Seismic Performance of Rail-Counterweight System of Elevator in Buildings

Rildova

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Engineering Mechanics

Mahendra P. Singh, Chair
Romesh C. Batra
David Y. Gao
Scott L. Hendricks
Saad A. Ragab

September, 2004
Blacksburg, Virginia

Keywords: counterweight, elevator, seismic response

Seismic Performance of Rail-Counterweight System of Elevator in Buildings

Rildova

(ABSTRACT)

Elevators serve a critical function in essential facilities such as hospitals and need to remain operational during and after earthquakes. However, they are still known to malfunction during earthquakes even after several design and sensing improvements required by the current code have been incorporated. Most of the damages were experienced or caused by the rail-counterweight system. Being the heaviest component of an elevator, the counterweight induced strong dynamic effects to the guiding system sometimes even collided and damaged the passenger car.

A realistic analytical model of rail-counterweight system of an elevator that includes details of the supporting system is developed in this study. The nonlinearities caused by closing of the code specified clearances play an important role in determining the dynamic behavior of the system, and are thus included in this study. Also included are the acceleration inputs from different floor of building and the effect of different location of the counterweight along the guide rail. Parametric study is carried out to investigate the effect of different parameters on the seismic responses of the rail-counterweight system.

In order to improve the seismic performance of the rail-counterweight system, several protective schemes are investigated. One simple approach is to increase the damping of the system using additional discrete viscous dampers. However, there is not much space available for installing the devices, and placement parallel to the spring at the roller guide assemblies is not quite effective due to contact between the restraining plate at the roller guide assemblies and the rail that makes the roller guides ineffective.

Another method is to convert the top part of the weights into a tuned mass damper. This method can reduce the maximum stress in the rail if designed properly. The effectiveness of the passive tuned mass damper can be improved further by using it in an

active mode by installing an actuator between the mass damper and the counterweight frame. The numerical results that confirm the effectiveness of such an active tuned mass damper are presented. As an alternative to the fully active control scheme, a semi-active control scheme using a magnetorheological damper device between the mass damper and the frame is also studied. This control approach is found to be as effective in reducing the seismic response as a fully active scheme. Since this MR damper can be operated using a simple battery, the external power requirements for implementation of this approach are quite minimal.

To my parents

To Inda, Faza, and ‘Adila, the joy of my life

Acknowledgment

I would like to sincerely express my gratitude to my advisor Professor M. P. Singh for his patience, support, and invaluable technical guidance and advice throughout my study. I would also like to thank Dr. R. C. Batra, Dr. D. Y. Gao, Dr. S. L. Hendricks, and Dr. S. A. Ragab for kindly making time of their busy schedules to serve in my committee.

Thanks are also due to Dr. L. E. Suarez, Dr. S. Preidikman, Dr. P. Kachroo, and Dr. R. K. Kapania for their valuable discussions, comments and suggestions that help me complete this work.

This research was supported by the Multidisciplinary Center for Earthquake Engineering Research at the State University of New York, Buffalo through a grant with the National Science Foundation, and by the National Science Foundation through grant no. CMS-0201475. These supports are gratefully acknowledged.

Contents

1 Introduction **1**

1.1 Components of Elevator System 2

1.2 Seismic Performance of Elevators 6

1.3 Objectives and Scope of the Study 8

1.4 Dissertation Lay-out 9

2 Seismic Response of Rail-Counterweight System **11**

2.1 Previous Studies on Rail-Counterweight in Elevators 11

2.2 Analytical Model for Rail-Counterweight System 14

2.2.1 Sources of Nonlinearities 14

2.2.2 In-Plane Motion 18

2.2.3 Out-of-Plane Motion 20

2.2.4 Damping Mechanism 23

2.2.5 Input Motion 23

2.3 Numerical Results 25

2.4 Concluding Remarks 34

3 Passive Protective Schemes **70**

3.1 Supplemental Damping 71

3.2 Tuned Mass Damper 72

3.2.1 Equations of Motion 73

3.2.2 Numerical Results 75

3.3 Concluding Remarks 77

4 Active and Semi-Active Schemes **90**

4.1 Tuned Mass Damper with an Actuator 91

4.2 State-feedback Approach 92

4.3 Acceleration-feedback Approach 95

4.4 Semi-active Approach 98

4.5 Concluding Remarks 103

5 Summary and Conclusions **128**

5.1 Summary 128

5.2 Conclusions 130

5.3 Suggested Future Works 131

References **133**

Appendix A Numerical Integration Methods **137**

List of Figures

1.1 Main components of a typical traction-type passenger elevator 3

1.2 Guide rail and bracket assembly 4

1.3 A typical three-wheel roller guide assembly 5

1.4 Guide rail restraining plate 5

2.1 Geometry of the five degree-of-freedom model of the rail-counterweight system 36

2.2 Bilinear force-deformation diagram due to contact between the restraining plate and the rail 37

2.3 Bilinear force-deformation diagram due to contact between the counterweight frame and the rail 37

2.4 Free body and kinetic diagram for the in-plane motion of the counterweight 38

2.5 Free body and kinetic diagram for the out-of plane motion of the counterweight 38

2.6 Location of the elevator hoistway on a typical floor plan 39

2.7 Mean and mean-plus-one-standard deviation of pseudo acceleration spectra of 50 sets of synthetic earthquake with maximum ground acceleration of 0.1g. 40

2.8 Natural frequencies of the system for different counterweight positions along the 10-story building for 18.5-lb. rail. 41

2.9 Time history of the in-plane displacement at the lower support of the counterweight. 42

2.10 Maximum stress in the rail flange, web, and brackets; and max. floor acc. in the x-direction and y-direction under Northridge earthquake 0.1g. 43

2.11 Maximum stress in the rail flange, web, and brackets; and max. floor acc. in the x-direction and y-direction under El Centro earthquake 0.1g 44
2.12 Maximum stress in the rail for different clearance at the restraining plate for 0.1g Northridge and El Centro earthquake 45
2.13 Maximum force in the bracket for different clearance at the restraining plate for 0.1g Northridge and El Centro earthquake 46
2.14 Maximum stress in the rail as a function of frame clearance for actual Northridge and El Centro earthquakes 47
2.15 Maximum in-plane force in the bracket as a function of frame clearance for actual Northridge and El Centro earthquakes 48
2.16 Maximum force in the bracket as a function of counterweight position on the top story for different frame clearance under actual Northridge earthquake 49
2.17 Maximum stress in different size of rail under actual Northridge earthquake 50
2.18 Maximum stress in different size of rail under actual El Centro earthquake 51
2.19 Maximum in-plane force in the bracket for different rail size, actual Northridge earthquake 52
2.20 Maximum stress in the rail for different base inputs (actual as recorded ground motion) 53
2.21 Maximum stress in the rail for different base inputs, all normalized to 0.5g 54
2.22 Maximum in-plane force in the bracket for different base inputs, all normalized to 0.5g 55
2.23 Average, maximum, and minimum values of the stress shown in Figure 2.20 56
2.24 Average, maximum, and minimum values of the stress shown in Figure 2.21 57
2.25 Average, maximum, and minimum values of the in-plane force shown in Figure 2.22 58
2.26 Maximum stress in the rail as a function of maximum ground acceleration for different earthquake inputs 59
2.27 Maximum stress in the rail with and without intermediate tie-bracket for actual Northridge earthquake 60

2.28 Maximum stress in the rail with and without intermediate tie-bracket for actual El Centro earthquake 61
2.29 Maximum in-plane force in the bracket for the system with and without intermediate tie-bracket under actual Northridge earthquake 62
2.30 Maximum in-plane force in the bracket for the system with and without intermediate tie-bracket under actual El Centro earthquake 63
2.31 Statistics of peak stress in the rail under 50 synthetic ground motions 64
2.32 Mean plus one standard deviation of the peak stress in the rail for system with and without intermediate tie-bracket 65
2.33 Fragility curves of system with and without intermediate tie-bracket 66

3.1 Counterweight with part of weights acting as mass damper 78
3.2 Stress ratio for different size of mass damper as a function of frequency ratio, Northridge earthquake 0.843g 79
3.3 Stress ratio for different size of mass damper as a function of frequency ratio, El Centro earthquake 0.348g 80
3.4 Stress ratio for different size of mass damper as a function of frequency ratio, El Centro earthquake 0.9g 81
3.5 Maximum displacement of different size of mass damper as a function of frequency ratio, Northridge earthquake 0.843g 82
3.6 Maximum displacement of different size of mass damper as a function of frequency ratio, El Centro 0.348g 83
3.7 Maximum displacement of different size of mass damper as a function of frequency ratio, El Centro 0.9g 84
3.8 Mean plus one standard deviation of peak stress in the rail 85
3.9 Mean and absolute maximum of peak displacement of the mass dampers 86
3.10 Fragility curves for different size of mass dampers 87
3.11 Fragility curves for different size of mass dampers 88

4.1 Maximum stress ratio for different as a function of frequency ratio under actual Northridge earthquake. 105

4.2 Maximum stress ratio for different as a function of frequency ratio under actual El Centro earthquake 106
4.3 Maximum control force for actual Northridge earthquake 107
4.4 Maximum control force for actual El Centro earthquake 108
4.5 Maximum displacement of mass damper for actual Northridge earthquake 109
4.6 Maximum displacement of mass damper for actual El Centro earthquake 110
4.7 Mean plus one standard deviation of the maximum stress in the rail for an ensemble of synthetic ground motions 111
4.8 Mean and absolute maximum of control force under an ensemble of synthetic ground motions 112
4.9 Fragility curves of the rail for passive and active control schemes 113
4.10 Ratio of maximum stress as a function of frequency ratio under actual Northridge earthquake 114
4.11 Ratio of maximum stress as a function of frequency ratio under actual El Centro earthquake 115
4.12 Mean plus one standard deviation of the maximum stress in the rail for an ensemble of synthetic ground motions 116
4.13 Fragility curves of the rail for passive and active control schemes 117
4.14 Mean and absolute maximum of peak control force under an ensemble of synthetic ground motions 118
4.15 Schematic of a magnetorheological damper 119
4.16 Mechanical model of MR damper as proposed by Spencer et al. (1997) 120
4.17 Force-displacement relationship of the mechanical model of MR damper under 2.5 Hz sinusoidal excitation for different voltage level 121
4.18 Force-velocity of the mechanical model of MR damper under 2.5 Hz sinusoidal excitation for different voltage level 122
4.19 Mean plus one standard deviation of the maximum stress in the rail for an ensemble of synthetic ground motions 123
4.20 Fragility curves of the rail for different control methods 124
4.21 Fragility curves of the rail for different control methods 125

List of Tables

2.1 Properties of the10-story torsional building 67

2.2 Frequencies of the 10-story torsional building 68

2.3 Moment of inertia and distance from centroid to outermost point for standard T-sections for guide rail 69

2.4 Seismic inputs used in the study 69

3.1 Reduction in maximum stress in the rail with increasing modal damping ratio, actual Northridge earthquake 89

3.2 Modal damping ratio of the rail-counterweight system with additional dampers parallel to the spring at the roller guide assemblies 89

3.3 Reduction in maximum stress with discrete damping devices at the roller guide assemblies, actual Northridge earthquake 89

4.1 Maximum stress in the rail for El Centro earthquake, mass ratio = 10%, frequency ratio = 0.9 126

4.2 Maximum stress in the rail for Northridge earthquake, mass ratio = 10%, frequency ratio = 0.9 126

4.3 Maximum stress in the rail for El Centro earthquake, mass ratio = 20%, frequency ratio = 0.9 127

4.4 Maximum stress in the rail for Northridge earthquake, mass ratio = 20%, frequency ratio = 0.9 127