage are often a concern.

Design of a new structure, successful seismic upgrade of an existing structure requires development of a thorough understanding of the existing construction, research into its limiting strength and deformation characteristics, quantification of the owner's economic and performance objectives, and selection of an appropriate design criteria to meet these objectives, which is also acceptable to the building official. It also includes selection of retrofit systems and detailing which can be installed within the existing structure (which may have to remain open during the upgrade) at a practical cost and with minimum impact on building appearance, function and historic features.

This paper presents important considerations for engineers upgrading the seismic resistance of Heritage Structures of Cultural importance structures including investigation of structural characteristics, identification of significant deficiencies, and selection of appropriate upgrade criteria and retrofit systems. The paper is organized into four sections. The differences between the seismic design philosophy for a new building and that for the seismic safety evaluation an existing building are discussed in the following section, Section 1.2. Seismic deficiencies commonly found in buildings are then discussed in Section 1.3. The importance of establishing a rational seismic safety evaluation criterion is presented in Section 1.4. Since performance based design techniques is not covered in the scope, we limit ourselves here to coverage of more traditional approaches to seismic rehabilitation.

2 AIM OF SEISMIC SAFETY EVALUATION

Many structural engineers believe that the purpose of seismic safety evaluation is for the up gradation of the structure, to the maximum extent practical, into conformance with the lateral force requirements of the current building code. As stated by the Structural Engineers Association of California(2) (SEAOC), the purpose of earthquake resistance provisions incorporated into the building codes is to maintain public safety in extreme earthquakes likely to occur at the building's site. Such provisions are intended to safeguard against major failures and loss of life, not to limit damage, maintain functions, or provide for easy repair. Specifically, it is expected that buildings designed to conform with the provisions of the building code would be able to:

- Resist a minor level of earthquake ground motion without damage;

- Resist a moderate level of earthquake ground motion wi1hout structural damage, but possibly experience some non-structural damage;

- Resist a major level of earthquake ground motion having an intensity equal to the strongest either experienced or forecast for the building site, without collapse, but possibly with some structural as well as non-structural damage.

These performance objectives can be reasonably attained in the design of new structures by carefully conforming to four basic sets of provisions specified by the code: strength, materials selection, structural detailing, and construction quality. Due to revision of codal provision the consideration of more than 3 times lateral force necessitates the retrofitting of structure. A typical four storey building has been examined by all five methods of IS: 1893-1984(3-4) and its latest revision and the results are presented in Fig. 1.1.

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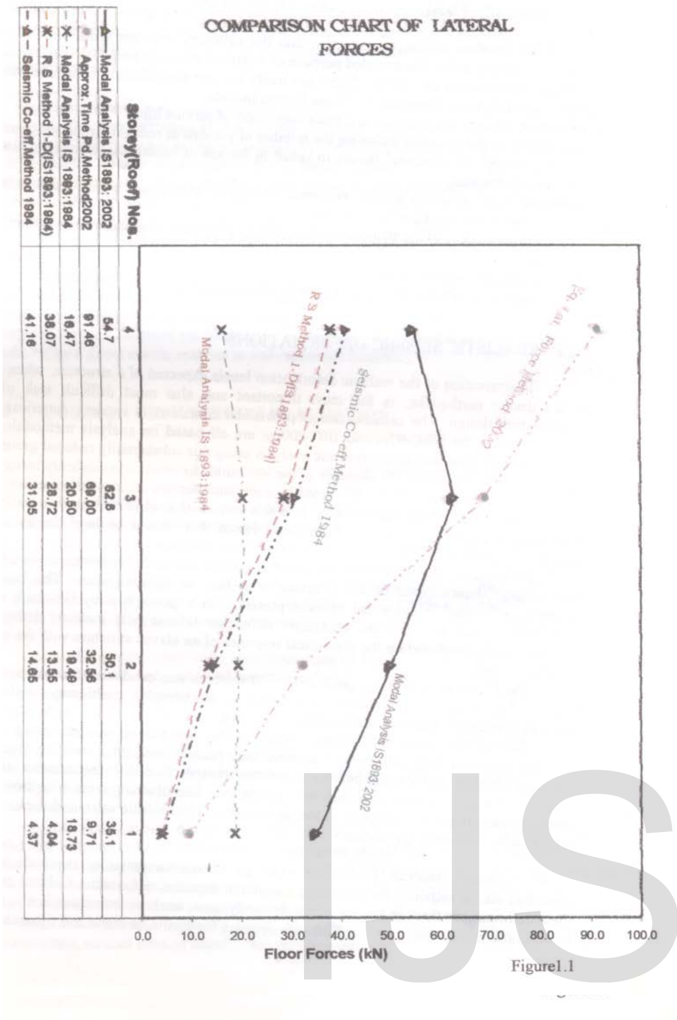

Figure1.1

2.1 Seismic Safety Evaluation Objective

It is therefore extremely important that the structural engineer work with the building owner to carefully define the intended purpose of seismic safety evaluation based on specific safety and economic performance objectives. These are likely to vary considerably from one structure to another based on several key factors. These factors include:

- Economic value of the structure and remaining years of service life.

- Occupancy of the structure including the number of persons at risk within the structure, as well as the potential for structural failure to result in release of hazardous substances and injuries outside the structure.

- Function of the structure and the economic or societal cost which would result from loss of service due to earthquake induced damage.

- Historic significance of the structure and the effects of seismic upgrades on the cultural resource.

- The site-specific seismic hazard.

- The relative cost of achieving evaluations to various criteria.

2.2 Realistic Seismic Deformations

Determination of the realistic deformation levels expected of a structure, when subjected to the design earthquake, is the most important and also most difficult task of seismic rehabilitation design. The seismic design provisions contained in modem American building codes including the UBC-97(5) and IBC-2000(6) are all based on analysis methodologies. The forces obtained from the elastic dynamic analysis using this substantially reduced ground motion are then used to proportion the elements of the structure. However, it is explicitly recognized that the structural deformation levels predicted by such analyses are substantially smaller than what will be experienced by the real building. It is this amplified level of deformation rather than the deflections predicted by the code base shear forces that should be used for evaluating the adequacy of existing structural elements in a retrofitted structure.

It should be noted that even the use of amplified elastic deformations as an indication of real inelastic deformations. of the structure is at best an approximation. The basis for this approach is founded in analytical research presented in a monograph by Newmark and Hall(8). That research indicates that the maximum deflection (elastic plus inelastic deflection) of a structure can be predicted by the theoretical response of an elastic structure with the same initial dynamic properties.

The Newmark and Hall(8) basic analytical research was conducted for very simple, single degree of freedom structures only, as opposed to the complex multi-story, multi-degree of freedom structures commonly encountered in practice.

Ductile structures will become softer as they are pushed into the range of inelastic response. However, they will continue to retain their plastic lateral force resisting capacity, and as they strain harden, will actually become somewhat stronger. Non-ductile structures, such as many older concrete and masonry structures will experience a loss of strength resulting from spalling of compressive material and slippage in tensile elements. The realistic seismic deformations can be estimated by following approaches:-

- Nonlinear Analysis Techniques - As an alternative to using the code approach of amplified elastic response for estimating maximum expected deformations, direct calculation of these deformations through the use of non-linear dynamic analysis techniques is also possible and has become increasingly popular. Software systems for nonlinear static and dynamic analysis of structures are becoming increasingly available in the design office environment. Use of such techniques is required for design of certain types of seismic force resisting systems including certain classes of base isolation and energy dissipation systems and may also be appropriate for some conventional structures.
- Quasi-inelastic analysis approaches are also available which permit evaluation of complex structures. The most common of these is the so-called "progressive yield" or "static pushover" analysis. A simple way to use this approach is to start with an elastic model of the structure which is analyzed for a static distribution of lateral forces. Stresses within the structure are evaluated and zones of yielding identified. The elastic model is then modified by placing "hinges" and "reduced stiffness" elements at locations of computed yielding. The revised model is then reanalyzed statically for additional static lateral forces. This process is repeated until the total

structural deformation required by design criteria is attained or the structure is found to become unstable.

Regardless of the technique utilized, in order to properly understand the seismic behaviour of an existing structure, it is critically important to understand the likely distribution of deformations throughout the structure under the criteria earthquake ground motion. One should recognize that deformations are likely to be substantially larger and differently distributed than is predicted by a direct elastic analysis to code specified forces.

3 GENERAL DEFICIENCIES EVALUATION

The deficiencies found in existing construction which can lead to poor earthquake performance is defined as endangerment of life safety through either partial or total. collapse. More previously discussed, for some types of structures and occupancies it may be desirable to obtain better performance than merely protection of life safety.

Some engineers have attempted to apply the current building codes as evaluation tools for Heritage Structures of Cultural importance structures. The problem with this approach is that since the codes are revised every few years, most Heritage Structures of Cultural importance buildings will not meet the current code to some extent, a few years down the road. This would result in a finding that nearly every building is hazardous and requires upgrade. Such a finding is obviously both technically incorrect and economically not feasible to manage.

One of the most seismically hazardous class of buildings common throughout the world are structures constructed with load bearing walls of unreinforced masonry. For these type of structures procedure described in code form as an appendix to the Uniform Code for Building Conservation(5). The procedures of these documents can be a useful guideline for the evaluation of masonry bearing wall structures. A number of more general-purpose evaluation guidelines have also been recently published on the subject of seismic safety evaluation.

These include, Rapid Visual Screening of Buildings for Potential Seismic Hazards and the NERHP Handbook for Seismic safety evaluation of Heritage Structures of Cultural importance Buildings(9). The common deficiency can be outlined as –

- Incomplete Lateral Force Resisting System: One of the most common causes of earthquake induced collapse is the lack of a complete lateral force resisting system. In order to successfully resist collapse, each element of a structure must be positively connected to the whole in such a manner that inertial loads generated by the element from motion in any direction can be transmitted back to the ground in a stable manner.
- As a minimum, a complete lateral force resisting system will include at least three nonconcurrent vertical lines of lateral force resisting elements (moment frames, braced frames or shear walls) and at each level of significant mass a horizontal diaphragm to .interconnect these vertical elements. There are a number of common building configuration and design features which often result in a building without a complete lateral force resisting system. These include open store fronts/house over garage, clerestory conditions, and expansion joint conditions. The open store front or house over garage condition, common in urban construction and for older buildings, has often lead to building collapse during strong ground motion.
- Structural Continuity and Inter-element deformations: Structural continuity is an important factor for good seismic performance. If all of the various components of a structure are not adequately tied together, the pieces can move independently and in different directions. This can result in dislodging elements from structures and the loss of bearing support for vertical load carrying elements.
- Excessive Lateral Flexibility: Buildings with complete lateral force resisting systems but excessive flexibility in the elements of their lateral force resisting systems have occasionally collapsed. Such buildings can experience very large lateral displacements when subjected to ground shaking. Structures with significant gravity loading can become unstable under large lateral deformation, as a result of P-delta effects.
- Brittle elements: Modem design practice for buildings expected to withstand strong ground shaking requires the incorporation of ductile materials and detailing in the design of structures, such that deformations substantially larger than those expected at normal service levels can be tolerated without loss of structural capacity. Older construction rarely was provided with this ductility. As a result, elements tend to be brittle, and can rapidly loose strength when strained beyond their elastic or nominal capacities. Examples of common non-ductile construction include: unreinforced masonry walls, certain classes of concrete fumes, and reinforced concrete and masonry walls, and some braced steel frame construction.
- Unreinforced masonry walls can be composed of common clay brick, stone, hollow clay tile, adobe, or concrete masonry materials. Walls of these materials have limited strength, and very little ductility for in-plane demands. Slender walls, with large ratios of unsupported length to thickness have often failed due to out of- plane demands. Inadequate anchorage of these walls to diaphragms is a common deficiency which contributes to poor out-of plane performance.
- Non-ductile Concrete Frames. If adequately designed, moment resisting frames of reinforced concrete can provide excellent behaviour in strong earthquake shaking. However, many earthquake induced collapses of structures relying on non-ductile concrete frames for their lateral resistance have occurred. These include deficiencies in: shear capacity, joint shear capacity, placement of reinforcement for load reversals, development of reinforcement, confinement of the concrete and lateral support for reinforcing steel.
- Shear failure of reinforced concrete columns and beams is a brittle failure mode and can result in sudden loss of load carrying capacity and collapse. In frames with adequate strength to remain elastic under real deformation levels, the beams and columns should have greater shear capacity than required at these deformation levels. In frames which experience flexural yielding at the joints under real deformation levels, the shear strength of the elements must be greater than their flexural capacity or failure can result. The shear strength capacity of members with relatively low axial compressive

stress levels should be limited to that provided by the reinforcing steel as the shear strength of the concrete in such members quickly degrades under cyclic loading.

- Shear failure of joints in moment resisting frames can also occur. The beam column joint of a moment resisting frame can be subjected to very large shears, resulting from the transfer of flexural stresses between the elements. Failure has occurred at such joints, particularly when the lateral confinement reinforcement in the columns does not run continuously through the joint zone. Frames with eccentric beam column joints or relatively slender beams tend to be weaker than those without such features. Moment resisting frames subjected to strong ground shaking win typically experience large flexural load reversals at their joints. Some concrete frames designed primarily for gravity load resistance have little if any positive beam reinforcing steel (located at the bottom face of the beam) continuous through the beam column joint. As a result, the frames do not have capacity to resist load reversals.
- Inadequate development of reinforcing steel is another common problem. In frames with inadequate strength to remain elastic at real deformation levels, the flexural reinforcing steel will yield. Repeated cyclic loading of the bars into the yield range results in a breakdown of the bond between the reinforcing steel and concrete, which can result in a loss of flexural strength and frame instability.
- Inadequate Concrete Confinement -Large compressive strains will result in crushing and spalling of the concrete and degradation of the element's capacity to carry load. Strong ground shaking can induce large compressive strains in concrete at flexural hinge regions of beam column joints. When a flexural hinge forms, large tensile strains and elongation will occur in the longitudinal reinforcing steel. When structural response reverses, under cyclic motion, the elongated steel is forced into compression, and if not provided with adequate lateral support:, will buckle. In addition to causing premature spalling of cover concrete, this can lead to low-cycle fatigue failure of the reinforcing and loss of structural capacity.
- Reinforced concrete and masonry walls can have many of the same problems described for reinforced concrete frames, particularly if they are highly perforated by openings, or are tall and slender. Generally, walls with relatively low levels of axial load, moderate quantities of vertical reinforcing steel and shear capacities greater than their flexural capacities behave in a ductile manner, while those without these features can be quite brittle.
- Inadequate diaphragms - Reliance on inadequate diaphragms can be another cause of earthquake-induced collapse. Although the floors and roofs of most structures provide diaphragm capacity, unless the structures were specifically designed to resist seismic loads, these features are often grossly inadequate. Common diaphragm deficiencies in buildings include inadequate shear capacity, inadequate flexural capacity, extreme flexibility, poor connectivity to vertical elements of the lateral force resisting system, and lack of continuity.
- Non-structural elements. Non-structural elements are those pieces of a structure which are not intended by the designer to act as structural load carrying elements. Common non-structural elements include non-load bearing walls, cladding, ceilings, ornamentation, and mechanical and electrical services and utilities.
- Non-load bearing walls including construction of hollow clay tile, concrete masonry, concrete, and other materials are a common problem in structures. Often not directly considered by the original structural designer of the building, these elements can have substantial influence on the performance of a structure. They can alter its stiffness, deformation patterns, lateral force resisting capacity and failure modes.
- Exterior ornamentation on structures including parapets, statuary, balustrades, balconies and similar items can also be problem areas. Often, these decorative elements have limited capacity to resist earthquake induced lateral accelerations. Failure typically results in a falling hazard.
- Mechanical and Electrical Utilities must be maintained in a serviceable condition for structures which are expected to remain functional following an earthquake. Even in less critical facilities, shaking induced damage to these elements can result in substantial consequential damage to architectural elements.
- Poor construction quality has contributed to the earthquake induced failure of many properly designed structures. Masonry structures tend to be particularly vulnerable. A number of failures have occurred in reinforced masonry walls because grout had not been placed in reinforced cells. Poor quality mortar is also common. In concrete structures, .under strength concrete has occasionally resulted in failures. Welded reinforcing steel splices are often quite brittle and can prematurely fail if proper procedures were not followed during construction.
- Deteriorated condition also contributes to earthquake induced failures. Common problems include dry-rot and infestation damage to wood structures, rusting of steel and spalling of concrete on marine structures, and weather deteriorated mortar in masonry structures.

Site characteristics are also too often overlooked by structural engineers with regard to building performance. Unstable sites with propensities for liquefaction, lateral spreading, land sliding or large earthquake induced differential settlements can lead to extensive damage to structures which are otherwise adequately designed. It is critically important to assess the nature and likely stability of the local geotechnical conditions as a first step in the evaluation and retrofit of any Heritage Structures of Cultural importance structure.

4 STRATEGY FOR TESTING AND EVALUATION

Up to very recently, there are no consensus documents defining seismic safety evaluation criteria and provisions with the exception of unreinforced masonry buildings structures. A multiyear two-phase project of the National Earthquake Hazard Reduction Program (NEHRP) which was underway for this purpose came to fruitation in 1997 by publication of the FEMA-273/274 documents. The identification of the design criteria is particularly important. Even if an upgrade is required by an ordinance, it is still important that a clear understanding exists between the engineer and the owner as to what the objectives and the seismic performance of the upgraded building is likely to be. The performance objectives, as stated earlier, are likely to vary considerably from one building to another based on several factors. These factors include: economic value of the structure, occupancy, function of the structure, historic significance, site specific seismic hazard, and the relative cost of achieving upgrades to various criteria. A building-specific design criterion should be established that defines how the designer will accomplish the specified performance objectives. As a minimum the design criteria should address the following issues.

i) Testing program to determine existing materials properties

Existing documentation, including original drawings and specifications, material test reports, and geotechnical reports are likely to be lacking for many buildings being evaluated. Important structural elements may often be concealed, requiring destructive investigations to determine element sizes and locations. The extent, type and location of exploration/testing for each building should be established to determine material properties of the lateral force resisting elements and other structural and non-structural elements that are to be assessed or strengthened to accomplish the performance objectives. The material testing program should provide not only material force capacity data but also deformation capacity data where practical.

ii) Design force levels

A design demand level has to be established, compatible with the performance objectives to be achieved. In selecting a design demand level, one should consider the performance objectives, the importance, the size, and type of lateral force resisting system of the structure, its ability to sustain damage without collapse and the consequences of varying levels of damage, as well as the available resources.

iii) Drift limitations

As has been previously discussed drift control is much more important in the upgrade design of an Heritage Structures of Cultural importance building than in the design of a new building. Hence global and/or element drift control parameters need to be established that will provide adequate assurance that the upgraded building will meet the performance objectives.

iv) Detailing criteria for existing and new elements

Detailing in Heritage Structures of Cultural importance buildings frequently does not meet the requirements of new construction and will therefore perform in a less ductile manner. Consideration for this less than desirable performance needs to be incorporated in the design criteria.

v) Compatibility of new and old construction

The stiffness and strength of existing elements should be compatible with new upgrade elements. Hence deformation and strength criteria that will provide adequate compatibility of old and new elements should therefore be specified.

vi) Construction quality control

Adequate connection of new elements to existing elements is both critical and highly dependent upon existing material properties, sizes, locations and contractor accessibility. The likelihood of encountering unexpected field conditions is much greater in retrofitting Heritage Structures of Cultural importance buildings than in the construction of new buildings. It is therefore important that a quality control program involving frequent inspection, testing, and observation by the design engineer, be established and accepted by the owner.

vii) Criteria for non-structural elements

Adequate performance of certain non-structural elements may be required to ensure performance objectives are achieved. Non structural elements such as hollow clay tile partition walls around exit corridors, heavy ornamentation, light fixtures, building cladding, etc. may require supplemental anchorage reinforcement or other upgrade measures may provide for adequate life-safety.

5 SUMMARY

The important Heritage Structures of Cultural importance structures selected for seismic safety evaluation should be investigated of it's structural characteristics by Push Over analysis or any established performance based analysis considering inelastic and non-linear behaviour of the structure. The significant structural deficiencies (global and local both) should be identified keeping in view of the economy, functional and architectural requirement of the structure.

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