Retrofitting of Flat Slab Building Members Undergone Damage by Earthquake Forces

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Abstract

Beamless slabs (“flat slabs”, called flat plates in North America if they are supported on columns directly without drop panels or column capitals) provide larger clear storey height, unobstructed passage of services under the slab, aesthetic look and freedom for irregular layouts of column grid and for potential modifications of the layout of partitions. Moreover, if labour is expensive, they may be cost effective for residential and office buildings. In spite of all these advantages, flat slabs often fail against consecutive cyclic loading caused by seismicity for not having adequate moment transfer capacity of connections which is available in normal beam-column concrete moment resisting buildings. Punching failure at slab column connections in non ductile flat slab buildings during earthquake can trigger progressive collapse of floor slab. The relatively poor performance of flat slab buildings during recent major earthquakes all over the world has renewed interest in evaluating their seismic resistance and in investigating necessary retrofit techniques for improving their performance. This paper aims at discussing several such retrofit techniques to protect flat slab building members from earthquake hazards.

Keywords: Flat slab, Retrofitting, Seismic resistance, Shear wall, CFRP, Infil wall, Damper.

Introduction

Flat slab buildings are designed and detailed for gravity loads only do not typically have the ability to resist moderate earthquakes without experiencing severe damage. The damage potential of such seismically deficient buildings therefore needs to be assessed and strategies developed to improve their seismic resistance. Frame analysis procedure is one of them which utilizes the equivalent frame concept to envelop both moment transfer capacity as well as stiffness for the interior and exterior slab-column connections. Building reliability tests were performed in US using this analysis procedure and study discovered that flat slab buildings constructed prior to 1960’s could experience significant damage during moderate intensity earthquakes [1]. Limitation of gravity load on floor slabs by controlling the lateral drift can be a short period solution, but highrise buildings often demand beamless construction for aesthetics which nullifies the mentioned case [2]. For high rise buildings, retrofitication of interior columns, utilization of infill and shear walls, improvising the connections, provision of column capital are some of the methods to augment the shock absorbing capacity of flat slab buildings against lateral loads [2].

Flat slab design follows ACI code 318-99 for concrete frame design and Bangladesh National Building Code has specified article 6.5 for unified design of flat slabs, flat plates and edge supported slabs. In case of flat slabs, structure is divided longitudinally and transversely into frames consisting of columns and strips of slab. The width of slab used to define the effective stiffness of the slab depends upon the aspect ratio of the panels and type of loading. In the case of vertical loading, stiffness of the rectangular panels may be calculated by taking into account the full width of panel and for horizontal loading those are taken half the value. Thus, after dividing the slab into frames, analysis is performed and frame stiffness is calculated [3].
Studies on Behavior of Flat Slabs

Research data on seismic resistance of slab column connections and on the modeling for seismic response analysis of older flat slab buildings is rather limited. Several analytical methods including finite element method, equivalent frame method have been used for analyzing flat slab buildings subjected to static gravity and lateral loads. Direct application of these procedures to evaluate the seismic response of existing flat slab building is inappropriate. Effective beam width model and equivalent column model were developed to predict the stiffness of flat slabs under lateral loads. The hysteretic response and moment transfer capacity of the slab-column connections under combined gravity and seismic loads are not considered in these models.

Other models such as the eccentric shear stress model and the beam analogy model have been developed to predict the shear and flexural strength of connections. The separate treatment of strength and stiffness however is not appropriate for predicting the seismic response of flat slab buildings. Seismic analysis requires that the strength, stiffness, non linearity of the response and the hysteretic behavior should all be included in the analytical model [4].

In order to develop economical and effective retrofit strategies for improving the safety of seismically deficient flat slab buildings the risk of punching failure of connections and the potential for collapse need to be investigated first. Fragility data can be generated from: (a) actual earthquake data, (b) probabilistic analysis and (c) engineering judgement [1]. Actual earthquake observations provide highly reliable, but very limited data. Engineering judgement is an economic way to construct fragility data, but the result is usually sensitive to subjective judgement. Probabilistic analysis uses advanced reliability analysis methods where the randomness and uncertainties of earthquakes and structures can be taken into account. Sues et al. and Hwang and have performed the seismic fragility [1]. Based on the seismic reliability analysis for concrete moment resisting frames, economical and practical retrofitting schemes can be developed to improve the serviceability of the flat slab buildings during strong and medium earthquake [3].

In Bangladesh, a few studies have been performed too. Shear walls, masonry infils or a bracing system can be employed to improve the lateral stiffness. The addition of shear wall, however may not be practical or economically attractive. But due to lack of knowledge about better technology, shear walls are used all over the country.

A study conducted on flat slabs by research engineer of Housing and Building Research Institute, Bangladesh specifically showed the behavior of beam supported slabs against flat slabs under the combined action of gravity and lateral load [5]. Pushover analysis was performed (a static, nonlinear procedure to determine seismic structural deformations) on several eight, ten and twelve storied building having two different types of slabs: flat slab and beam supported slab which were constructed according to BNBC 1993 and lateral loading according to UBC 97. Results of the pushover analysis concluded the fact beyond dispute that beam supported buildings are quite efficient in handling seismic loads against flat slabs. Results of eight and ten storied buildings are shown in tabular format in figure and table section.

We can classify the retrofitting techniques used in different countries accordingly [6].

![Figure 1: Some common techniques for retrofitting flat slab buildings](image-url)
• Adding new shear walls are frequently used for retrofitting of non ductile reinforced concrete frame buildings. These elements can be either cast in place or precast concrete elements. New elements preferably be placed at the exterior of building but not in the interiors mouldings.

• Adding steel bracing is an effective solution in flat slab buildings when large openings are required. It has potential advantage of higher strength and stiffness, ventilation, less amount of cost, work and less self weight of structure.

• Local retrofitting techniques as such jacketing are used for strengthening of columns. Several of them are: steel jacket, Reinforced concrete jacket, Fiber reinforced polymer jacket. Jackets can be used to increase concrete confinement, increase shear strength and increasing flexural strength.

• In recent days, research on advanced materials has mainly concentrated on FRP composites. Studies have shown that externally bonded FRP composites can be applied to beamless structures in order to improve their structural performance such as stiffness, load carrying capacity and ductility.

• Base Isolation is another technique for passive structural vibration control.

Significantly increasing the period of structure and damping so that the response is significantly reduced. Base isolation mainly includes elastometric bearings and sliding system.

• Elastometric base isolators are most widely used base isolators, which are made of natural rubber or neoprene. The structure is decoupled from the horizontal components of the earthquake ground motion-a layer with low horizontal stiffness is introduced between the structure and the foundation. Sliding base isolation systems are second basic type isolators. This works by limiting base shear across isolator interface. Advantages of base isolation includes: isolation of buildings from ground motion, buildings can remain serviceable throughout construction, does not involve major intrusion upon existing superstructure.

• Seismic dampers are also used in place of structural elements, like diagonal braces, for controlling seismic damage in structures. It partly absorbs the seismic energy and reduces the motion of buildings. Three types of dampers are used: Viscous damper, friction damper and yielding damper. Tuned mass dampers are also used in several countries.

Table 1: Difference of lateral load handling capacity between several flat slab and beam supported eight storied building

<table>
<thead>
<tr>
<th>Plan Dimension</th>
<th>Beam Supported Slab</th>
<th>Flat plate slab without edge beams</th>
<th>% of higher resistance than flat plate slab</th>
<th>Average of percentages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lateral Load Resistance (kN)</td>
<td>Displacement (mm)</td>
<td>Lateral Load Resistance (kN)</td>
<td>Displacement (mm)</td>
</tr>
<tr>
<td>18.3m x18.3m</td>
<td>467.57</td>
<td>45</td>
<td>363.09</td>
<td>45</td>
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<tr>
<td>18.3m x27.45m</td>
<td>600.15</td>
<td>45</td>
<td>480.92</td>
<td>45</td>
</tr>
<tr>
<td>18.3m x36.6m</td>
<td>739.09</td>
<td>45</td>
<td>600.15</td>
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</tbody>
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Table 2: Difference of lateral load handling capacity between several flat slab and beam supported ten storied building

<table>
<thead>
<tr>
<th>Plan Dimension</th>
<th>Beam Supported Slab</th>
<th>Flat plate slab without edge beams</th>
<th>% of higher resistance than flat plate slab</th>
<th>Average of percentages</th>
</tr>
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<tbody>
<tr>
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<table>
<thead>
<tr>
<th>Dimension</th>
<th>Max. Stress</th>
<th>Yield Stress</th>
<th>Min. Stress</th>
<th>Yield Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.3m x18.3m</td>
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<td>45</td>
<td>353.66</td>
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<td>598.19</td>
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<td>469.22</td>
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<td>18.3m x36.6m</td>
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<td>45</td>
<td>587.07</td>
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Figure 2: Column jacketing process for retrofitting

Figure 3: A retrofit Application combining Conventional and Composite Retrofitting
A 3D model of a building, Wall stresses before retrofitting, After installation of steel window frames, Additional FRP retrofitting [7]

Figure 04: Base isolator [8]
**Conclusion**

Prevention of flat slab, ribbed slab, waffle slab structures from lateral loading and strengthening of its members from seismic loading has become an urgent need as architects are becoming more inclined to design beamless structure for aesthetic purposes. Recent researches have opened new window for newer and newer invention of retrofitting techniques of similar structures. But before provision of any technique we should keep in mind about aesthetics, eco friendliness, cost effectiveness and obviously, structural safety etc.

**References**

8. [https://nees.org/resources/3832](https://nees.org/resources/3832)