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PhD Thesis

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

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…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*

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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 algoritm 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.

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List of Symbols

c	damping coeficient 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 ($\lvert F_{\text{max}}\rvert = \mu N$)
g	acceleration of gravity ($g = 980.7$ cm/s^2, 386.1 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

nsl	number of sliding dissipators
nst	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	coeficient of static friction between mass m and the ground
ξ	damping ratio of the main structure
ξ'	damping ratio of the dissipador

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)

AAI	absolute acceleration index
AED	area under the time-history strain energy plot of the frame with dissipators
AED_0	area under the time-history strain energy plot of the bare frame
$EDFI$	energy dissipated by friction index
IEI	input energy index
IDI	interstory drift index
MAA	maximum absolute acceleration of the frame with dissipators
MAA_0	maximum absolute acceleration of the bare frame
MID	maximum interstory drift of the frame with dissipators
MID_0	maximum interstory drift of the bare frame
MSE	maximum strain energy of the frame with dissipators
MSE_0	maximum strain energy of the bare frame
OSL	optimal slip load
PGA	peak ground acceleration
RPI	relative performance index

Abbreviations

ADINA	automatic dynamic incremental non-linear analysis
ALMA	**a**utomatic non-**l**inear **m**atrix **a**nalysis
EDR	energy dissipating restraint
FD	fricion 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 fricion dissipator
SSM	single-story model
SSMFD	single-story model with friction dissipators
TSM	two-story model
TSMFD	two-story model with friction dissipators