Handbook for Seismic Rehabilitation of Existing Buildings

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ABSTRRACT

Advances in earthquake-related technology during the past few decades have led to a realization that seismic risk to life and property can be reduced significantly by improving seismic performance of existing seismically deficient buildings. Detailed post-earthquake investigations of building failures have provided engineers with considerable information concerning the details of building design and construction that enhance earthquake resistance. Since the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake, a large number of research programs for the development of seismic rehabilitation methods have been carried out in the United States. This paper presents the scope of a seismic rehabilitation handbook being developed by the Interagency Committee on Seismic Safety in Construction for use by U.S. federal government agencies.

KEYWORDS: buildings, earthquake, rehabilitation, seismic engineering, structures

1.0 INTRODUCTION

One of the objectives of the *Earthquake Hazards Reduction Act of 1977* (P.L. 95-124 as amended) is ". . . the development of methods for rehabilitation and utilization of man-made works so as to effectively resist the hazards imposed by earthquakes . . . ." In response to Public Law 101-614, which requires the President to adopt "standards for assessing and enhancing the seismic safety of existing buildings constructed for or leased by the federal government which were designed and constructed without adequate seismic design and construction," President issued Executive order 12941 in December 1994 requiring federal government agencies to reduce seismic risk of those structures which pose risk in terms of occupancy and potential secondary impact.

Since 1984, the Federal Emergency Management Agency (FEMA, now part of the Department of Homeland Security) published a series of earthquake-related documents including: FEMA 310 *Handbook for the Seismic Evaluation of Buildings* (FEMA 1998) and FEMA 356 *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (FEMA 2000). These two documents have either gone through or being processed as *Standards* of the American Society of Civil Engineers (ASCE). This document (*Handbook*), as a companion to these two documents, will guide design professionals seismic rehabilitation techniques for various types of buildings. The techniques are based on input from a group of experts involved in seismic rehabilitation and on a review of existing literature published through 2003.

The handbook is divided into three parts. Part 1 provides background on seismic evaluation, categories of seismic deficiencies, classes of rehabilitation techniques, and general strategies to develop rehabilitation schemes. Part 2 includes detailed description of seismic deficiencies that are characteristic of each FEMA model building type (FEMA 1998) and techniques commonly used to mitigate seismic deficiencies. Part 3 includes seismic rehabilitation techniques not necessarily related to a specific building type such as those related to diaphragms, foundations, and nonstructural components. Part 3 also includes global techniques that seismic isolation or addition of damping.

2.0 SEISMIC VULNERABILITY

The vulnerability of a building subjected to an earthquake is dependent on seismic deficiency of that building relative to a required performance objective. The seismic deficiency is defined as a condition that will prevent a building from meeting the required performance objective. Thus, a building evaluated to provide full occupancy immediately after an event may have significantly more deficiencies than the same building evaluated to prevent collapse.

Depending on the vulnerability assessment, a building can be condemned and demolished, rehabilitated to increase its capacity, or modified so that the seismic demand on the building can be reduced. Thus, structural rehabilitation of a building can be accomplished in a variety of ways, each with specific merits and limitations related to improving seismic deficiencies.

3.0 COMMON SEISMIC DEFICIENCIES

Regardless of the evaluation method used, failure to meet the stipulated performance objective implies certain seismic deficiencies. These deficiencies are described below:

3.1 Global Strength

Global strength typically refers to the lateral strength of the vertically oriented lateral force-resisting system. For degrading structural systems characterized by a negative post yield slope on the pushover curve, a minimum strength requirement may apply. In certain cases, the strength will also affect the total expected inelastic displacement and added strength may reduce nonlinear demands into acceptable ranges.

A deficiency in global strength is common in older buildings either due to a complete lack of seismic design or a design to an early building code with inadequate strength requirements.

If prescriptive equivalent lateral force methods or linear static procedures have been used for evaluation, inadequate strength will directly relate to unacceptable demand-to-capacity ratios within elements of the lateral force-resisting system.

3.2 Global Stiffness

Global stiffness refers to the stiffness of the entire lateral force-resisting system although the lack of stiffness may not be critical at all levels. For example, in buildings with narrow walls, critical drift levels occur in the upper floors. Conversely, critical drifts most often occur in the lowest levels in frame buildings. Stiffness must be added in such a way that drifts are efficiently reduced in the critical levels.

Although strength and stiffness are often controlled by the same existing elements or the same retrofit techniques, the two deficiencies are typically considered separately. Failure to meet evaluation standards is often the result of a building placing excess drift demands on existing poorly detailed components.

3.3 Configuration

This deficiency category covers configuration irregularities that adversely affect performance. In codes for new buildings, these configuration features are often divided into plan irregularities and vertical irregularities. Plan irregularities are features that may place extraordinary demands on elements due to torsional response or the shape of the diaphragm. Vertical irregularities are created by uneven vertical distribution of mass or stiffness between floors that may result in concentration of force or displacement at certain levels. In older existing buildings, such irregularities are seldom taken into consideration in the original design and, therefore, normally require rehabilitation measures to mitigate.

3.4 Load Path

A discontinuity in the load path, or inadequate strength in the load path, may be considered overarching because this deficiency will prevent the positive attributes of the seismic system from being effective. The load path is typically considered to extend from each mass in the building to the supporting soil. For example, for a panel of cladding, this path would include its connection to the supporting floor or floors, the diaphragm and collectors that deliver the load to components of the primary lateral force resisting system (walls, braces, frames, etc.), continuity of these components to the foundation, and finally the transfer of loads between foundation and soil.

Many load path deficiencies are difficult to categorize because the strength deficiency may be considered to be part of another element. For example, an inadequate construction joint in a shear wall could be considered a load path deficiency or a shear wall deficiency in the category of global strength.

3.5 Inadequate Component Detailing

Detailing, in this context, refers to design decisions that affect a component's or system's behavior beyond the strength determined by nominal demand, often in the nonlinear range. An example of a detailing deficiency is poor confinement in concrete gravity columns. Often in older concrete buildings, the expected drifts from the design event will exceed the deformation capacity of such columns, potentially leading to degradation and collapse. Although the primary gravity load design is adequate, the post elastic behavior is not, most often due to inadequate configuration and spacing of ties.

Identification of detailing deficiencies is significant in selection of mitigation strategies because acceptable performance often may be achieved by local adjustment of detailing rather than by adding new lateral force-resisting elements. In the case of gravity concrete columns, acceptable performance can be achieved by enhancing deformation capacity by adding confinement rather than by reducing global deformation demand by adding lateral force-resisting elements.

3.6 Diaphragm Deficiencies

The primary purpose of diaphragms in the overall seismic system is to act as a horizontal beam spanning between lateral force-resisting elements. Diaphragm deficiencies include such factors as inadequate shear or bending strength, stiffness, or reinforcing around openings or reentrant corners. Inadequate local shear transfer to lateral force-resisting elements or missing or inadequate collectors are categorized as load path deficiencies.

3.7 Foundation Deficiencies

Foundation deficiencies can occur within the foundation element itself, or due to inadequate transfer mechanisms between foundation and soil. Element deficiencies include inadequate bending or shear strength of spread foundations and grade beams, inadequate axial capacity or detailing of piles and piers, and weak and degrading connections between piles, piers and caps. Transfer deficiencies include excessive settlement or bearing failure, excessive rotation, inadequate tension capacity of deep foundations, or loss of bearing capacity due to liquefaction.

3.8 Other Deficiencies

Deficiencies that do not fit into one of the categories described above may include:

- Geologic hazards
- Adjacent buildings
- Deteriorated structural materials

4.0 STRATEGIES FOR REHABILITATION SCHEMES

4.1 Technical Considerations

Selected techniques must eliminate deficiencies, preferably more than one deficiency. First one should consider enhancing existing elements such as shear walls, moment frames, and bracing frames. The deformation compatibility between new elements and existing elements must be considered. In some cases, the application of base isolators or damping devices is the most efficient way to eliminate deficiencies.

4.2 Non-technical Considerations

The solution chosen for rehabilitation is almost always dictated by building-user oriented issues rather than by merely satisfying technical demands. There are five basic issues that are of concern to building owners or users:

1. Construction cost,
2. Seismic performance,
3. Short term disruption of occupants,
4. Effects on long-term functionality of building, and
5. Aesthetics, including consideration of historic preservation.

All of these characteristics are always considered, but an importance will eventually be put on each of them, either consciously or subconsciously, and a combination of weighting factors will determine the scheme chosen.

4.3 Cost

Construction cost is always important and is balanced against one or more other considerations deemed significant. However, sometimes other economic considerations, such as the cost of disruption to building users, or the value of contents to be seismically protected, can be orders-of-magnitude larger than construction costs. Thus, cost may be the only criterion applied when choosing among equivalent rehabilitation options.

4.4 Seismic Performance

Prior to the emphasis on performance based design, perceived qualitative differences between the probable performance of difference schemes would be used to assist in choosing a scheme. Specific performance objectives are often set prior to the development of schemes. Objectives that require a limited amount of damage or "continued occupancy" will severely limit the retrofit methods that can be used and may control the other issues.

4.5 Short-term Disruption of Occupants

When seismic rehabilitation is done at the time of major building remodeling, disruption issue is minimized. However, in cases where the building is partially or completely occupied, this parameter commonly becomes dominant and controls the design.

4.6 Effects on Long-term Functionality of Building

This characteristic is often judged less important than others. The planning flexibility is only subtlety changed. However, it can be significant in building occupancies that need open spaces such as retail spaces and parking garages.

4.7 Aesthetics

In historic buildings, considerations of preservation of historic fabric usually control the design. Performance objectives are controlled by limitations imposed by preservation. In non-historic buildings, aesthetics is commonly stated as a criterion, but is often sacrificed, particularly in favor of minimizing cost and disruption to tenants.

5.0 REHABILITATION TECHNIQUES

Different building types require different mitigation techniques for a specific seismic deficiency. Depend on building types and associated seismic deficiencies, alternative recommendations are made to satisfy the performance objective of rehabilitation.

5.1 Building Types

Rehabilitation techniques are being developed for 17 common building types, which are defined in the FEMA documents. They are:

- *Wood light-frames*
  One- and two-detached dwellings of one or more stories in height.

- *Multi-story, multi-unit residential wood frames*
  Large residential buildings with commercial space at the ground floor.

- *Steel moment frames*
  Buildings consist of steel beams and columns, and lateral forces are resisted by moment frames.

- *Steel braced frames*
  Buildings consist of frame assemblies of steel beams and columns. Lateral forces are resisted by diagonal steel members placed in selected bays.

- *Steel frames with infill masonry shear walls*
  Buildings are normally older buildings that consist of gravity frames with unreinforced masonry, tightly infilling the space between columns.

- *Concrete moment frames*
  A complete system of concrete beams and columns. Lateral loads are resisted by cast-in-place moment frames.

- *Concrete shear wall buildings (Bearing wall systems)*
  Usually all concrete with flat slab or precast plank floors and concrete bearing walls. Little, if any, of the gravity loads are resisted by beams and columns. Lateral loads are resisted by shear walls.

- *Concrete shear wall buildings (Gravity frame systems)*
  Buildings have columns and beams or columns and slabs that essentially carries all gravity loads. Lateral loads are resisted by concrete shear walls surrounding shafts, at the building perimeter, or isolated walls placed specifically for lateral resistance.

- *Concrete frames with infill masonry shear walls*
  Buildings are normally older buildings that consist of essentially complete gravity frame assemblies of concrete columns and floor systems. The floors can be of a variety of concrete systems including flat plates, two way slabs, and beam and slab. Exterior walls are constructed of unreinforced masonry, tightly infilling the space between columns horizontally and between floor structural elements vertically, such that the infill interacts with the frame to form a lateral force resisting system.

- *Tilt-up concrete shear wall buildings*
  Buildings are constructed with perimeter concrete walls cast on the site and tilted up to form the exterior of the building. The majority of these buildings are one

story with wood roof framing; however, a good number of multi-story buildings also exist with composite deck floors and a wood or steel framed roof.

- *Precast concrete frames with shear walls*
  Buildings consist of concrete columns, girders, beams and/or slabs that are precast off the site and erected to form a complete gravity load system. This building type has a lateral force-resisting system of concrete shear walls, cast-in-place or precast. In California, precast floor T-beams or hollow core planks are covered by a cast-in-place topping slab, reinforced to provide diaphragm action. In other areas, methods of joining floor sections vary, and include use of welded insert plates.

- *Reinforced masonry bearing wall buildings*
  (Similar to tilt-up concrete shear wall buildings)
  Building are constructed with reinforced masonry (brick cavity wall or concrete masonry unit) perimeter walls with a wood or metal deck flexible diaphragm.

- *Reinforced masonry bearing wall buildings*
  (Similar to unreinforced masonry bearing wall buildings)
  Buildings are multistory, and typically has interior concrete masonry unit walls and shorter diaphragm spans.

- *Reinforced masonry bearing wall buildings*
  (Similar to concrete shear wall buildings with bearing walls)
  Building consist of reinforced masonry walls and concrete slab floors that may be either cast-in-place or precast. This building type is often used for hotel and motels and is similar to the concrete bearing wall type**.**

- *Unreinforced masonry bearing wall buildings*
  Buildings consist of unreinforced masonry bearing walls, usually at the perimeter and usually brick masonry. The floors are typically of wood joists and wood sheathing supported on the walls and on interior post and beam construction.

5.2 Rehabilitation techniques

For each of 8 categories of deficiencies described in 3.0, rehabilitations methods are recommended for the following five categories of techniques as appropriate:

- Add new elements,
- Enhance existing elements,
- Improve connections between elements,
- Reduce demand, and
- Removal deficient elements.

6.0 REHABILITATION TECHNIQUES NOT RELATED TO SPECIFIC BUILDING TYPES

Seismic rehabilitation techniques (1) not necessarily related to a specific building type such as those related to diaphragms, foundations, and nonstructural components, and (2) significant global techniques that could be applied to any building, such as seismic isolation or addition of damping are included in this category.

7.0 CONCLUDING REMARKS

A handbook of techniques for seismic rehabilitation of existing buildings is being developed by the Interagency Committee on

Seismic Safety in Construction. This handbook will be a companion publication to related publication on the seismic evaluation of existing buildings published by the Federal Emergency Management Agency, namely FEMA 310 (the NEHRP seismic evaluation handbook) and FEMA 356 (the NEHRP seismic rehabilitation handbook).

At the present time, there is a variety of approaches to seismic rehabilitation, each with specific merits and limitations. This handbook will serve as a guidance document for Federal government agencies involved in seismic rehabilitation. This handbook will provide:

- A general understanding of the common deficiencies in the structural and nonstructural elements that cause seismic performance problems, and

- Recommended techniques that might be used to correct deficiencies for various building types.

8.0 REFERENCES

FEMA 1998, *FEMA 310 Handbook for the Seismic Evaluation of Buildings – A Prestandard*, Federal Emergency Management Agency, Washington, D.C. January.

FEMA 2000, *FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, Federal Emergency Management Agency, Washington, D.C. November.