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Review of Documents on Seismic Strengthening of Existing Buildings

by

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1. GENERAL

A higher degree of damage in a building is expected during an earthquake if the seismic resistance of the building is inadequate. The decision to strengthen it before an earthquake occurs depends on the building's seismic resistance. The seismic evaluation procedure discussed earlier (IITK-GSDMA-EQ03-V1.0), gives a measure of the seismic resistance of the structure. The structural system of deficient building should be adequately strengthened in order to attain the desired level of seismic resistance. The term *strengthening* comprises technical interventions in the structural system of a building that improves its seismic resistance by increasing the strength, stiffness and/or ductility.

2. REVIEWED SEISMIC STRENGTHENING DOCUMENTS

The following documents on the strengthening of existing buildings, to increase its seismic resistance, are studied:

1. FEMA 273 – NEHRP Guidelines for the Seismic Rehabilitation of Buildings
2. New Zealand Draft Code [NZDC]– The Assessment and Improvement of the Structural Performance of Earthquake Risk Buildings
3. SERC Report – Formulation of Guidelines for Assessment of Strength and Performance of Existing Buildings and Recommendations on Retrofitting Schemes to Ensure Resistance to Earthquake
4. UNIDO Vol. 4 – Post-Earthquake Damage Evaluation and Strength Assessment of Buildings under Seismic Conditions
5. Euro Code 8 – Design Provisions for Earthquake Resistance of Structures – Part 1-4 General Rules for Strengthening and Repair of Buildings

3. KEY CONCEPTS OF SEISMIC STRENGTHENING

As a first step towards the process of seismic strengthening, the basic construction characteristics and earthquake resistive capacity of the existing building is determined. The performance objectives for rehabilitation are decided and the corresponding seismic hazard level is determined.

A brief explanation of the key strengthening strategies and its provisions in different documents is discussed below.

3.1 Local Modification of Components

A few components (such as beams, columns, connections, shear walls, diaphragms, etc.) in an existing building may not have adequate strength or deformation capacity, though the building in whole may have substantial strength and stiffness. For such components, local modifications can be performed, while retaining the basic configuration of the building's lateral force resisting system. The local modifications considered are component connectivity, their strength, and/or deformation capacity.

FEMA 273 and NZDC explain that the component is allowed to resist large deformation levels without failure by improving the deformation capacity or ductility of the component, without necessarily increasing the strength. For example, placement of a jacket around a reinforced concrete column to improve its confinement increases its ability to deform without spalling or degrading reinforcement splices. As per FEMA 273, the cross section of selected structural components can be reduced to increase their flexibility and response displacement capacity. According to Eurocode 8, local or overall modification of damaged or undamaged elements (repair or strengthening) can be done, considering their stiffness, strength and/or ductility. It also suggests full replacement of inadequate or heavily damaged elements. Structural rehabilitation, as defined in UNIDO manual, may also consist of a modification of the existing structural members so that their individual strength and/or ductility are improved. As a result, the respective characteristics of the structure are influenced (e.g., jacketing of the columns), even though the overall structural scheme is unmodified.

3.2 Removal or Lessening of Existing Irregularities and Discontinuities

Irregularities of strength, stiffness and mass have major contribution in unsatisfactory earthquake performance. Distribution of uneven structural displacements, with large concentrations of high values within one storey or at one side of a building, indicates the presence of an irregularity. Asymmetrical plan distribution of resisting members, abrupt changes of stiffness from one floor to the other, concentration of large masses, large openings in walls without a proper peripheral reinforcement are further examples of such irregularities. Such features that are sources of weakness or that produce concentrations of stresses in some members should be eliminated.

FEMA 273 and NZDC provide some corrective measure for removing such irregularities. As per these documents, irregularities such as soft or weak stories can be removed by addition of braced frames or shear walls, while torsional irregularities can be removed by addition of moment frames, braced frames or shear walls to balance the distribution of stiffness and mass within a storey. Components such as columns or walls which abruptly end at certain floors can be extended through the zone of discontinuity for smooth transfer of forces to the foundation. An irregular building can be transformed into a number of simple regular structures by isolating them through the provision of movement joints. However, this should be done with due consideration to problems associated with the provision of insufficient gap, which can lead to damage due to pounding. Eurocode 8 states the modification of the structural system, like elimination of some structural joints, elimination of vulnerable elements, and modification into more regular and/or more ductile arrangements.

3.3 Global Structural Stiffening and Strengthening

Large lateral deformations induced in the structure due to ground shaking, impose high ductility demand on the components of the structure. Also flexible structures with components having inadequate ductility behave poorly. It is essential that such structures be stiffened at a global level.

FEMA 273 and NZDC propose the addition of new braced frames or shear walls within an existing structure for increasing the stiffness. While some existing structures have inadequate strength, which result into inelastic behaviour at very, low levels of earthquake forces and cause large inelastic deformation demands throughout the structure. By strengthening the structure, the threshold of lateral force at which the damage initiates, can be increased. Moment resisting frames can be provided as they are more flexible and add strength to the structure without significantly increasing its stiffness, as per these two documents. Eurocode 8 suggests addition of new structural elements like bracings or infill walls; steel, timber or reinforced concrete belts in masonry construction; etc. or addition of a new structural system to take the seismic action.

As per UNIDO manual, strengthening of whole structure can be undertaken to improve its lateral force resistance, stiffness and ductility. This can be achieved through the addition of new structural members to increase the respective characteristics of the structure, like bracing in a frame or skeleton structure or new shear walls in a shear wall structure in order to reduce the eccentricity of the masses. A new lateral force resistant structure can be introduced to act integrally with the existing system to resist seismic forces (e.g., stiff shear walls introduced in a flexible frame or skeleton structure). Such an intervention produces significant changes of the stress distribution in the structure as well as in the structural layout. FEMA 273 and Eurocode 8 also suggest mass reduction of the structural system, wherever possible.

3.4 Base Isolation

An overall advantage of base isolation is reduction in demands on the elements of the structure. This technique is most effective for relatively stiff low rise buildings with large mass compared to light, flexible structures. However, base isolation is technically complex and costly to implement and can be considered for historic structures or where a performance level greater than life safety is required. FEMA 273, NZDC and Eurocode 8 propose base isolation as an option for seismic rehabilitation. However, they generally refer to specialist literature for details of analysis and design.

3.5 Supplemental Energy Dissipation

Energy dissipation helps in the overall reduction in displacements of the structure. This technique is most effective in structures that are relatively flexible and have some inelastic deformation capacity and can be less costly compared to base isolation. As per FEMA 273 and NZDC devices such as hydraulic cylinders, yielding plates, or friction pads, can be used for energy dissipation. According to Eurocode 8, addition of local friction, global damping devices or active control at appropriate locations of the building can be done. Design of strengthening scheme using energy dissipation devices are very sensitive to characteristics of devices used and therefore, require a higher degree of sophistication in the analysis and design.

4. GENERAL STRENGTHENING TECHNIQUES

A strengthening scheme consists of one/many strengthening techniques to remedy structural deficiency. Such schemes are specific to structural system and material type. Following is a brief description of major techniques that are used for reinforced concrete and masonry buildings.

4.1 Reinforced Concrete

The provisions in different documents for the strengthening of reinforced concrete elements is as discussed below:

4.1.1 FEMA 273

The rehabilitation measures as given in this document are as follows:

4.1.1.1 **Concrete Moment Frames**

(a) Jacketing existing beams, columns, or joints with new reinforced concrete, steel, or fiber wrap overlays.

(b) Post-tensioning existing beams, columns, or joints using external post-tensioned reinforcement.

(c) Modification of the element by selective material removal from the existing element.

(d) Improvement of deficient existing reinforcement details.

(e) Changing the building system to reduce the demands on the existing element.

(f) Changing the frame element to a shear wall, infilled frame, or braced frame element by addition of new material.

(g) Strengthening of individual diaphragm components by addition of additional reinforcement and encasement.

(h) Increasing the diaphragm thickness.

(i) Reducing the demand by adding lateral-force-resisting elements, introducing additional damping, or base isolating the structure.

4.1.1.2 **Rehabilitation Measures for Shallow Foundations**

(a) Enlarging the existing footing by lateral additions.

(b) Underpinning the footing.

(c) Providing tension hold-downs.

(d) Increasing effective depth of footing.

(e) Increasing the effective depth of a concrete mat foundation with a reinforced concrete overlay.

(f) Providing pile supports for concrete footings or mat foundations.

(g) Changing the building structure to reduce the demand on the existing elements.

(h) Adding new grade beams.

(i) Improving existing soil.

4.1.1.3 **Rehabilitation Measures for Deep Foundations**

(a) Providing additional piles or piers.

(b) Increasing the effective depth of the pile cap.

(c) Improving soil adjacent to existing pile cap.

(d) Increasing passive pressure bearing area of pile cap.

(e) Changing the building system to reduce the demands on the existing elements.

(f) Adding batter piles or piers.

(g) Increasing tension tie capacity from pile or pier to superstructure.

4.1.2 New Zealand Draft Code

Typical retrofit methods involve adding new structural components to the existing structure, such as movement restrainers, walls, steel bracing, and jacketing.

4.1.2.1 **Retrofitting of Columns**

(a) Providing jackets of new concrete containing longitudinal and transverse reinforcing, grouted site welded elliptical thin steel jackets filled with concrete, grouted stiffened or built-up rectangular steel jackets, grouted composite fiberglass/epoxy jackets, or prestressing steel wrapped under tension.

(b) Providing only additional transverse reinforcement for concrete confinement, restraint against buckling of existing longitudinal bars, shear resistance and restraint against bond failure of lap splices of longitudinal reinforcement.

(c) Using thin steel jackets for providing additional transverse reinforcement, without additional longitudinal reinforcement.

4.1.2.2 **Retrofitting of Beam-Column Joints**

(a) Retrofitting by jacketing, using either external steel jacketing or jacketing with new reinforced concrete.

4.1.2.3 **Retrofitting of Footings**

(a) Placing an overlay of reinforced concrete, dowelled to the existing footing.

(b) Addition of a new widened portion to the footing or additional piling and placing a new footing surrounded to it.

(c) Strengthening the foundation soil by grouting or consolidation.

4.1.3 SERC Report

Strengthening of RC members could be done in the following ways:

4.1.3.1 **RC Members**

(a) Strengthening of RC columns by jacketing, and by providing additional cage of longitudinal and lateral tie reinforcement around the columns and casting a concrete ring.

(b) In case of jacketing a reinforced concrete beam, stirrup can be held by drilling holes through the slab.

(c) Strengthening of RC shear walls can be done in the same manner.

(d) Strengthening inadequate sections of RC column and beams by removing the cover to old steel, welding new steel to old steel and replacing the cover.

(e) Strengthening RC beams by applying prestress.

4.1.3.2 **Strengthening of Foundations**

(a) Introducing new load bearing members including foundations to relieve the already loaded members.

(b) Improving the drainage of the area to prevent soaking of foundation directly and draining off the water.

(c) Providing apron around the building to prevent soaking of foundation directly and draining off the water.

(d) Adding strong elements in the form of reinforced concrete strips attached to the existing foundation part of the building.

4.1.4 Eurocode 8

The type of intervention include:

(a) Injection of cracks.

(b) Local replacement of damaged concrete and steel.

(c) Using thin steel plates for flexural or shear strengthening of reinforced concrete slabs or beams.

(d) Confinement of reinforced concrete element (mainly of columns) by means of collars, spirals, packing-bands, etc.

(e) Providing additional reinforced concrete layers for flexural or shear strengthening of beams.

(f) Providing infills in the frames.

(g) Providing reinforced concrete jackets on columns.

4.2 Masonry

Strengthening of masonry elements can be done in the following ways:

4.2.1 FEMA 273

Enhancement of masonry walls and infills can be done as follows:

4.2.1.1 **Masonry Walls**

(a) Infilled Openings

(b) Enlarged Openings

(c) Shotcrete

(d) Coatings for URM Walls

(e) Reinforced Cores for URM Walls

(f) Prestressed Cores for URM Walls

(g) Grout Injections

(h) Re-pointing

(i) Braced Masonry Walls

(j) Stiffening Elements

4.2.1.2 **Masonry Infills**

In addition to above techniques, the following two enhancement methods shall also apply to masonry infill panels.

(a) Boundary Restraints for Infill Panels

(b) Joints Around Infill Panels

4.2.1.3 **Masonry Foundation Elements**

(a) Injection grouting of stone foundations

(b) Reinforcing of URM foundations

(c) Prestressing of masonry foundations

(d) Enlargement of footings by placement of reinforced shotcrete

(e) Enlargement of footings with additional reinforced concrete sections

4.2.2 SERC Report

(a) Repairing cracks by injection of cement/epoxy grout depending on the thickness.

(b) For load bearing elements, introducing vertical and horizontal reinforcing bands with a check that all gravity loading is carried through vertical reinforcing band.

4.2.3 Eurocode 8

The types of intervention on masonry buildings are as follows:

(a) Reduction of the mass, particularly at high levels, e.g., by removal of heavy roof covering, heavy canopies and parapets, etc.

(b) Reduction of the eccentricity between the mass and the stiffness centers, to avoid large torsional effects, especially in buildings with strong diaphragmatic action of the floor.

(c) Addition of new bracing walls

(d) Improvement of the connections between the resisting elements, (e.g. tying of intersecting walls, tying of opposite parallel walls, proper anchorage of the horizontal diaphragms in the vertical bearing elements, etc.)

(e) Improvement of the diaphragmatic action of the floors by increasing their in-plane shear stiffness and resistance

(f) Improvement of the quality of the masonry (e.g. by grouting). Due consideration should be given to the subsequent increase of stiffness and decrease of damping.

(g) Repair of cracked walls.

(h) Application of vertical and horizontal confining elements to the walls.

(i) Application of transversal confinement to the edges of masonry piers.

(j) Strengthening and stiffening of horizontal diaphragms.

(k) Strengthening of buildings by means of steel ties.

(l) Strengthening of walls by means of reinforced concrete "jackets" or steel profiles.

(m) Repair or strengthening of foundations.

5. CONCLUDING REMARKS

A detailed seismic evaluation of structural system of existing building needs to be performed to determine the nature and extent of deficiencies, which can cause poor performance in future earthquakes. This evaluation also helps to decide whether structural modifications are required at few locations in the structure for deficient components only or interventions are needed at the structure level so that its global behavior is improved and thus seismic demands on components are reduced. The success of strengthening scheme is very much dependent on the choice of strengthening techniques, which are very specific to structural type and materials of construction. Further, the design and analysis of such schemes/techniques are quite complex and require a great level of sophistication than ordinarily required for new components/elements. All documents of structural strengthening such as FEMA 273, NZDC, Eurocode 8, etc. provide a general framework of rehabilitation process and do not provide much specific design/detailing procedure. However, a few of them provide code like provisions for commonly used techniques such as column jacketing, addition of shear wall, braced frame, etc.

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REFERENCES

BIA (1996), "The Assessment and Improvement of the Structural Performance of Earthquake Risk Buildings – Draft for General Release", New Zealand National Society for Earthquake Engineering

CEN (2001), "Eurocode 8 – Design Provisions for Earthquake Resistance of Structures – Part 3", Brussels

FEMA (1997), "FEMA 273 – NEHRP Guidelines for the Seismic Rehabilitation of Buildings", Federal Emergency Management Agency, Washington DC, USA

SERC (2002), "Formulation of Guidelines for Assessment of Strength and Performance of Existing Buildings and Recommendations on Retrofitting Schemes to Ensure Resistance to Earthquakes", Structural Engineering Research Centre, September 2002, Madras

UNDP/UNIDO (1985), "Post-Earthquake Damage Evaluation and Strength Assessment of Buildings under Seismic Conditions", Volume 4, Vienna