Chapter 1

Introduction

Elevators are the most commonly used mode of vertical transportation in modern buildings having more than three stories. More than a decade ago, it was estimated that there were more than half a million passenger elevators in the United States transporting people day and night every day of the year (Swerrie, 1991). Many of these elevators are located in urban area in highly seismic regions. For example, there were close to twenty thousand elevators in the area affected by the 1989 Loma Prieta earthquake in California, and this figure does not include elevators in federal buildings or private residences (Swerrie, 1991). Therefore, it is quite certain that these elevators are vulnerable when a strong ground motion shakes the building.

In the past earthquake events, the disruptions and economic losses caused by the damage of elevators due to earthquakes have been significant. However, it is noted that there have not been any direct fatalities associated with elevators failure during earthquakes in the United States. From the point of view of avoiding life casualties, elevators have performed very well due to combined efforts of industry and regulatory agencies. These efforts have, however, not completely eliminated the possibility of damages to the elevators, especially in highly seismic areas. This has serious implications for essential facilities such as hospital and high-rise buildings where they serve a very important function and must deliver crucial services after a damaging earthquake. In such buildings, damages in elevators can affect the flow of services and prevent them from functioning properly. Therefore, there is still a strong need to enhance the performance of elevator systems in buildings.

1.1 Components of Elevator System

Elevators consist of complex structural, mechanical, and electrical components. Janovsky's monograph (1993) gives a description of the engineering detail of elevator systems. The main components of a typical traction elevator are shown in Figure 1.1. The components related to the rail-counterweight system are explained briefly here.

The central and most visible component of an elevator is the passenger car. The car frame, consists of the upper crosshead beam, two vertical uprights (stiles) joining upper and lower members, and lower safety plank, provides the supporting structure for the car. The suspension ropes are attached to the crosshead beam. The safety plank supports the car platform, on which passengers or other loads rest during travel. A pair of guide rails is placed on two opposite sides of the car, guiding the car during its vertical motion.

The weight of the car and part of its load is balanced by the counterweight. The counterweight consists of steel frame and stacked fillers or weights secured by two or more tie-rods. These weights fill up to two-third of the height of the counterweight. Both passenger car and counterweight are connected through traction ropes that pass through traction system at the top of the hoistway consisting of driving sheaves and electric motor. Similar to the passenger car, the counterweight is also guided by two guide rails along its sides during the vertical motion.

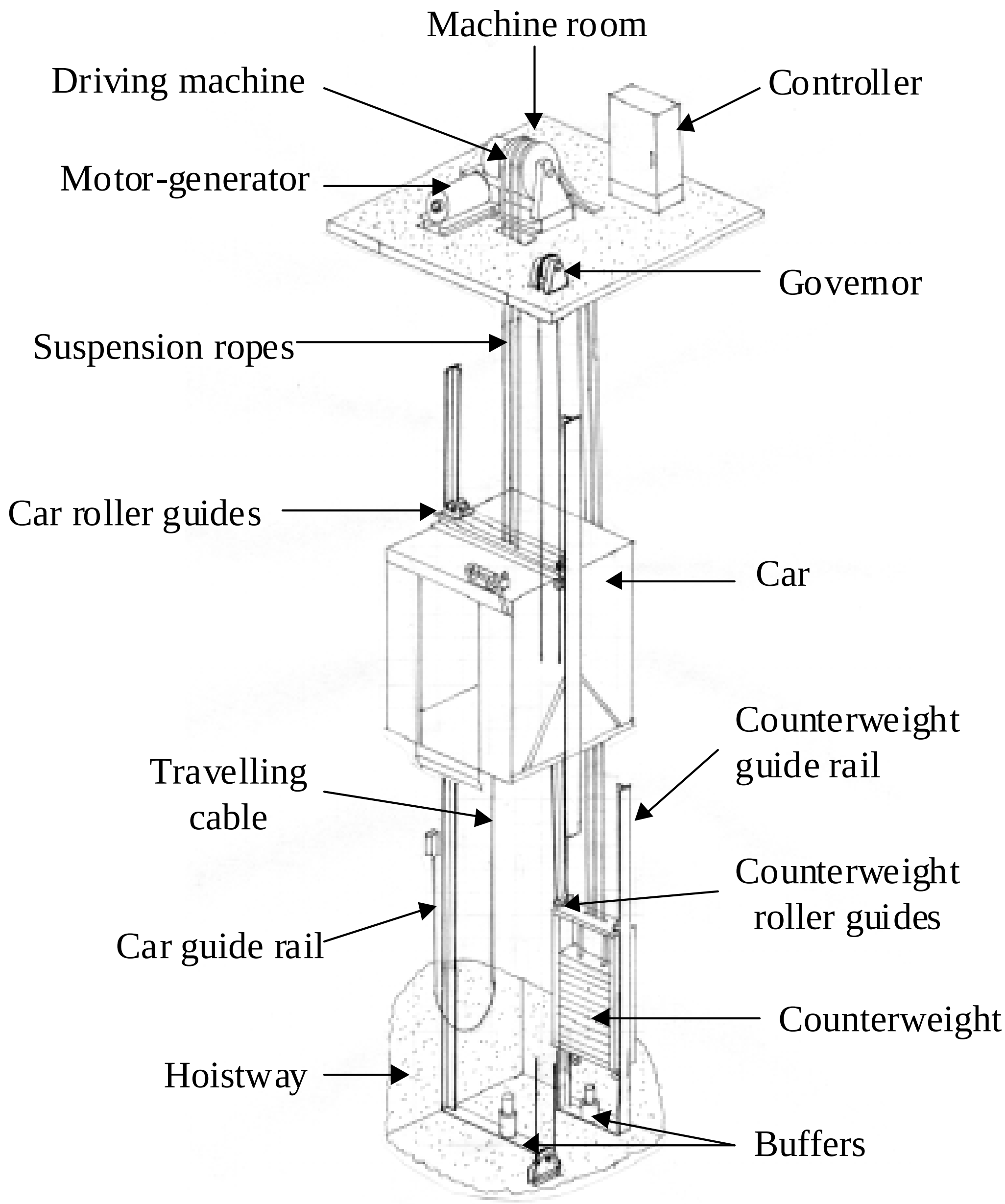

Figure 1.1 Main components of a typical traction-type passenger elevator.

The guide rails are made of structural steel with a T-shaped cross section. The specifications in ASME A17.1 (ASME, 1996) code provide several sizes of T-section structural steel that can be used as guide rails for different sizes of counterweight. The guide rails are fixed on brackets, usually at each floor level, by means of clips. Figure 1.2 shows the arrangement of this guide rail and bracket assembly. The guide rails can also be strengthened with intermediate tie-brackets. The code requires that both guide rails and brackets have at least 55 ksi tensile strength.

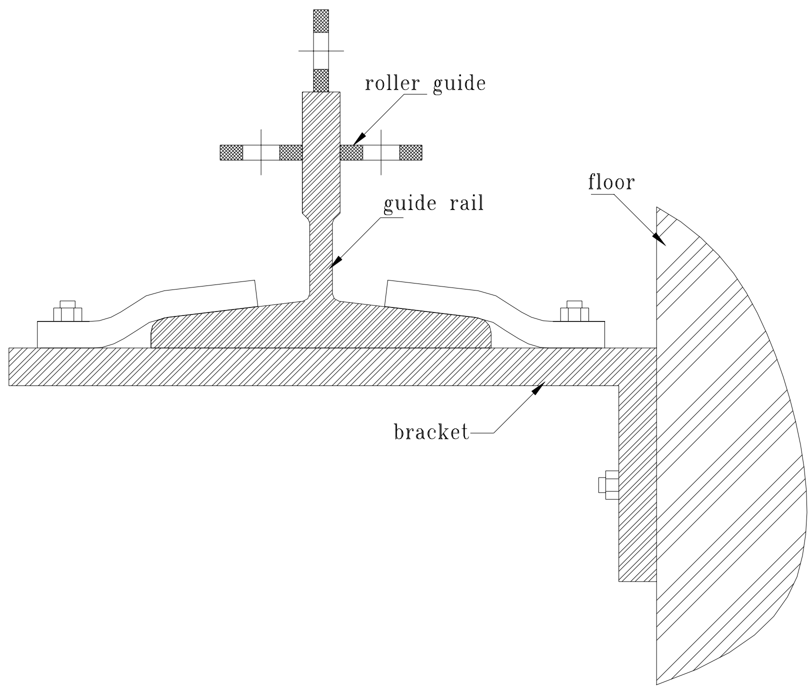

Figure 1.2 Guide rail and bracket assembly.

During its vertical motion, the counterweight and passenger car are guided by roller guide assemblies. Each counterweight is guided by four roller guide assemblies, one located at each corner of the frame. Each roller guide consists of at least three rollers fitted with rubber or polyurethane tires which are kept in contact with the rail by pivoted rocker arms and preloaded helical spring, as shown in figure 1.3.

To prevent excessive displacement and disengagement of counterweight from the rail during earthquake-induced motion, the A17.1 Code requires installation of restraining plates at the upper and lower roller guide assembly. The clearance between the retainer plate and the guide rail, as shown in figure 1.4, must not be more than 3/16 of an inch. This feature contributes to the nonlinearity of the rail-counterweight system during earthquake-induced vibration.

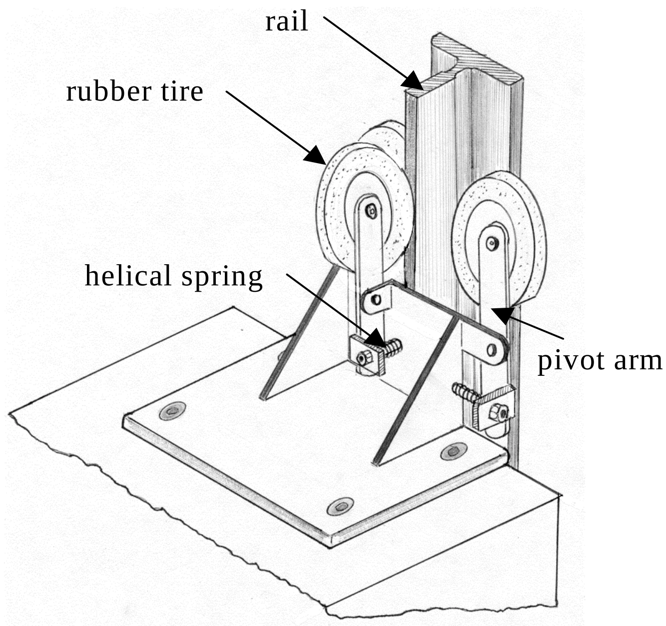

Figure 1.3 A typical three-wheel roller guide assembly.

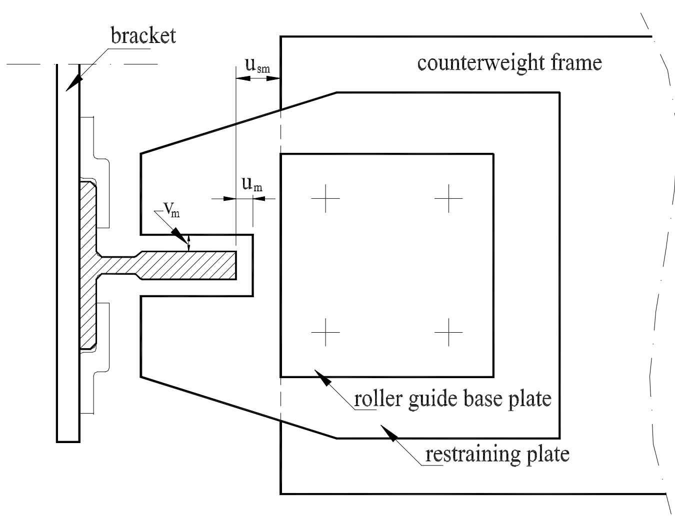

Figure 1.4 Guide rail restraining plate

1.2 Seismic Performance of Elevators

Suarez and Singh (2000) presented a comprehensive review of seismic performance of elevators during earthquakes. A short description of elevator damages observed after several earthquakes is discussed here.

Extensive damage to elevators was first observed after the 1964 Alaska earthquake. Ayres et al. (1973) described different type of damages observed during the inspection after the earthquake. The most common damage was counterweight popped out of their guide rails.

A more systematic study about damages on elevators during earthquake was performed after 1971 San Fernando earthquakes (Ayres and Sun, 1973). A large number of elevators were damaged in this earthquake. Again, the most common damage was counterweight thrown out of their guide rail. Furthermore, about 15% of the derailed counterweight collided and damaged the passenger cars. Other damages include passenger cars out of guide rail, damaged bracket, broken or loose roller guides, and bent rails. After this earthquake, the first design improvements to minimize seismic damage were proposed (Ayres et al., 1973; and McGavin, 1981), and later included in the California and A17.1 Code. In particular, it was proposed to use guide rail heavier that the 8-lb T-section, place brackets at closer intervals, and use tie-bracket to connect two rails from spreading apart causing derailment of the counterweight.

In spite of this improvement, however, the elevator still got damaged in the 1987 Whittier earthquake (Schiff, 1988), the first earthquake to affect elevators since the provisions of the Carolina code became effective. Although the overall performance of the elevators was better than during San Fernando earthquake, there were still 91 cases of derailment, 11 of which resulted in collision with the passenger cars.

Ding and Arnold (1990) and Swerrie (1990a, 1990b, 1991) reported the performance of elevators during 1989 Loma Prieta earthquake. Similar to all other earthquakes observed, derailment of counterweight was the main problem. Bent rails and brackets and failures of bolts holding the brackets were pointed out as the main factors that caused the derailment. Ding and Arnold (1990) and Swerrie (1991) also observed that the derailment generally occurred when the counterweight was located in the upper portion of the buildings.

The elevator damages during 1994 Northridge were considered more severe than 1989 Loma Prieta and 1987 Whittier earthquakes (Pavlow, 1994; Schiff, 1994). More than 600 derailments were recorded. Finley et al. (1996) reported specifically about the performance of elevators in hospitals. The report suggested minor changes in the existing California seismic requirements to take into account modes of failures observed during this earthquake.

Damages to the elevators due to earthquake were also observed in several earthquakes outside United States. Fukuda (1990) reported the elevator damages during 1978 Miyagi earthquake and Caporale (1995) and Wada and Kitamura (1995) reported the elevator performance during 1995 Kobe earthquake. In both earthquakes that occurred in Japan, similar problems were encountered. Derailment of counterweight was still the main problem. Other damages include bent guide rails and brackets, cars out of guide rails, dislocated weights, ropes and cables damages, and overturned traction machines and controllers. Nazarova (1990) also found that derailment and crashes between cars and counterweights were the most common damages during the 1986 Carpathian earthquake, which occurred when the elevators were not explicitly design for earthquakes in the former USSR. Levy et al. (2000) described that the rails that commonly used in Israel could not withstand the 1995 Gulf of Eilat-Aqaba earthquake. Therefore, stronger rails and improved fasteners were proposed to increase the safety of the elevators.

1.3 Objectives and Scope of the Study

Several analytical studies on the dynamics of rail-counterweight system have been performed by various researchers (Yang et al., 1983; Schiff, 1980; Tzou, 1985; Tzou and Schiff, 1984, 1987, 1988, 1989; Segal et al., 1994, 1995, 1996; and Rutenberg et al., 1996) using different models and assumptions. In these previous studies, not much attention was given to proper modeling of the rail-counterweight system, especially their roller guide supports on the guide rails. Furthermore, these studies were focused on analyzing the dynamics responses of the rail-counterweight system with very little treatment to reduce the responses.

The objectives of this study are to evaluate the seismic performance of elevator system using a more realistic model, and propose protective methods to improve their seismic performance. The performance and its improvement will be evaluated through a fragility evaluation of the counterweight and its supporting system. These objectives require completion of the following tasks:

- Development of the equation of motion of the rail-counterweight system using realistic analytical models.
- Development of accurate and efficient analytical procedures to obtain the seismic response of the system.
- Perform parametric study to examine the effect of different system parameters and components.
- Development of response control methods to reduce or prevent the damage.

- Fragility analysis of the system with and without protective devices to examine the effectiveness of the proposed protective systems

1.4 Dissertation Layout

This dissertation is organized into five chapters. A brief description of the contents of each chapter is presented here.

The analytical model used to study the seismic response of rail-counterweight system is derived in Chapter 2. Numerical results are obtained for rail-counterweight system on a typical ten-story building under different earthquakes with different intensities. Results using different set of parameters, such as gap clearances, rail sizes, ground acceleration types and intensities, and the use of optional tie-brackets are generated to study their effect on the dynamic responses of the rail-counterweight system. The performance is measured by comparing the maximum stress with the maximum allowable by the Code, and also by fragility analysis with 50 sets of artificially generated ground acceleration as input to the building.

Seismic response control methods using passive damper are proposed and analyzed in Chapter 3. The advantages and limitations of adding discrete viscous damping devices on the roller guide assemblies and using part of the weights as tuned mass damper are discussed in this chapter. This tuned mass damper approach is then extended to active control method by installing actuator between the mass damper and the frame. Another protective scheme that is also investigated is using semi-active control method with magnetorheological damper device. These active and semi-active control approaches are discussed in Chapter 4.

The final chapter summarizes the findings and conclusions of this work, followed by recommendations for future research. For completeness, a side-study on the numerical methods used to solve the equations of motions with its nonlinearities is added in Appendix A.