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Systematic design of unbonded fiber reinforced elastomeric isolators

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ABSTRACT

Fiber reinforced elastomeric isolators (FREIs) comprise alternating bonded layers of elastomer and fiber reinforcement sheets. In an unbonded application the isolator is located in place without any bonding or mechanical fastening provided at its contact supports. The unbonded application results in an increased seismic isolation efficiency, however, it introduces few design limitations as it relies on friction to transfer shear loads, and no vertical tension can be taken by the isolator. These limitations may restrict the use of isolators where the superstructure overturning is of concern or in regions where large vertical ground accelerations are expected. This paper presents a systematic method for the design of structures supported on unbonded-FREIs. The design calculations conform the equivalent static force (ELF) procedure outlined in current seismic codes and account for the vertical component of earthquake in the analysis. A stability parameter has been introduced to verify both the overturning and sliding stability of the isolated system. The efficacy of the design method is illustrated by extensive response history simulations for several prototype frame structures.

1. Introduction

An unbonded fiber reinforced elastomeric isolator (FREI) is an isolator bearing which comprises alternating bonded layers of elastomer and fiber reinforcement sheets and is employed in an unbonded application. In such application the isolator is placed between the superstructure and substructure without bonding or any mechanical fastening (Fig. 1a). As a result of unbonded application and also the lack of flexural rigidity of fiber reinforcing layers, the isolator experiences a unique rollover deformation under the application of horizontal shear loads. During rollover deformation the contact surfaces of isolator are partially rolled off the top and bottom supports (Fig. 1b and c). Therefore, the effective horizontal stiffness of the isolator is beneficially decreased with its increasing rollover deformations [1]. This phenomenon results in an increased seismic isolation efficiency.

Research on unbonded-FREIs has gained increasing attention in the recent past. The load-deflection response of the prototype isolators has been investigated experimentally by many scholars e.g., [1–6]. Analytical models have been developed to predict the vertical, bending, and horizontal stiffness values of unbonded-FREIs [2,7,8]. The load-deflection response of the isolators has been simulated with the aid of finite element methods [9–13]. Shake table testing on test-structures supported on unbonded-FREIs have been conducted [14,15]. The response history of isolators under the application of ground accelerations have been simulated [16–18]. The rollout instability [19,20] and potentials for relative slip [21] at the contact surfaces of the unbonded-isolators have been investigated experimentally. The common outcome of the previous research studies is that unbonded-FREIs offer desirable response characteristics as seismic isolators. Furthermore, there is a significant potential for this type of isolators to perform as a cost-effective strategy for seismic mitigation of many structures including ordinary buildings.

Despite the increased seismic isolation efficiency, the unbonded application introduces a few design limitations in comparison to conventional elastomeric isolators which are employed in bonded applications. Unbonded-FREIs are not capable of taking tensile forces, making them inappropriate for situation where the superstructure overturning is of concern or in regions where large vertical accelerations are expected. Additionally, since unbonded FREIs rely on friction to transfer horizontal shear forces, permanent slip at the contact surfaces of isolator could occur. The occurrence of slip depends on the level of compression at the contact surface of the isolator, as well as the rate of lateral displacements imposed on the isolator. For any given rate of lateral displacement, a minimum-level of vertical compression can be found such that prevents permanent slip at the contact surfaces of isolator [21]. Concerns over both transfer of tensile forces (i.e., overturning instability) and permanent slip (sliding instability) must be

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Nomenclature

a	width of isolator
A_{eff}	effective plan area of isolator
b	length of isolator in the direction of shear loading
B_M	numerical coefficient for effective damping of the isolation system at the maximum displacement
C	damping coefficient of the isolator in Fig. 7a
D_M	maximum displacement of the isolation system at the maximum considered earthquake (MCE)
D_{max}	maximum displacement demand in the isolation system
F_a	short-period site coefficient
F_v	long-period site coefficient
$F_{v,i}$	effective vertical load acting on bearing isolator i
F_k	total horizontal force applying on Level k of the superstructure
g	acceleration of gravity
G	shear modulus of rubber material within the isolator
h	overall thickness of isolator
H_k	height of Level k above the base isolation system
H	total height of superstructure
k_h	stiffness of the horizontal nonlinear spring in Fig. 7a
$k_{H,eff}$	effective horizontal stiffness of the isolator
k_M	effective horizontal stiffness of the isolator at maximum displacement D_M
K_M	horizontal stiffness of the isolation system at the maximum horizontal displacement
kv	stiffness of the vertical spring in Fig. 7a
L	length of superstructure in the direction of shear loading
M_R	overturning-resisting moment
M_O	overturning moment
n	number of elastomer layers within the isolator
N_C	number of isolators (columns) in the isolation system
N_H	number of stories in the superstructure
N_P	number of isolators that carry a compressive stress greater than P_{min}
N_R	number of isolators which remain under vertical compression
p_i	vertical compression applied on isolator i.
Ri	vertical reaction force of isolator i
R	aspect ratio (the ratio of length to total thickness) of isolator
S	shape factor (the ratio of plan area to perimeter area of a single elastomer layer) of isolator
S_1	mapped MCE, 5 percent damped, spectral response acceleration parameter at a period of 1 s
S_s	mapped MCE, 5 percent damped, spectral response acceleration parameter at short periods
S_{M1}	the MCE, 5 percent damped, spectral response acceleration at a period of 1 s adjusted for site class effects
S_{MS}	the MCE, 5 percent damped, spectral response acceleration at short periods adjusted for site class effects
SF_{ove}	superstructure safety factor against overturning
t	thickness of individual elastomer layers within the isolator
t_{cover}	thickness of cover elastomer layers of the isolator
tf	thickness of individual fiber reinforcement layers within the isolator
tr	total thickness of elastomer layers in the isolator
T_D	design effective period of the base isolated structure
T_F	fundamental period of the fixed-base superstructure
T_M	maximum effective period of the base isolated structure
V_S	base shear of the superstructure
W_k	the effective weight lumped at Level k
w	the effective weight of superstructure that is supported by an individual isolator
W_T	total effective weight of superstructure
W_{T-av}	effective weight of superstructure including the upward direction of ground acceleration
W_{T+av}	effective weight of superstructure including the downward direction of ground acceleration
W_{eff}	total effective weight of superstructure in the analysis (any of W_T, W_{T+av}, or W_{T-av})
Z	stability parameter as defined in Eq. (11)
α	ratio of base isolated to fixed base period of structure
δ_i	horizontal displacement of bearing isolator i
δ_{fc}	full contact horizontal displacement of isolator
$\sigma_{v,i}$	effective vertical compression that is applied on an isolator at time step i
ε	a maximum permissible error (defined by user)

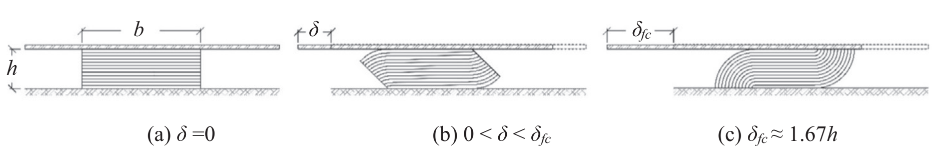

Fig. 1. An unbonded-FREI under the effect of various lateral displacements δ.

addressed in the design of a seismic isolation system that employs unbonded-isolators. The main objective of this paper is to propose a systematic methodology that addresses the said concerns in the design of unbonded-FREIs. The design calculations are based on the equivalent lateral force (ELF) procedure outlined in ASCE/SEI 7-10 [22]. The vertical component of earthquake is accounted for in the analysis as it may affect adversely both the overturning and sliding stability of the superstructure. The efficacy of the proposed design method for a large group of frame structures has been examined by extensive time history analysis runs that include both the horizontal and vertical components of ground accelerations in the analysis.

2. Preliminary design of unbonded fiber reinforced isolators using the equivalent lateral force (ELF) procedure

The provisions of ASCE/SEI 7-10 [22] have been employed in this paper for the preliminary design of a typical unbonded-FREI shown in Fig. 1. The preliminary design is carried out on the basis of the algorithm shown in Fig. 2. As seen in this figure the amplitudes of a set of design parameters are defined by the user before the design calculations are initiated. One of the essential steps in the design is the calculation of lateral displacement of the isolator, D_M, for the maximum considered earthquake (MCE) based on the following code specified relationship: