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TESTING PROTOCOLS AND ACCEPTANCE CRITERIA FOR PERFORMANCE CHARACTERIZATION OF PENDULUM ISOLATORS

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Abstract

This paper addresses common issues of testing requirements for seismic isolators in current building standards. The extensive results collected from current prototype tests are only partially utilized to support structural models and design procedures, which often rely on a number of assumptions and simplifications that may significantly affect the prediction of the isolation system performance. The unique database of the behavior of full scale seismic isolators, subjected to a wide range of seismic actions at the experimental facility of the University of California San Diego, is used for a rational review of current testing protocols, with the aim of simplifying and refining pendulum isolators' performance characterization process. At the same time, observed ranges of variation of critical response parameters allow to propose physically motivated acceptance criteria for the most common technologies currently in use. Examples are provided to show how the results from revised testing programs can be integrated into the design of isolated structures preventing over-simplification in the modelling phase of the device performance.

Keywords: Seismic isolation; testing protocols; property modification factors; pendulum isolators

1. Introduction

Prototype testing protocol is a crucial step in the development of seismic isolation systems. Proper assessment of the isolation devices' performance is required in order to prove the system capabilities that protect the isolated structure. The design and testing of seismically isolated civil structures in the United States is regulated by the American Society of Civil Engineering Standard ASCE-7 [1]. The importance of prototype testing was early recognized in Standards incorporating the use of seismic isolation systems [2]. The experimental variability of design parameters for seismic isolators was extensively investigated in [3], in which the use of property modification factors was proposed to bound the properties of seismic isolation systems within acceptable values. As in other standards such as the AASHTO Guide Specification for Seismic Isolation Design [4] and the Eurocodes [5], the most recent ASCE 7-16 use property modification factors (λ) to account for the variation of the isolators' performance parameters due to a variety of effects, including cyclic motion, loading rate, variability in production, temperature, aging, and environmental exposure and contamination.

The practical advantage of the property modification factors approach over other approaches relies on allowing the use of simplified predictive models based on upper and lower bound characteristics rather than sophisticated models that consider all sources of parameters variability. Idealized bilinear lateral force-displacement models are used for common seismic isolators. These models rely on a limited number of nominal design parameters such as friction and restoring stiffness for sliding isolator [6] and characteristic strength, post-elastic stiffness and yield displacement for lead rubber isolators [7]. The actual mechanical properties of an isolation system during an earthquake are expected to differ from the nominal values used in the analyses while remaining confined between the boundary limits. The main limitations of this approach consist in the difficult translation of the experimentally observed behavior into nominal design parameters and reliable modification factors (λ) that can be safely used for the design. Since the first use of property modification factors, the availability of new experimental evidence from extensive testing programs has been constantly incorporated into the definitions of updated upper and lower bound values. Modification were proposed in [5a] to properly account for scragging phenomena and strain rate effects on elastomeric isolators. Further updates for elastomeric isolators were later proposed by [5b], which also included the definition of property modification factors for sliding isolators. As the technology advances and new materials/designs are incorporated into modern seismic isolators, additional sources and entities of variability for isolators' properties are evidenced by prototype tests, which need to be included into current Standards. Even during a single test, mechanical properties of isolators may significantly vary, and diverge from nominal design parameter [10], which makes the interpretation of experimental data controversial.

One of the major amendments in the ASCE 7-16 is the presentation of a modified rational approach to property modification factors for seismic isolators [11]. The procedure suggested by the ASCE-7 is presented and discussed in light of available full scale experimental data on sliding pendulum isolators. This study focuses on the modification factors λ_{test}, which account for the variability of the design parameters during protocol tests. A regular reinforced concrete building equipped with single pendulum isolators is used as a reference case study. The current characterization procedures from the ASCE 7-16 are discussed for the case study. A recent friction coefficient model [12] is used in order to perform detailed structural analysis and to simulate the isolators' performance when not experimentally available. Based on the observed discrepancies between the simulated behavior of the structure and the simulated testing data, modifications are proposed to the current testing adequacy verifications of the ASCE 7-16.

2. Research significance

The use of property modification factors is a simplified way of accounting for the inherent variability of seismic isolators' properties, and is strictly paired with standardized prototype testing protocols. An experimental model, validated against a unique set of data from an extensive experimental campaign, is used to predict the expected variability for friction isolators during seismic events in comparison with recent prototype tests proposed by the revised ASCE 7-16. This comparison is aimed at evaluating the adequacy of testing protocols and acceptance criteria, and at verifying their level of comprehensiveness and severity. Modifications of the current prototype testing protocol are proposed in order to represent expected seismic shaking conditions, and to allow a comprehensive characterization of the isolators' performance.

3. Experimental evidence and model

Experimental tests on full scale pendulum isolators show that the restoring forces developed at the curved sliding interfaces are only affected by the level of the applied vertical force [12], while the coefficient of friction may depend on a variety of factor [13, 14, 15]. For typical steel-polymer interfaces, the four main effects affecting the coefficient of friction μ are:

1. "Breakaway effect", i.e. the sudden increase of μ at each motion beginning/reversal;
2. "Load effect", i.e. the reduction of μ for increasing contact pressure;
3. "Cycling effect", i.e. the continuous reduction of μ due to the increasing temperature of the sliding interface induced by cyclic sliding;
4. "Velocity effect", i.e. the gradual increase of μ with the increasing sliding velocity.

These effects may significantly affect the frictional performance of the even within the duration of a single test. A detailed experimental model for the variation of the frictional properties was demonstrated as suitable for capturing most of the effects of load, velocity, and repetitive motion (cycling). The experimental data used for the model calibration derived from an extensive mono- and bi-directional test campaign conducted on full-scale single-pendulum isolators under a wide range of vertical loads and velocity [12, 13]. Exemplificative experimental and predicted force-displacement loops are presented in Fig. 1 for two different levels of vertical load.

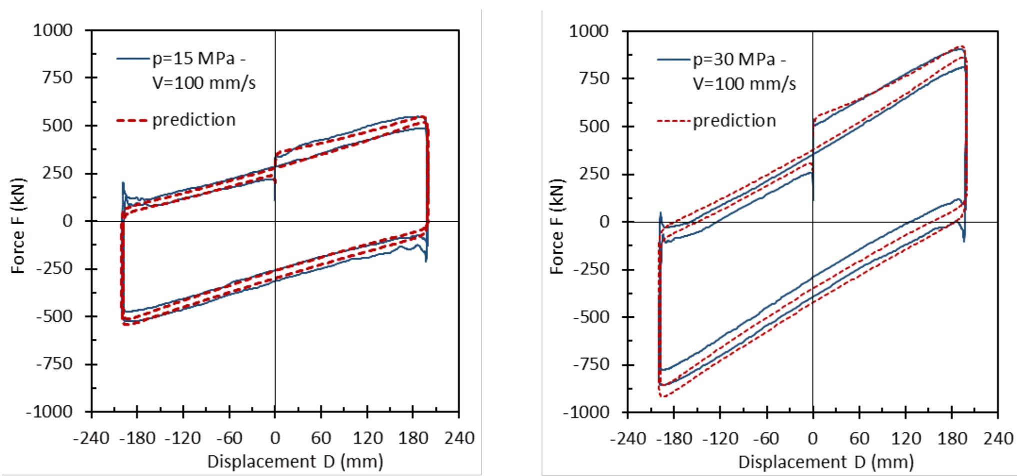


Fig. 1 – Exemplificative experimental and predicted force-displacement loops

The proposed friction model accounts for load, velocity, and cycling effects through the functions $f_N(N)$, $f_v(v)$, and $f_C(C)$, respectively:

$$\mu(N,C,v) = f_N(N) \cdot f_C(C) \cdot f_v(v) \tag{1}$$

In this study, a modification to the original formulation was implemented in order to allow the application of the model to isolators of different size with respect to the specimens actually tested. The parameters affected by scale effects are N_{ref} and C_{ref}, as presented hereafter.

Vertical load effect. This effect is accounted for through the function:

$$f_N(N) = \mu_{s0} \cdot e^{-N/N_{ref}} \tag{2}$$

where μ_{s0} = 0.103 = zero-load static coefficient of friction, N>0 vertical compression load on the isolator, $N_{ref} = \sigma_{ref,0}\, \pi a^2$ = load associated to a 63% friction reduction, a = 180 mm = in-plane radius of the slider, and $\sigma_{ref,0}$ = 121 MPa = average contact pressure associated to a 63% friction reduction, determined as

$$\sigma_{ref,0} = N_{ref,0} /(\pi a_0^2) \tag{3}$$

in which the subscript *0* refers to variables of the isolator actually tested.

Velocity effect. The velocity effect is described by:

$$f_v(v) = \gamma + (1-\gamma) \cdot e^{-|v|/v_{ref}} \tag{4}$$

where v = sliding velocity, γ = 1.4 = fast / slow friction coefficient ratio, v_{ref} = 10 mm/s = experimental value of v related to a 63% increment of the coefficient of friction.

Cycling effect. Degradation of the coefficient of friction due to sustained motion is taken into account by:

$$f_C(C) = e^{-(C/C_{ref})^\beta} \tag{5}$$

where β = 0.5 = exponential rate of the friction degradation determined from experimental data, C = cycling variable with the dimension of a heat rate evaluated as

$$C(t) = \frac{2}{a\pi} \int_{t_0}^{t} N v^2 dt \tag{6}$$

in which N= vertical compression load, v=sliding velocity, a=in-plane radius of the slider, C_{ref} = value of the variable C associated with a 63% friction reduction for cycling effects: $C_{ref} = c_{ref,0}\, \pi A^2$, A = in-plane radius of the concave surface, and

$$c_{ref,0} = C_{ref,0} /(\pi A_0^2) \tag{7}$$

where the parameters of the tested isolator are: $C_{ref,0}$ = 5766 kN/ms and A_0 = 435 mm.

The experimental validation of the model [12, 13] proved the importance of considering appropriate vertical loads, sliding velocity, and generated heat flux (or cycling variable) for the assessment of the seismic behavior of friction isolators. A similar experimental model relying on three functions for the above mentioned effects was presented later by [16], proving the importance of the inclusions of these effects in the analysis of seismic isolaton systems. Consistently, the ASCE 7-16 (Sec. 17.8.2) requires that prototype tests protocols shall be based on preliminary structural analysis of the structural system, to determine the expected levels of vertical load, wind lateral force, lateral displacement, as well as effective vibration periods.

3. Test protocol and adequacy requirements

The ASCE 7-16 prototype testing protocol suggests the sequence of tests summarized in Table 1. Three different levels of vertical loads are considered:

1. Vertical load level 1 (average): 1.0D + 0.5L

2. Vertical load level 2 (maximum): 1.2D + 1.0E + 1.0L +0.2S
3. Vertical load level 3 (minimum): 0.9D + 1.0E

where D = Dead Load, L = Live Load, S = Snow Load, E = Earthquake Load (Maximum Considered Earthquake MCE). A total of 8 tests need to be performed including repetitions of test #2 for 3 vertical loads, and of test #5 for 2 vertical loads.

The above mentioned variability of the coefficient of friction is acknowledged by the ASCE 7-16 that defines modification factors that shall be applied to the friction properties of pendulum isolators for the structural analysis. No modification factors are instead applied to the restoring stiffness property. The seven requirements that need to be satisfied in order to verify the specimen adequacy for each individual isolator (Sec. 17.8.4 ASCE 7-16) are summarized in Table 2. However, only requirements # 3 to 6, are used to verify the adequacy of nominal design values of the coefficient of friction, and the variability of the coefficient of friction for the above mentioned effects. An indirect check of the variability of the friction properties is carried out through the variation of the effective stiffness k_{eff}, and damping ratio ξ_{eff}. This indirect check raises the question of the adequacy of the current procedures, as they are not directly related to the sources of variability experienced during testing.

Table 1 – Sequence and cycles of prototype tests for ASCE 7-16

Test	Vertical load	# of cycles per displ. level	Peak displacement	Peak force	Period
1	1	20	-	F_W	T_M / - (1)
2	1, 2, 3	3	$0.25D_M$, $0.5D_M$, $0.67D_M$, $1.0D_M$	-	T_M / - (1)
3	1	3	$1.0D_M$	-	T_M / - (1)
4	1	$30S_{M1}/(S_{MS}B_M) \geq 10$ (2)	$0.75D_M$		T_M / - (1)
5	2, 3 (3)	1	$1.0D_M$		-

Notes:

(1) Dynamic testing at the effective period T_M are not required if dynamic prototype testing has already being performed on similar sized isolators, at similar loads, velocity, and displacement

(2) S_{MS} and S_{M1} are the Maximum Considered Earthquake spectral acceleration values at short periods and 1 sec period, respectively. B_M is the spectrum reduction factor that accounts for the effective damping of the isolation system. Dynamic testing is performed in sets of 5 cycles.

(3) Maximum and minimum downward vertical load on any one isolator of an individual type must be used, instead of average maximum and minimum values

Table 2 – Specimen adequacy requirements according to ASCE 7-16

Req. #	Reference tests	Specimen adequacy requirement
1	1, 2, 3, 4	$dF/dx > 0$
2	3	$\lambda_{spec,min}-5\% \leq k_{d,av}/(\Sigma\, k_{d,av}/N) \leq \lambda_{spec,max}+5\%$ $\lambda_{spec,min}-5\% \leq E_{loop,av}/(\Sigma\, E_{loop,av}/N) \leq \lambda_{spec,max}+5\%$
3	2, 3	$\lambda_{test,min} \leq k_{d,i}/k_{d,nom} \leq \lambda_{test,max}$ $0.85 \leq k_{eff,i}/(\Sigma k_{eff,i}/N) \leq 1.15$
4	4	$0.80 \leq k_{eff,i}/k_{eff,1} \leq 1.20$
5	4	$\lambda_{test,min} \leq k_{d,i}/k_{d,nom} \leq \lambda_{test,max}$ $\lambda_{test,min} \leq E_{loop,i}/E_{loop,1} < \lambda_{test,max}$
6	4	$0.80 \leq \xi_{eff,i}/\xi_{eff,1}$
7	5	Stability

Notes:

F and x are the lateral force and lateral deflection, respectively

k_d and k_{eff}, are post-yield and effective stiffness, respectively

E_{loop}, and ξ_{eff} are energy dissipated per cycle and effective damping ratio, respectively

Subscripts $_1$, $_i$, $_{av}$, and $_{nom}$ mean 1st cycle, i-th cycle, average value for all cycles in a single test, and nominal value

N is the number of tested isolators of a common type

In addition, current testing protocols are not suited for calibration of detailed friction models. The sources of variability of the coefficient of friction are not directly addressed by any specific tests. Extrapolation of useful data from the current testing procedures may be complicated and can discourage the use of most accurate predictive models. The adequacy of the current testing protocol will be investigated for a specific case study.

5. Case study

A reinforced concrete moment-frame structure is used as reference case study to initiate the prototype testing procedure. The structure consists of 5 floors with inter-storey height of 3.0 m. Each floor is square in plan and is supported by double-bay 5.0 m span beams in longitudinal and lateral directions.

The ASCE 7-16 standard implies the use of simplified models for sliding isolators. Upper-bound and lower-bound friction values are used to account for any possible variation of the friction properties (Sec. 17.2.8.4 ASCE 7-16). The upper-bound and lower-bound modification factors applied to the friction properties are λ_{max} = 2.1 and λ_{min} = 0.6. These values are determined upon λ_{ae} factors ($\lambda_{ae,max}$ = 1.56 and $\lambda_{ae,min}$ = 1.0, accounting for variability due to environmental exposure and aging), λ_{test} factors ($\lambda_{test,max}$ = 1.3 and $\lambda_{test,min}$ = 0.7, for heating and sliding rate effects), and λ_{spec} factors ($\lambda_{spec,max}$ = 1.15 and $\lambda_{spec,min}$ = 0.85, accounting for manufacturing variability).

Two analyses are completed with a lower and higher limit of the friction coefficient obtained by multiplying the λ_{min} and λ_{max} for the nominal coefficient of friction $\mu = 0.08$, assumed for load combination 1. A state-of-the-practice SAP 2000 © model is used to evaluate the structural response of the isolated building. The isolators are modeled through nonlinear T/C friction isolator links, with a nominal effective radius of curvature R=2450 mm. Sets of accelerograms from the three ground shaking events reported in Table 3 are used to simulate three different Maximum Considered Earthquake (MCE) conditions. Nonlinear time history analyses with the two lateral components of each ground motion are used to determine the expected seismic performance of the isolation system.

Table 3 – Ground shaking events

Name	Year	Earthquake	Mw	Mech.*	Station	Site	PGA (g)	PGV (cm/s)	PGD (cm)
LP	1989	Loma Prieta	7.0	OB	LGPC	Soil	0.56	94.8	41.1
KO	1995	Kobe	6.9	SS	KJMA	Stiff soil	0.82	81.6	17.7
ER	1992	Erzincan	6.7	SS	Erzincan	Soil	0.50	64.3	21.9

* Fault Mechanism = SS Strike-slip; OB Oblique

6. Simulated testing protocols

Peak displacement (D_M) and effective period (T_M) are extracted from the preliminary structural analysis, in order to establish a prototype testing protocol. The peak displacement D_M is evaluated as the largest displacement value from upper- and lower-bound analyses under bi-directional input. The effective period T_M is instead determined as the lower of those determined from upper-bound and lower-bound values. For lack of better specifications, the effective period was based on bi-directional rather than mono-directional motions.

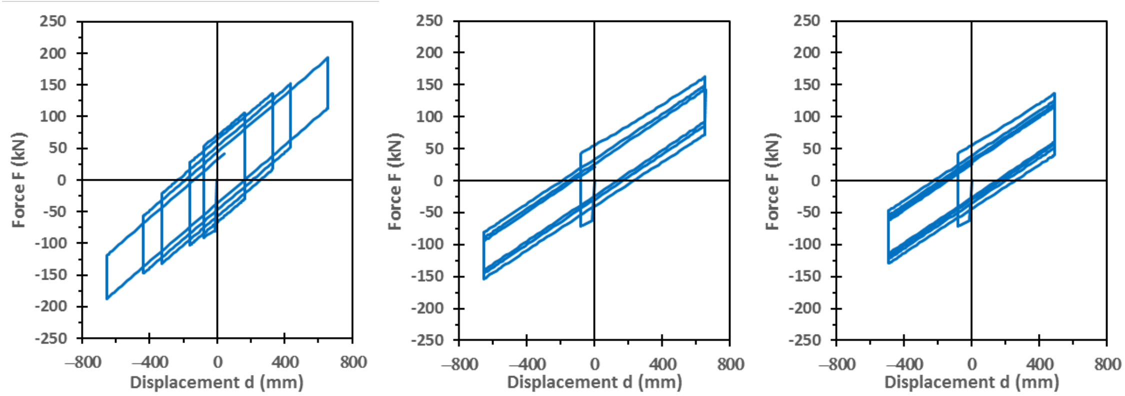
Values of D_M and T_M from structural analyses based on upper-bound, lower-bound and nominal values are summarized in Table 4, with percentage differences from nominal values in brackets. A consistent trend for the variation of the peak displacement with the coefficient of friction is not evidenced. For the Erzincan earthquake, an unexpected larger displacement is determined by using upper-bound values rather than lower-bound values. This is most probably due to a combination of the nonlinear response of the isolation system, the bi-directional nature of the input, and the shape of the acceleration record. The values in bold in Table 4 were used to define test parameters for the experimental campaign.

Table 4 – Peak displacement and effective period from preliminary analysis

	Peak displacement D_M (mm)			Effective period T_M (s)		
Event	Upper-bound	Nominal	Lower-bound	Upper-bound	Nominal	Lower-bound
LP	188 (-60%)	466	**656** (+41%)	**2.01** (-5%)	2.50	2.64 (-5%)
KO	155 (-59%)	375	**525** (+40%)	**1.90** (-5%)	2.39	2.55 (-5%)
ER	**255** (+12%)	228	217 (-5%)	2.19 (-5%)	2.13	**2.10** (-5%)

Vertical loads are also extracted, in order to define the three values of axial force to be applied to the isolators during testing. Vertical loads of 440 kN, 573 kN, and 344 kN are determined for the three above mentioned load combination 1, 2 and 3, respectively.

For each MCE event, the complete testing protocol of Table 1 was simulated by using the friction model presented above. Exemplificative simulated force-displacement loops are shown in Fig. 2 based on the LP event.



a) b) c)

Fig. 2 – Force-displacement loops for: a) test 2 (ascending, N=573 kN), b) test 3, and c) test 4

The results of the simulated tests are summarized in Table 5 in terms of adequacy requirements. In two of the three considered earthquake scenarios, the isolators failed the adequacy checks (values in bold). A detailed discussion of the specimen adequacy requirements is presented in the next section.

Table 5 – Verifications of the ASCE 7-16 adequacy requirements # 3 to 6

Req. #	Reference tests	Specimen adequacy requirement	LP		KO		ER	
			min	max	min	max	min	max
3	2, 3	$0.70 \leq k_{d,i}/k_{d,nom} \leq 1.30$	0.96	1.00	0.94	0.99	0.81	0.97
4	4	$0.80 \leq k_{eff,i}/k_{eff,1} \leq 1.20$	0.95	1.00	0.94	1.00	0.90	1.00
5	4	$0.70 \leq k_{d,i}/k_{d,nom} \leq 1.30$	0.93	0.99	0.91	0.99	0.86	0.98
		$0.70 \leq E_{loop,i}/E_{loop,1} \leq 1.30$	**0.65**	1.00	**0.66**	1.00	0.73	1.00
6	4	$0.80 \leq \xi_{eff,i}/\xi_{eff,1}$	**0.69**		**0.70**		0.80	

7. Discussion of specimen adequacy requirements

Based on the results from the simulated tests, the following considerations are carried out for the ASCE 7-16 testing protocols and adequacy requirements.

Requirement #1 targets possible softening behavior of the isolator for increasing levels of displacement. A softening behavior is not expected in pendulum isolators, unless a mechanical failure occurs. This requirement is currently assessed on tests 1, 2, 3, and 4, but may be verified based on tests 1, 4 and 5. Test 5 appears preferable as it includes maximum levels of displacement under the largest vertical load (level 2).

Requirement #2 addresses the adequacy of the manufacturing process in terms of restoring stiffness and energy dissipated per loop, which is a direct representation of the frictional property of the isolator. Tests 1 and 5 can be used in substitution of the required test 3, as they provide minimum and maximum repeated stress conditions for the isolator.

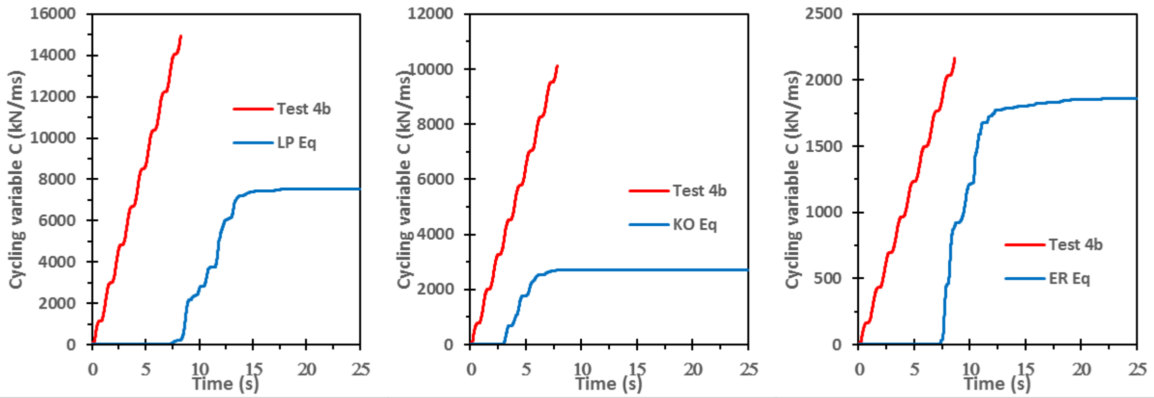
Requirement #3 aims at verifying the consistency of the restoring stiffness. The restoring stiffness depends on the geometry of the isolator and the level of compression force. The restoring stiffness k_d appears marginally affected by the testing conditions, as it is related to the geometry of the sliding surfaces and the vertical compressive load, which is kept constant during the tests. The reduction of the coefficient of friction due to cycling effects produces an apparent reduction of the restoring stiffness. This apparent variation is more significant in tests with lower level of lateral displacement, as proved by the maximum reduction of -19% detected for the ER test 2. Being most significantly affected by cycling effects, results from test 4 can be used rather than from test 3.

The requirement also addresses the variability in effective stiffness among tests on similar isolators, which is not directly representative of the variability of any individual physical parameters of the isolators. The variability of the coefficient of friction has minor effects on the effective stiffness k_{eff} of the isolators. The maximum reduction (-10%) of the effective stiffness due to cycling is observed for the ER test. This requirement may be removed, and as a direct control of the variability of the friction property is already performed in Req. #2.

Requirement #4 focuses on the effective stiffness variation during a single test. This requirement is again not representative of the actual variation of the friction property, and may be removed. The variability of coefficient of friction is already addressed by Req. #5.

Requirement #5 relates to the variability of the restoring stiffness and the energy dissipated per loop during test #4. The requirement about the variability of the restoring stiffness may be removed, since a similar check is already provided in Req. #3. The variation of the energy dissipated per loop is equivalent to the variation of the average coefficient of friction during each loop of the test. This variation includes velocity and cycling effects while it neglects any load effect on the frictional properties. This adequacy requirement is aimed at avoiding uncontrolled reduction of the coefficient of friction due to heating phenomena even though the related test cannot isolate this single phenomenon from the effect of velocity. The dissipated energy per loop E_{loop} is not expected to increase from the first cycle to following cycles for any of the possible effects affecting the coefficient of friction. The velocity effect causes an increase of the coefficient of friction, which is however the same in each deformation cycle of test 4. Also, the load effect is not affecting the coefficient of friction as the vertical compressive load is held constant during the test. Based on the predictive model, the cycling effect is responsible for a significant reduction of the coefficient of friction (up to -51% for the LP test 4), which is directly related to the reduction of the dissipated energy per cycle (up to -35% for the LP test 4). The entity of the reduction of the dissipated energy is so significant that results in the rejection of the isolator.

Even though load effects are neglected, test 4 may be appropriate to verify the variability of the coefficient of friction during the design seismic event, because the vertical load on the isolator is on average approximately equal to load level 1 during a full seismic displacement cycle. However the number of cycles of the test was found to be in disagreement with the actual cycling degradation during the design seismic event. A comparison between the earthquakes and the tests 4 is here presented in terms of cycling variable, which represents the heat generated during the sliding motion and is related to the average increase in temperature of the sliding surface (Fig. 3).



a) **b)** **c)**

Fig. 3 – Cycling variable vs time for earthquake and test 4: a) Loma Prieta, b) Kobe, and c) Erzincan

It is evident from the plots that the cycling variable associated with the tests is generally higher than the cycling variable associated with their relative earthquakes. This is indicative of a higher heat generation during the tests, with respect to the heat generated during the seismic event. The largest differences are evidenced for the LP event (+99%) and the KO event (+275%), while a smaller difference is noticeable for the ER event (+16%). These results suggest that test 4b is not representative of the thermodynamic phenomena associated with seismic events. As a consequence, it may be excessively conservative for some design earthquakes, and induce unrealistic reductions of the coefficient of friction. Friction isolator may then be considered inadequate based on adequacy Req. # 5. It is the Authors' opinion that the prototype testing protocol shall account for realistic thermodynamic effects. A revision of the testing protocol is envisioned in order to modify Req. # 5 to make it more representative of real loading conditions, with the key parameter being the cycling variable C. Variation of the energy dissipated per cycle and the damping ratio shall be verified for levels of the cycling variable comparable to those expected in seismic events. In case of dynamic analyses, a practical way of implementing these considerations could be to limit the adequacy requirements verification from test 4 to the first loop that exceeds the maximum cycling variable value determined by the preliminary structural analysis. For the analyzed cases, the verification for the LP and KO inputs shall be limited to the third and second displacement loop, respectively. By doing so, the reduction in E_{loop} with respect to the first loop would be limited to -27% for the LP test, and to -17% for the KO test. These values would be a better representation of the design shaking conditions and would guarantee adequacy of the isolators by ASCE 7-16 (greater than $\lambda_{test,min}$ = 0.70).

Requirement #6 is aimed at limiting uncontrolled variations of the effective damping ratio during a single test. The reduction in damping ratio may be significant (up to -31% for the LP test 4) and is partially contained by the simultaneous reduction of the energy dissipated per cycle E_{loop} and of the effective stiffness k_{eff}. The effective damping ratio is not directly representative of the actual variation of the friction property, and may be removed. The variability of coefficient of friction is already assessed by Req. #5.

Requirement #7 relates to the overall stability of the isolator at the maximum displacement level. Since an unstable behavior for pendulum isolators can only be induced by high downward forces, the requirement may be considered satisfied by only considering the maximum level of vertical load (level 2) in test #5.

8. Proposed testing protocols and specimen adequacy requirements

Based on the previous analysis, the following testing protocol and specimen adequacy requirements are proposed. The proposed tests are summarized in Table 6. Tests P1, P2 replace tests 1, 4, while test P3 replaces tests 2, 5. Tests 3 is not included in the proposed protocol, as it is mostly suited for rubber isolators, for which the force-displacement property is affected by the strain level in the rubber. For pendulum isolators, instead, intermediate levels of displacement are not expected to cause any source of variation on the isolators' physical properties.

Table 6 – Proposed sequence and cycles of prototype tests

Test	Vertical load	# of cycles per displ. level	Peak displacement	Peak force	Period
P1	1	20	-	F_W	T_M
P2	1	$30S_{M1}/(S_{MS}B_M) \geq 10$ (1)	$0.75D_M$		T_M
P3	1, 2, 3	3	$1.0D_M$		T_M

Notes:
(1) S_{MS} and S_{M1} are the Maximum Considered Earthquake spectral acceleration values at short periods and 1 sec period; B_M is the spectrum reduction factor that accounts for the effective damping of the isolation system. Dynamic testing is performed in sets of 5 cycles.

The proposed adequacy requirements are presented in Table 7. The requirements about variability of effective stiffness and damping ratio are removed from the list, while the variability requirements for restoring stiffness and energy dissipated per cycle are condensed in Req. #P3.

Table 7 – Proposed specimen adequacy requirements

Req. #	Reference tests	Specimen adequacy requirement
P1	P1, P2, P3	$dF/dx > 0$
P2	P1, P2, P3	$\lambda_{spec,min}\text{-}5\% \leq k_{d,av}/(\Sigma\, k_{d,av}/N) \leq \lambda_{spec,max}+5\%$ $\lambda_{spec,min}\text{-}5\% \leq E_{loop,av}/(\Sigma\, E_{loop,av}/N) \leq \lambda_{spec,max}+5\%$
P3	P2	$\lambda_{test,min} \leq k_{d,i}/k_{d,nom} \leq \lambda_{test,max}$ $\lambda_{test,min} \leq E_{loop,i}/E_{loop,1} < \lambda_{test,max}$
P4	P3	Stability

The combined variability due to velocity and cycling effect may be assessed through test P2. However, the number of loops considered in order to determine the maximum variation shall be limited to account for the expected maximum value of cycling variable during the design earthquake.

In case the coefficient of friction exceed the limits set by the modification factors $\lambda_{test,min}$ and $\lambda_{test,max}$, the designer shall have the opportunity of using a more refined friction model from the tests, in order to assess the seismic behavior of the isolated structure. With this aim, three tests are proposed for the evaluation of the load, velocity and cycling effects.

The vertical load effect can be assessed through a quasi-static test in which velocity and cycling effects are negligible. A triangle displacement pattern is used, and the downward force is varied from the minimum value Load 3 (but not less than 20% Load 1) to the maximum value Load 3 by means of a linear function. The displacement pattern, and the vertical load pattern are presented in Fig. 4. A 300 s duration was used in this case to keep the sliding velocity below 2.5 mm/s. The maximum displacement reached in the test is D_M.

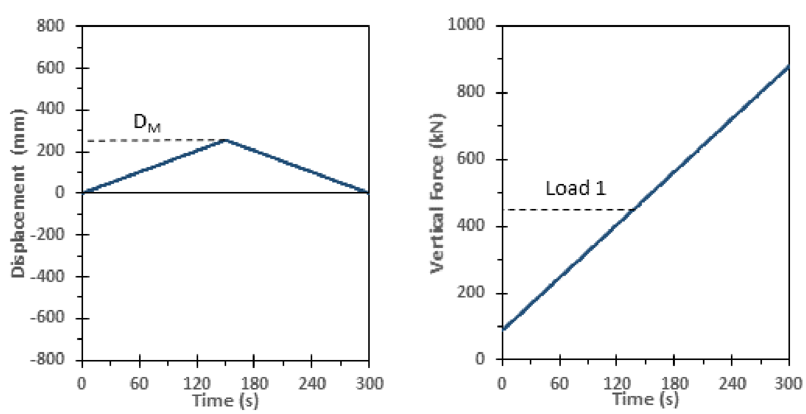


Fig. 4 – Displacement pattern and vertical force for the vertical load test

Simulated results from this test are presented in Fig. 5, in terms of force-displacement loop and coefficient of friction variation versus the applied vertical load. This test allows assessing the maximum variability of the friction coefficient for the applied vertical load within the whole design range.

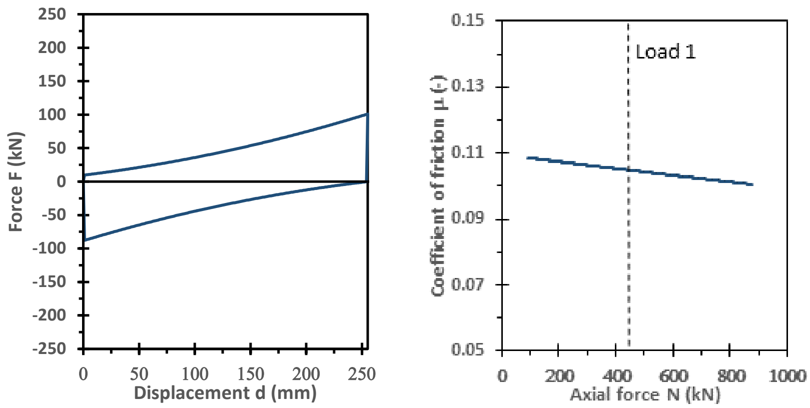


Fig. 5 – Force-displacement loop and friction variability from the vertical load test

The velocity as a source of variability can be assessed through a velocity test with a quadratic displacement pattern. The maximum displaced is D_M, and the time scale is set in order to reach a maximum velocity of 50mm/s. The value of the maximum velocity is kept low in order to reduce cycling effects. The maximum velocity may be increased if the coefficient of friction does not reach a plateau at 50mm/s. The plateau is considered reached if the variation of the coefficient of friction for in the last 20% of the velocity range (40mm/s to 50mm/s) is less than 5%. The downward force is kept constant during the test, at a level which is 10% Load 1. Such a low level of vertical force is chosen to minimize cycling effects during the test. The displacement pattern and the force-displacement behavior are presented in Fig. 6 along with the simulated variability of the coefficient of friction with the sliding velocity.

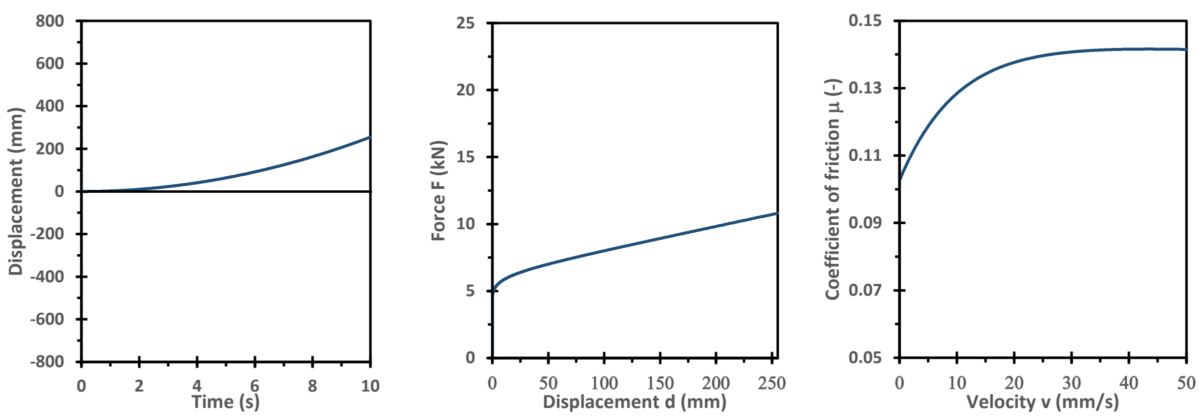


Fig. 6 – Displacement pattern, force-displacement and coefficient of friction variability from the velocity test

Finally a cycling test is proposed to assess, separately from other effects, the friction property variation due to heating phenomena. The test is performed at constant velocity and vertical load. The test is performed with a triangular displacement function (peak displacement D_M) with period T_M. The number of loops are limited based on the expected value of the cycling variable from the preliminary structural analysis. Displacement pattern and simulated results for the cycling test are presented in Fig. 7.

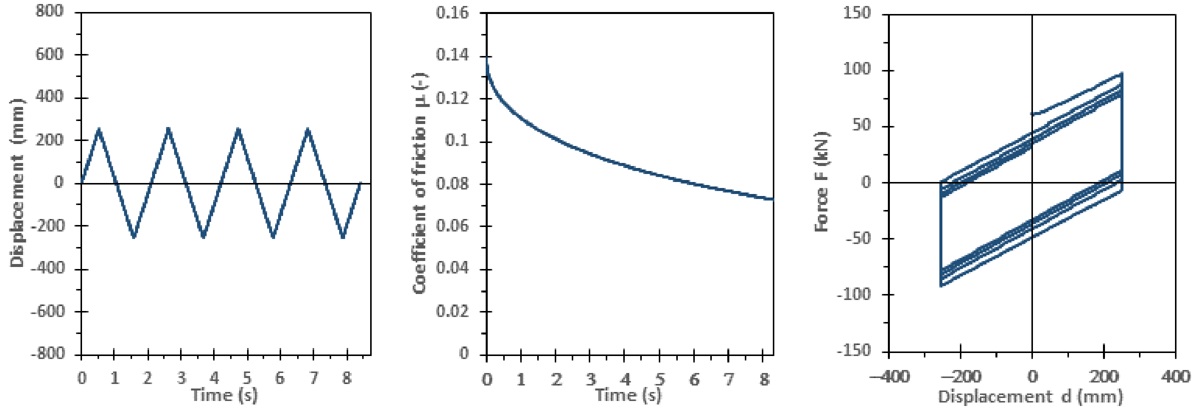


Fig. 7 – Displacement pattern, coefficient of friction variation, and force-displacement loops for the cycling test

9. Conclusion

The use of a numerical model of a simple structure and of an experimentally validated phenomenological model of the frictional performance of sliding isolators allowed the investigation of the testing and acceptance criteria proposed by ASCE 7-16. Some of the current test requirements proved to be unjustified and weekly informative for the property modification factors approach. They can also neglect critical performance variations that significantly affect the efficiency of the isolators while potentially penalizing devices based on unrealistic loading conditions. A modified testing protocol is proposed in order to account for the device performance observed during several full scale tests at the Caltrans SRMD Testing Facility. Specific tests are proposed to characterize single performance parameters that can be directly used for reliable numerical simulations.

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