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Effect of long-duration earthquakes on the low-cycle fatigue damage in RC frame buildings

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ABSTRACT

Several cases of failure due to rupture of reinforcing bars in RC buildings were reported by inspection teams after the 2010 Muale earthquake in Chile that triggered further research efforts.

This paper studies the effect of long-duration earthquakes on the damage potential due to low-cycle fatigue through nonlinear analysis of three existing RC frame buildings. The number of strain cycles and their amplitudes for reinforcing bars at the critical locations within each building were obtained from nonlinear time history analyses. The reduction in the fatigue life has been estimated using S-N curve obtained from the experimental literature and by applying the Palmgren-Miner damage rule.

The results showed significant reduction in fatigue life for the low- and medium-rise buildings larger than high-rise buildings. It was found that A706 steel has longer fatigue life than A615 steel. Also, larger diameter steel bars tend to experience less fatigue damage within RC members.

1. Introduction

Earthquakes induce loading cycles on structures based on the dynamic properties of their structural systems and the ground motion parameters. Due to the cyclic nature of the earthquake loading, deterioration of both strength and stiffness is expected to happen for different structural members resulting in a cumulative reduction in the service life. The occurrence of long-duration earthquakes increases the total number of loading cycles which the building might experience during its lifetime. The accumulation of seismic damage within the elements of a structure due to long-duration earthquakes can lead to increased vulnerability to failure.

Long-duration earthquake can be more damaging than short-duration earthquakes due to the increased number of response cycles associated with the longer shaking which can lead to more significant damage. Higher collapse risk can be expected due to strength degradation of RC elements, and Low-cycle fatigue damage in steel structure as well as reinforcing bars in concrete structures. Also, the longer period of shaking could impose large seismic energy demands which requires greater ability to of energy dissipation within the different structural elements. Current building codes and guidelines for analysis and design of structures subjected to seismic loading don't account for the effects of longer duration of shaking on the structural response which can result in accumulation of damage within structural and non-structural elements. Short-duration earthquakes could lead to prolonged response in lightly damped structures due to the beating effect that increases the number of vibrating cycles especially for building with light damping which is out of the scope of this paper [1–5].

2. Damage in the 2010 Chile earthquake

The most recent evidence on damage accumulation in RC buildings (especially those due to low-cycle fatigue effect) is the severe damage that happened in numerous buildings during the Maule earthquake in Chile. After the earthquake on February 27, 2010, certain types of damage were observed repeatedly in existing RC buildings that were inspected by an investigation team of the Los Angeles Tall Buildings Structural Design Council (LATBSDC). One of the most observed failure modes was the rupture of main bars at the extreme ends of RC walls at the location of failure, particularly at the bottom levels of the affected buildings as shown in Fig. 2. The investigation team reported that they believe the tearing of these bars is related to low-cycle fatigue caused by the numerous cycles of loading and unloading due to the long duration of the earthquake and the large inelastic deformations due to the magnitude of the earthquake as well [6,7]. Two common types of failure that were observed after the earthquake are concrete crushing and buckling of vertical bars due to lack of confinement within moment frame columns and shear wall boundary zones. Improper detailing of cross-ties which didn't meet the 135 degree hook criteria as stated in most modern building codes for seismic design and detailing which experienced major updates since the San Fernando earthquake in 1971.

After the earthquakes in June 2010, researchers and professional

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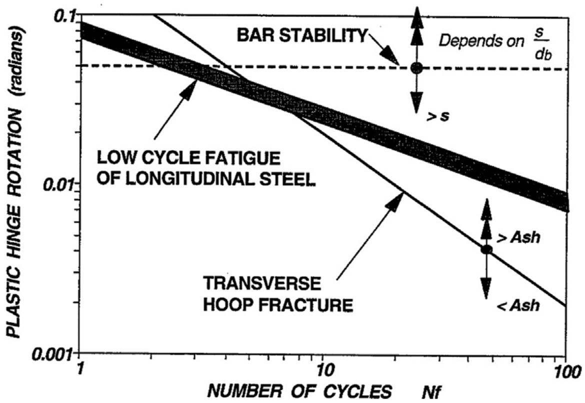

Fig. 1. Schematic graph of the possible modes of failure for an RC member during loading cycles [9].

engineers from the United States and Chile met to discuss the lessons learned from the earthquake. A one day workshop was held under the umbrella of the American Society of Civil Engineers (ASCE), the National Institute of Standards and Technology (NIST), and the Pacific Earthquake Engineering Research (PEER) Center to analyze the U.S. building codes in the light of the 2010 Chile earthquake [8]. Based on the previous observations, one of the major conclusions of the meeting was the significant research need to study the damage accumulation due to a relatively small number of loading cycles (low-cycle fatigue) induced by long-duration earthquakes which can lead to higher damage potential and a possibility of collapse. Hence, the evaluation of the current state of an existing building should estimate the effects of low-cycle fatigue.

3. Low-cycle fatigue of reinforcing bars

The fatigue effect on the structural response is one of the major contributors to the damage accumulation phenomenon which depends on the amplitude and the number of loading cycles. Various construction materials have different fatigue characteristics which affect the remaining life of the structure subjected to a loading history of earthquakes. Since the number of cycles induced by earthquake loading is relatively low, the fatigue behavior of materials in the low-cycle range (less than 1000 cycles) is controlling. Also, the deformations and straining actions due to earthquake loadings are expected to be in the inelastic range which leads to high stress and strain amplitude for the loading cycles.

The current seismic design practice relies on the inelastic flexural response at the plastic hinges as the primary source of energy dissipation. This requires that proper care be taken in detailing the locations where plastic hinges are expected to occur. For reinforced concrete (RC) structures, potential plastic hinge locations are designed to experience large rotations in order to dissipate energy which requires the longitudinal reinforcing steel bars to undergo high strain amplitudes during earthquake loading cycles. Based on numerous experimental studies, it has been observed that failure in RC members is influenced by the number of loading cycles during the history of events that affects the structure and can arise in the following modes:

a. Rupture of longitudinal reinforcing steel bars due to low-cycle fatigue.
b. Fracture of transverse reinforcement which leads to failure of the confined concrete core.
c. Compression buckling of the longitudinal reinforcing bars.

Fig. 1 shows that mode (b) could be avoided by providing a sufficient amount of transverse reinforcement "A_{sh}" where mode (c) could be avoided by using the proper spacing for transverse reinforcement to reduce the slenderness ratio of the longitudinal bars "s/d"[9].

Mode (a) is the rupture of reinforcing steel bars due to earthquake induced low-cycle fatigue. It is one of the unavoidable modes of failure that increases the damage potential of RC members that satisfies all of the code design and detailing requirements which significantly improved the response of RC members in terms of strength and ductility. Although these requirements have improved the response of RC members, low-cycle fatigue failure of reinforcing bars is a potential cause for the loss of the energy dissipation capacity and the strength of RC members.

Multiple cases of failure in RC buildings due to rupture of reinforcing bars were reported after the 2010 Muale earthquake in Chile which were believed to result from the numerous high strain cycles induced by the earthquake. Earthquake resistant code provisions for RC design have been updated through the years to overcome any deficiency based on the lessons learned from previous earthquakes. This study is another step toward improving evaluation and rehabilitation guidelines for existing buildings to account for low-cycle fatigue of reinforcing steel bars. A better evaluation of existing RC buildings is needed in order to assess the different types of damage especially those that may not be readily apparent to visual inspection (such as the reduction in the fatigue life of reinforcing bars) after a certain event. By estimating the reduction in the fatigue life of steel reinforcement at each of the critical locations within an RC building, the building could be classified according to its vulnerability to low-cycle fatigue failure.

The goal of this paper is to estimate the damage potential due to the low-cycle fatigue behavior of reinforcing steel bars used in RC moment frame buildings during long-duration earthquakes. This paper is a continuation of the preliminary work by the authors on the effect of multiple and long-duration earthquakes on the low-cycle fatigue damage potential [10–12]. The paper discusses in detail the parameters affecting the damage in terms of the dynamic characteristics of the buildings and the rebar material properties and geometry.

Fig. 2. Low-cycle fatigue failure due to rupture of the main bars at the end of RC walls, Chile [6,7].