

UNIVERSITAT POLITÈCNICA DE CATALUNYA



DEPARTAMENT D'ENGINYERIA DEL TERRENY,
CARTOGRÀFICA I GEOFÍSICA

PhD Thesis

Contribution to the Assessment of the
Efficiency of Friction Dissipators for
Seismic Protection of Buildings

Author: **Servio Tulio de la Cruz Cháidez**

Director: **Prof. Francesc López Almansa**

Barcelona, Spain, July 2003

...Construction of earthquake-resistive buildings is a problem with many unknown quantities ranging from the features of the earthquake loads to the characteristics of the buildings involved, and one known stating that the human lives in the buildings in question must be saved in case of an earthquake.

B. Kirikov in 'History of Earthquake Resistant Construction from Antiquity to Our Times'.

To my wife and son

Alma Rosa (Conejita) and *Tulio Martin* (Gusanito)

To my parents

Carlota and *Sócrates*

To my sisters and brothers

Marivel, Aida, Elizabeth and *Maricela*
Jaime, Sócrates and *Francisco Javier*

Contents

Summary	xiii
Resumen	xv
Acknowledgements	xvii
List of Symbols	xix
1 Introduction	1
1.1 Background to this Research	1
1.2 Overview of Structural Control	2
1.2.1 Introduction	2
1.2.2 Passive control	3
1.2.2.1 Seismic isolation	3
1.2.2.2 Energy dissipation devices	5
1.2.2.3 Mass dampers	7
1.2.3 Active and semi-active systems	10
1.2.4 Hybrid systems	14
1.2.5 Summary	14
1.3 Friction Dissipators	16
1.4 Motivation and Objective of this Research	19
1.5 Organization and Thesis Contents	20
2 State of the Art	23
2.1 Introduction	23
2.2 Dry Friction	23
2.2.1 Friction principles	24
2.2.2 Coulomb law of dry friction. Coefficient of friction	24
2.2.3 True contact surfaces	26
2.3 Friction Dissipators (FD)	28
2.3.1 Definition	28
2.3.2 Advantages and disadvantages of friction dissipators	28
2.3.3 Environmental effects	29
2.4 Types of Friction Devices and Structural Implementations	30
2.4.1 Limited slip bolted (LSB) joint	30
2.4.2 Pall's friction damper	33

2.4.3	Sumitomo's friction damper	38
2.4.4	Energy dissipating restraint (EDR)	40
2.4.5	Slotted bolted connections (SBC)	40
2.4.6	Summary	44
2.5	Present Knowledge on Friction Dissipators	45
2.5.1	Numerical simulation of friction dissipators	45
2.5.2	Numerical simulation of buildings equipped with friction dissipators	45
2.5.3	Testing of FDs and buildings equipped with FDs	46
2.5.4	Codes	46
2.5.5	Open questions	47
2.5.5.1	Design criteria	47
2.5.5.2	High frequencies	47
2.5.5.3	Sudden pulses	47
2.5.5.4	Durability	47
2.5.5.5	Seismic efficiency	48
2.5.5.6	Numerical simulation	48
2.6	Contribution of this Thesis to the Present Knowledge	48
3	Numerical Model of Single-Story Buildings equipped with a Friction Dissipator	49
3.1	Introduction	49
3.2	Numerical Model of Friction Dissipators (FD)	49
3.3	Numerical Model of a SSBFD	50
3.3.1	Simplified model	50
3.3.2	Mechanical model	51
3.3.3	Equations of motion of SSBFD	51
3.4	Proposed Solution of the Equations of Motion	53
3.4.1	Step-by-step algorithm	53
3.5	Energy Balance Relations	55
3.6	Numerical Examples	57
3.6.1	Structure description	57
3.6.2	Free vibration	57
3.6.3	Harmonic loading applied to the main structure	58
3.6.4	Seismic input	62
3.7	Comparison between the Proposed Algorithm and ADINA	63
3.8	Efficiency of Friction Dissipators	65
4	Numerical Model of Multi-Story Buildings Equipped with Friction Dissipators	69
4.1	Introduction	69
4.2	Numerical Model of MSBFD	69
4.2.1	Frame with dissipators	69
4.2.2	Mechanical model	70
4.2.3	Equations of motion	70
4.3	Proposed Solution of the Equations of Motion	76
4.3.1	Previous considerations	76

4.3.2	Proposed algorithm	77
4.3.3	Stability and accuracy	83
4.3.4	ALMA program	83
4.4	Practical Applications	86
4.4.1	Pulse loading on a 3-story building	86
4.4.1.1	Description of the structure	86
4.4.1.2	Results	88
4.4.2	Ground acceleration on a benchmark building	88
4.4.2.1	Description of the structure	88
4.4.2.2	Results	92
4.4.3	Ground acceleration on a 10-story building	92
4.4.3.1	Description of the structure	92
4.4.3.2	Results	94
4.5	Comparison between ALMA and ADINA	94
4.5.1	Agreement of results	94
4.5.2	Computational efficiency	95
4.6	Efficiency of Friction Dissipators	98
5	Experimental Study	103
5.1	Introduction	103
5.2	Scale Models	103
5.2.1	Description	103
5.2.2	Determination of the dynamic parameters of the rigs	106
5.2.2.1	Structural model	106
5.2.2.2	Bare frame masses	106
5.2.2.3	Bare frame stiffness coefficients	106
5.2.2.4	Bare frame damping coefficients	109
5.2.2.5	Bracing and FD masses	112
5.2.2.6	Bracing stiffness coefficients	112
5.2.2.7	Bracing damping coefficients	113
5.2.2.8	Summary	113
5.3	Friction Dissipators	114
5.3.1	Description	114
5.3.2	Numerical modelling	114
5.4	Tests	114
5.4.1	Description	114
5.4.2	Single-story model with a friction dissipator (SSMFD)	117
5.4.2.1	Response to a sine-dwell	117
5.4.2.2	Response to the Northridge earthquake	120
5.4.3	Two-story model with friction dissipators (TSMFD)	120
5.4.3.1	Response to the Northridge earthquake	120
5.5	Comparison between Experimental and Numerical Results	122
5.5.1	SSMFD	122
5.5.2	TSMFD	123
5.6	Summary	123

6	Methodology for Assessing the Seismic Efficiency of Friction Dissipators	133
6.1	Introduction	133
6.2	Parametric Analysis	133
6.3	Performance Indices	134
6.3.1	Description	134
6.3.2	Interstory drift index	134
6.3.3	Absolute acceleration index	135
6.3.4	Relative performance index	135
6.3.5	Energy dissipated by friction index	136
6.4	Parameters of the Analysis	136
6.4.1	Description and classification	136
6.4.2	Seismic input	136
6.4.3	Building	137
6.4.4	Dissipators	137
6.4.5	Summary	137
6.5	Design Plots	138
6.6	Robustness Assessment	141
6.7	Preliminary Conclusions	141
7	Conclusions and Final Remarks	143
7.1	Introduction	143
7.2	Summary	143
7.3	Conclusions	144
7.4	Further Research	145
	Bibliography	147
	Appendices	
A	Fundamentals of Contact Analysis	155
A.1	Introduction	155
A.2	Bi-dimensional Contact	155
A.3	Perfect Friction	158
B	Some Aspects of Structural Dynamics	163
B.1	Single-Degree-of-Freedom (SDOF) Systems	163
B.1.1	General formulation	163
B.1.2	Equation of motion with viscous damping	163
B.1.3	Free vibration with viscous damping	165
B.1.4	Free vibration with Coulomb damping	168
B.1.5	Steady-state response to a harmonic input with Coulomb damping	172
B.1.6	Solution of the equation of motion	174
B.1.6.1	Direct analysis in time domain for non-linear systems	174
B.1.6.2	Incremental equation of dynamic equilibrium	174
B.1.6.3	Step-by-step integration	176
B.1.6.4	Summary of the procedure	179
B.1.7	Energy formulation	179

B.2	Multi-Degree-of-Freedom (MDOF) Systems	180
B.2.1	General formulation for buildings	180
B.2.2	Equations of motion	181
B.2.3	Properties of system matrices	185
B.2.4	Solution of the equations of motion using the linear acceleration method	185
B.2.5	Energy formulation	186
C	Solution of Contact Problems using Lagrange Multipliers	189
C.1	Introduction	189
C.2	Restrained Equation of Motion	189
C.3	Method of Lagrange Multipliers	190
C.4	Numerical Solution of the Equations of Motion	191
C.5	The ADINA Program	192
D	Facilities and Testing Equipment	193
D.1	Introduction	193
D.2	Shaking Table	193
D.3	Instrumentation	193
D.3.1	Amplifier	196
D.3.2	Spectra analyzer	196
D.3.3	Accelerometer 'Setra'	196
D.3.4	Displacement transducers 'Celesco' and 'Penny and Giles'	200
D.3.5	Load cell 'Teda'	200
E	Comparison between Experimental and Numerical Results	201
E.1	Introduction	201
E.2	SSMFD Input Data	201
E.3	TSMFD Input data	202
E.4	Results	202

Summary

This Thesis aims to contribute to the evaluation of the efficiency of friction dissipators to reduce the lateral seismic response of buildings. Thus, the global objective is the assessment of the seismic usefulness of friction dissipators.

The research approach to reach the global objective consists of the following steps:

1. To build a reliable and accurate numerical model of the lateral dynamic behavior of multi-story buildings protected with friction dissipators. This algorithm is implemented in a new software code called ALMA. Its accuracy is checked by means of comparisons with results from other commercially available packages.
2. To perform experiments on two reduced-scale models of building structures, with one and two floors, respectively. These experiments are carried out at the University of Bristol, UK.
3. To compare the numerical and the experimental results to calibrate again the proposed model.
4. To perform a comprehensive numerical parametric analysis of the seismic efficiency of friction dissipators.
5. To derive practical conclusions and design guidelines, mainly to obtain the optimal values of the sliding loads.

Steps 1 to 3 are completed while, regarding step 4, the methodology to carry out the analysis is defined. With respect to step 5, preliminary conclusions are issued. Further research needed to reach the global objective is identified.

Resumen

Esta Tesis pretende contribuir a evaluar la eficacia de los disipadores de fricción para reducir la respuesta sísmica lateral de edificios. Por tanto, el objetivo global es la evaluación de la utilidad sísmica de los disipadores de fricción

El procedimiento para alcanzar el objetivo global consta de las etapas siguientes:

1. Construir un modelo numérico, confiable y exacto, para analizar el comportamiento dinámico de edificios de varias plantas equipados con disipadores de fricción. Este algoritmo se implementa en un programa de ordenador llamado ALMA. Su exactitud se comprueba mediante la comparación de sus resultados con otros obtenidos usando programas comerciales.
2. Llevar a cabo experimentos en modelos de edificios a escala reducida: un modelo de una planta y otro modelo de dos plantas. Estos ensayos se llevan a cabo en los laboratorios de la Universidad de Bristol, GB.
3. Comparar los resultados numéricos y experimentales para validar nuevamente el modelo numérico propuesto.
4. Desarrollar un estudio paramétrico de la eficacia sísmica de los disipadores de fricción.
5. Deducir conclusiones prácticas que permitan formular criterios de diseño, principalmente para obtener la carga óptima de deslizamiento de los disipadores.

Las operaciones 1 a 3 anteriores se han completado satisfactoriamente. En cuanto a la etapa 4, se ha definido la metodología para llevar a cabo el estudio propuesto. Con respecto a la operación 5, se han emitido conclusiones preliminares. La investigación futura requerida para completar satisfactoriamente el objetivo global propuesto se ha identificado claramente.

Acknowledgements

I want to thank to my wife and son for their patience. Despite the distance, they were always in my thoughts. My parents, brothers and sisters were always willing to cheer me up when I needed to.

I want to thank to my thesis director, Francisco López Almansa (*'Inge'*), for his guidance, valuable help and overall for his friendship. I would like to thank also to the Department of Geotechnical Engineering and Geosciences of the Technical University of Catalonia for its support, specially to Prof. Luis Pujades.

I want to thank to the National Council of Science and Technology (*CONACYT*) of Mexico for its financial support.

Finally, I want to thank to all my friends whom shared with me great moments and experiences: Ulixes, Fortunato, Esperanza, Andres, Salvatore, Rosangel, Jorge's team (Mata, Cepeda and Alarcon); and the people of the soccer games: Agustin, Arturo, Alberto, Armando, Mauricio, Hugo, Enrique.

Thanks to all of you.

List of Symbols

c	damping coefficient of the main structure
c'	damping coefficient of the dissipators
C	constant of adhesion
\mathbf{C}^{dd}	damping matrix of the bracing system
\mathbf{C}^{ss}	damping matrix of the main structure
\mathbf{D}	vector of material coordinates
D	dynamic magnification factor: $D = x_0/(P_0/k)$
E_D	energy dissipated by viscoelastic damping
E_F	energy dissipated by friction
E_I	input energy
E_K	kinetic energy
E_S	strain energy
\mathbf{f}	vector of contact tractions
\mathbf{F}, F	friction force vector, magnitud of friction force
F^{FD}	friction force along the diagonal brace
F_{\max}	maximum friction force ($ F_{\max} = \mu N$)
g	acceleration of gravity ($g = 980.7 \text{ cm/s}^2, 386.1 \text{ in/s}^2$); gap function
\mathbf{G}	matrix of restrained displacements
H	column height, Housner intensity
i	floor number
k	stiffness coefficient of the main structure, instant
k'	stiffness coefficient of the bracing
k_N	penetration stiffness coefficient
\mathbf{K}^{dd}	stiffness matrix of the bracing system
\mathbf{K}^{ss}	stiffness matrix of the main structure
L	girder length
m	lumped mass acting on the main structure
m'	lumped mass acting on the dissipator
\mathbf{M}^{dd}	mass matrix of the bracing system
\mathbf{M}^{ss}	mass matrix of the main structure
\mathbf{n}	unit normal vector

ns_l	number of sliding dissipators
ns_t	number of sticking dissipators
\mathbf{N}	normal force vector
N	normal force, number of floors
\mathbf{P}, P	vector of external forces, external force
P_0	harmonic loading amplitude
\mathbf{q}_i	differential operator of second order
\mathbf{Q}	vector of internal forces
\mathbf{r}	unit vector
\mathbf{R}	vector of external forces
\mathbf{s}	unit tangential vector
sl	sliding condition
st	sticking condition
S	surface
t	time
T	natural period of the bare frame
T_{br}	natural period of the braced frame
T_d	damped period of the bare frame
T_F	fundamental period of a building
\mathbf{T}^{ss}	vector of periods of the bare frame
u, \dot{u}	relative displacement, relative velocity
u_N	penetration displacement
x, \dot{x}, \ddot{x}	displacement, velocity and acceleration of the main structure
x', \dot{x}', \ddot{x}'	displacement, velocity and acceleration of the friction dissipator
$\mathbf{x}^d, \dot{\mathbf{x}}^d, \ddot{\mathbf{x}}^d$	vectors of displacement, velocity and acceleration of the dissipators
x_0	initial displacement
x^{FD}	sliding displacement along the diagonal brace
x_F	yielding distance
x_g, \ddot{x}_g	ground displacement, ground acceleration
$\mathbf{x}^s, \dot{\mathbf{x}}^s, \ddot{\mathbf{x}}^s$	vectors of displacement, velocity and acceleration of the main structure
\mathbf{W}, W	weight vector, weight
α	dimensionless variable equal to $\tau/\mu\gamma$
β	ratio between the input frequency and the natural one: $\beta = \bar{\omega}/\omega$
γ	normal traction component
λ	root of a second-grade equation, Lagrange multiplier
Δ	increment, displacement
ε_a	prescribed tolerance for the acceleration
ε_f	prescribed tolerance for the friction force
μ	coefficient of static friction
μ_g	coefficient of static friction between mass m and the ground
ξ	damping ratio of the main structure
ξ'	damping ratio of the dissipator

σ	normal stress
τ	shear stress, time
ϕ	phase angle
ϕ^{fric}, ϕ_0	roughness angle
ω	undamped natural frequency of the bare frame
ω_d	damped natural frequency of the bare frame
$\bar{\omega}$	driving force frequency (harmonic loading)
<i>AAI</i>	absolute acceleration index
<i>AED</i>	area under the time-history strain energy plot of the frame with dissipators
<i>AED₀</i>	area under the time-history strain energy plot of the bare frame
<i>EDFI</i>	energy dissipated by friction index
<i>IEI</i>	input energy index
<i>IDI</i>	interstory drift index
<i>MAA</i>	maximum absolute acceleration of the frame with dissipators
<i>MAA₀</i>	maximum absolute acceleration of the bare frame
<i>MID</i>	maximum interstory drift of the frame with dissipators
<i>MID₀</i>	maximum interstory drift of the bare frame
<i>MSE</i>	maximum strain energy of the frame with dissipators
<i>MSE₀</i>	maximum strain energy of the bare frame
<i>OSL</i>	optimal slip load
<i>PGA</i>	peak ground acceleration
<i>RPI</i>	relative performance index

Abbreviations

ADINA	automatic dynamic incremental non-linear analysis
ALMA	a utomatic n on- l inear m atrix a nalysis
EDR	energy dissipating restraint
FD	friction energy dissipation device
LBS	limited bolted slip (joint)
MDOF	multi-story-degree-of-freedom (system)
MSB	multi-story-building
MSBFD	multi-story-building equipped with friction dissipators
SBC	slotted bolted connection
SDOF	single-degree-of-freedom (system)
SSB	single-story building
SSBFD	single-story building equipped with a friction dissipator
SSM	single-story model
SSMFD	single-story model with friction dissipators
TSM	two-story model
TSMFD	two-story model with friction dissipators

