Seismic Retrofit Design of a Multi-Story Non-Ductile Reinforced Concrete Building in Downtown Los Angeles

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Abstract

The design of the seismic retrofit of a 15-story non-ductile reinforced concrete building, located in downtown Los Angeles, is presented. Built circa 1927, the building was first used as a parking structure. Then, in 1953, it was used as an office building after moderate alterations. In 2016, an adaptive reuse of the building as a hotel was envisioned, triggering the seismic retrofit. The designed retrofit complies with Los Angeles newly adopted mandatory ordinance for earthquake hazard reduction of existing non-ductile concrete building. The building is one of the first being permitted through the ordinance. As such, the strength of the lateral-force resisting system was designed to seventy-five percent (75%) of the base shear specified in the current Los Angeles Building Code seismic provisions. New concrete shear walls at strategic locations were selected for the retrofit scheme. New concrete collectors were designed to strengthened existing pan joist concrete floor diaphragms in areas with large openings. FRP wrapping is indicated for column members not designated to be part of the new lateral-force resisting system. The FRP wrapping was designed to adequately sustain gravity load effects and seismic displacement due to the full (100%) of the design story drift specified in the current L.A. Building Code seismic provisions. A seismic soil-structure interaction analysis was performed in order to design the foundation retrofit. The results were incorporated into a separate foundation model, which included compression-only springs for foundation uplifting effects. New concrete foundation was designed based on a separate analysis. A comparison between the building performance before and after retrofit demonstrates compliance with the aforementioned ordinance. Finally, a rough exercise to develop fragility curves for the building is discussed in order to prepare information for a probable maximum loss (PML) analysis for further understanding of the retrofit benefits.

Introduction

Non-ductile reinforced concrete buildings constitute an important percentage of buildings in dense populated cities around the world. In the city of Los Angeles (LA) California, approximately 1,500 buildings have been classified as non-ductile concrete buildings. These are serving as one story family dwellings to multi-story critical service facilities. Due to brittle failure, this type of construction poses a significant threat to Life Safety in regions of high seismicity, and their damage can result in significant financial losses. Inadequate seismic performance and brittle failure of non-ductile concrete buildings have been observed in 1985 in Mexico City, 1994 Northridge, and following the 2011 Christchurch New Zealand earthquakes. In California, non-ductile concrete buildings constructed to building code standards earlier than the code improvements in 1976 are at a particular risk for collapse. For these reasons, the city of LA, through the Los Angeles Department of Building and Safety (LADBS), has passed ordinance 183893 “Mandatory Earthquake Hazard Reduction in Existing Non-ductile Concrete Buildings” (2015). This ordinance became effective in November of 2015, the ordinance is mandatory for the continuous use and adaptive reuse of existing non-ductile concrete buildings, constructed prior to 1977.

In this paper, a case study of a retrofit for a non-ductile concrete building, located in downtown LA, is presented, see Figure 1. The retrofit is one of the first to comply with the requirements of the aforementioned ordinance. The case study illustrates a traditional design procedure based on code regulations adopted by LADBS including LABC, CBC, ASCE7, and ACI requirements.
The retrofit design is based on the linear dynamic procedure or response spectrum analysis outlined in section 12.9 of ASCE 7. As dictated in the ordinance the seismic forces used for the design are 75% of current code minimum requirements. The retrofit design does not rely on the existing lateral force resisting system and relies solely on the new lateral force resisting system which for this building consists of special reinforced concrete shear walls. Although the existing elements are not relied on for strength the stiffness of the existing elements is accounted for in the determination of base shear and the evaluation of the structure for irregularities defined in Table 12.3-1 & 12.3-2 of ASCE 7. To assess deformation compatibility of the existing concrete elements a limit state analysis is employed.

With the retrofit scheme compliant with the ordinance, a conceptual seismic loss analysis is performed using the PS8 methodology and the SP3 platform from Hasleton Baker Risk Group (2017). The seismic loss assessment provides a breakdown of building components that contribute to loss in the event of a major earthquake. Based on potential losses, a comparison of the performance for pre- and post-retrofit conditions is given. The results demonstrate the benefits of the retrofit scheme and illustrates a simplified and practical method to evaluate cost-effective retrofit solutions.

Non-ductile reinforced concrete buildings

Non-ductile reinforced concrete buildings consist of concrete floors and/or roofs, with or without supporting beams, which in turn are supported by concrete walls and/or concrete columns. Masonry infills may be present within the concrete frames. These buildings are brittle structures with limited capacity to absorb energy released from ground shaking during major earthquakes. This behavior causes the likelihood of shear failure and/or hinging of main structural components leading to collapse. Among the non-ductile characteristics observed in these buildings are (Kurama, 1993):

- Beam bottom (positive) flexural reinforcement with short embedment length (typically 6-inches) into the beam-column joint
- Beam flexural reinforcement cut-off and bend regions according to gravity load requirements
- Columns with wide spacing of transverse reinforcement
- Columns with poor confinement of reinforcement splices located just above floor level
- Insufficient or no transverse reinforcement in the beam-column joint
- Insufficient transverse reinforcement in beams

Post-earthquake studies have shown that old reinforced concrete buildings, damaged during earthquakes, were detailed with one or more of the items mentioned above, which resulted in a non-ductile behavior (PEER, 2009). Such studies enforced modern seismic codes for ductile detailing post 1976. However, it is likely that construction of non-ductile concrete buildings continued until 1980, as few years passed before the new codes could take full effect. To minimize the seismic risk from non-ductile concrete buildings, the city of LA issued a mandatory ordinance to enforce retrofit of such buildings. It is expected most buildings will be retrofitted or demolished by the year 2041.

Ordinance for non-ductile buildings

Officially effective on November 22, 2015, the city of LA, through the Los Angeles Department of Building and Safety (LADBS), enforced ordinance 183893 “Mandatory Earthquake Hazard Reduction in Existing Non-ductile Concrete Buildings”. The ordinance is mandatory for the continuous use and adaptive reuse of existing non-ductile concrete buildings, for which construction permit was applied for prior to January 13, 1977. The ordinance excludes detached single-family dwellings and detached duplexes. Also, previously retrofitted buildings in conformance with provisions in either Chapter 85 or former Chapter 95 of the LABC are exempt. The timeline for compliance is similar to that for wood-frame soft-story buildings addressed in the same ordinance and are as follows:

- 2016-2019: Building owners have three years to begin the assessment process
- 2019-2029: Owners have ten additional years to determine retrofit status
- 2029-2041: Owners have an additional twelve years to perform building retrofits
In addition to the exemptions explicitly mentioned in the ordinance, buildings meeting the design criteria are exempt from retrofit. The design criteria corresponds to a lateral-force resisting system minimum strength of 75% of the base shear specified in the current LABC seismic provisions, with elements not designated to be part of the lateral-force resisting system adequate to accommodate seismic displacements due to full (100%) of the design story-drift. Alternatively, the design criteria can be met using an ASCE 41 approach with the corresponding “Basic Safety Objectives” and ground motions. Other equivalent methods can be applied if approved by the LADBS.

The case study building presented in this paper is within the scope of the mandatory ordinance.

**Description of existing building**

The case study building is a 15-story structure, built circa 1927, approximately 155 ft x 78 ft in plan, see Figure 2(a). As mentioned above, the building is considered a non-ductile structure. It was first used as a parking structure, with large hydraulic elevators allowing cars to park throughout the height of the building as the floors in the building are flat and not sloped as is typical in parking garages. In 1953 the building was repurposed into an office building. The alterations required as part of this adaptive reuse included relocation of vehicular ramps, and addition of a service elevator.

**Structural gravity system**

The self-weight of the building and its occupant loads are carried by the building gravity system, which consists of reinforced concrete (RC) floors, beams and columns. Building floors consist of concrete pan-joist slabs spanning in the longitudinal direction, see Figure 2(b). Some portions of the floor are concrete on metal deck supported on steel wide-flange beams that were installed during the alterations in 1953. The concrete joists and steel beams are supported on RC girders spanning in the transverse direction, which in turn are supported on RC columns. Columns are either square, circular or interlocking-core cross-section. Circular and interlocking-core sections are provided with pitched spiral reinforcement. The building foundation consists of concrete spread footings, which vary in thickness from 5’ 7” to 5’ 9”.

**Lateral-force resisting system**

The existing seismic or lateral-force resisting system (LFRS) in the east-west direction consists of 8-in thick concrete walls, one along the south elevation extending full-height of the building, and one along the north elevation extending from floors 9 and up. For the lower floors (1st to 8th) on the north side, the solid wall changes to a concrete frame with brick infill. In the north-south direction, the LFRS consists of the frame action between the existing perimeter concrete girders and concrete columns. During site observations, it was found the existing concrete ramps were not seismically separated from the building and were rigidly connected to the floors, which increased their vulnerability under earthquake events.

**Site soil conditions**

According to available geotechnical data (USGS), the property is underlain by Alluvium and the groundwater level in the area is estimated to be more than 50 ft below ground. This indicated a low probability of soil liquefaction at the site. Regarding seismic faults, the nearest potentially active fault is the Hollywood fault located at approximately 8 mi from the building site. Since no fault crosses the property, a low probability is expected for surface rupture at the site.

**Adaptive reuse building modifications**

The current owners are seeking to adaptively reuse the building to accommodate 180 luxury hotel rooms which is considered a change in use. As part of the alterations an existing mezzanine level will be extended into a new second floor. On the lower floors, the existing parking ramps will be replaced by new ramps.

**Seismic retrofit scheme**

Special reinforced concrete shear walls (SRCSW) were selected as the retrofit LFRS in the two principal and orthogonal directions of the building, see Figure 2(a). Two new SRCSW, one on the north and one on the south elevation, will resist seismic loads in the east-west direction. Similarly two SRCSW, one on the east and one on the west elevation will resist seismic loads in the north-south direction. These shear walls vary in thickness, from 18-in at the base to 12-in in upper floors. At the basement, an extension of the foundation was required to support the retrofit walls. New spread foundation beams were designed to support the retrofit walls and tied into the existing foundation to spread the load across the building foot-print in order to minimize bearing pressures and to keep these under the 10,000psf recommended geotechnical value.
Figure 2. (a) Building plan view, (b) Concrete column and beam sections, (c) Longitudinal building section, (d) Transversal building section
Seismic loads

The seismic loads used for the evaluation and retrofit design of the building were estimated per LABC and ASCE7. The seismic base shear corresponds to 75% of the code prescribed calculated value. The parameters used to estimate the seismic base shear are shown in Table 1.

Table 1. Parameters for seismic base shear

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Analysis procedure

The seismic analysis procedure for the retrofit design was selected in accordance to LABC and ASCE7. Given the building structural characteristics, a Dynamic Modal Response Spectrum analysis procedure was applied with a minimum cumulative mass participation of 90% in each of the principal building directions. The response spectrum analysis was performed using a 3D computer model of the building. For this, beam and column members were idealized as linear-elastic frame elements whereas RC walls and concrete floors were idealized as two-dimensional linear-elastic shell elements. Pin supports were assigned to building base nodes. This assumption required modeling of the foundation in a second stage where reaction loads from the superstructure analysis were used as input loads for analysis of the foundation.

Retrofit for deformation compatibility

The existing structural members in the building not considered part of the LFRS were evaluated for deformation compatibility as required per the mandatory ordinance. This was addressed using a limit state analysis per ASCE7 where existing columns were checked to have sufficient capacity to develop the capacity of connecting RC girders, and the girders in turn were checked to have sufficient capacity to carry gravity loads for the new building use. Also, beams were checked to have enough shear capacity at mid-span to resist seismic induced shear. Based on analysis results, columns located on floors above level 9 were found inadequate to develop the capacity of connecting beams. These were retrofitted using Fiber Reinforced Polymer (FRP) wraps to increase confinement and shear strength. This ensured compliance with the deformation compatibility requirement from the ordinance.

Enhanced building performance

Building drifts due to seismic loads were considerably reduced, an average of about 70%, for the retrofitted condition, see Figure 3(c) & (f). It is observed drifts are more prominent for lower floors between levels 2 and 9, and less prominent for floors above level 9, this is more evident for the existing condition than for the retrofitted case. The reason is attributed to a discontinuous concrete wall, which does not extend to the lower floors, resulting in more rigid upper floors and more flexible lower floors. In the case of the retrofitted condition, the drifts are reduced and a more uniform drift profile is observed. This is because retrofit walls extend full height on all four sides of the building. It is also worth noting the FRP wraps for columns on the upper levels increases the deformation capacity of such columns to accommodate drifts due to the interaction between existing structure and retrofit elements.

FEMA P58 analysis

To better understand the benefits of the retrofit scheme, a Probable Maximum Loss (PML) analysis, by means of the FEMA P58 Simplified Method approach, as implemented by the commercially available SP3 software, was used to compare the seismic performance before and after retrofit. In the P58 approach, building seismic performance is expressed in terms of casualties (probability of injury or death), economic losses (repair costs) and downtime (time to reoccupy following repairs). Repair costs include estimates of structural and non-structural damage and other building components. The PML is based upon the estimated repair cost.

A linear-elastic structural model was used to estimate building modal displacements. These were used as input for the aforementioned Simplified Method for estimation of peak story drifts median values. The Simplified Method was applicable as the retrofitted building configuration generally complies with key assumptions of the method. Among these assumptions are: (1) Building response along each horizontal axis is uncoupled, (2) Building is regular in plan and elevation, i.e., there are no substantial discontinuities in lateral strength and stiffness, (3) Story drifts do not exceed four times the corresponding yield drift, (4) Story drift ratios are less than 4%, beyond which nonlinear P-delta effects may become important, (5) The building is less than 15 stories in height, minimizing the potential for significant higher mode effects.

A comparison of the P58 analysis results between existing and retrofitted conditions demonstrates the benefits of the retrofit scheme, see Figure 4.
Figure 3. (a) Existing building computer model, (b) Calculated modal displacements for existing condition, (c) Drift inter-story ratios for existing condition, (d) Retrofitted building computer model, (e) Calculated modal displacements for retrofitted condition, (f) Drift inter-story ratios for retrofitted condition

Figure 4. Comparison of P-58 results between existing and retrofitted condition for Scenario of Expected (mean) Loss (SEL), and Scenario of Upper (90th percentile) Loss (SUL), (a) Mean and 90th percentile loss, (b) Mean repair time: Parallel for all floors at a time; series for one floor at a time, (c) Casualties
According to the FEMA P58 analysis results, the retrofitted condition reduced drifts in the order of 70% in both orthogonal directions. Also, the repair time significantly reduces for the retrofitted building, especially for the 5% in 50 years event. Regarding predicted casualties, it is noted there is a slight increase for the retrofitted condition. This is attributed to the fact that the increase in building stiffness results in higher spectral accelerations inducing higher vulnerability of partitions and non-structural components within the building. However, in the retrofitted condition, potential failure of partitions and non-structural components of the building is expected to be negligible given that these comply with current design standards. Thus, reducing probability of casualties.

A breakdown of the building total loss is given in the results from the P58 analysis. The total loss is estimated as the summation of building component individual losses. Building components contributing to the total loss during a major earthquake include structural members, partition walls, exterior cladding, interior finishes, plumbing and HVAC systems, and other components. By looking at these results, it is noted the contribution from building components to the total loss changed before and after retrofit. Before retrofit, the structural components constituted more than 50% of the total loss, whereas for the retrofitted building, this is down to 43% and 38% for the 20 and 5% in 50 years probability of exceedance, respectively.

Figure 5. P-58 results for existing condition: (a) 5% in 50 years, (b) 20% in 50 years

Figure 6. P-58 results for retrofitted condition: (a) 5% in 50 years, (b) 20% in 50 years

Comparing building loss between pre- and post-retrofit, see Figure 5 & Figure 6, it is observed the expected (mean) loss or the Scenario of Expected Loss (SEL) with no retrofit is approximately 37% whereas for the retrofitted condition the expected loss is reduced to approximately 12%. This is a nearly 68% reduction in losses. Similar results were observed for the 90th percentile or the Scenario of Upper Loss (SUL).
Conclusions

The following conclusions were derived from the retrofit design and the P58 analysis presented in this paper:

- Retrofit of non-ductile concrete buildings per the LADBS 183893 ordinance, considerably reduces the probability of damage under earthquake loads, e.g. approximately 70% reduction in story drifts was estimated for the case study building.
- According to PML analysis results, building losses after retrofit are reduced approximately 68%, with retrofit elements designed to sustain 75% of standard code seismic loads for new buildings.
- It is noted the contribution, to the total loss, of structural building components considerably reduces for the retrofitted condition.
- Based on the structural analysis and PML approach, it is economically feasible to adaptively reuse this older non-ductile concrete building, helping the City of Los Angeles to become a more resilient community.

References


