16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING
THESSALONIKI
18 - 21 JUNE 2018

THE USE OF EXPERIMENTAL RESULTS IN SEISMIC ISOLATION DESIGN

Arsen ADZHEMYAN[1], Gianmario BENZONI[2], Giuseppe LOMIENTO[3]

ABSTRACT

The extensive results collected from prototype tests of Seismic Isolators and Energy Dissipators 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 structural performance. It must be recognized that a major difficulty for engineers is the translation of results of lengthy and expensive experimental programs into design tools. Tests are, in fact, often proposed for a "macroscopic" validation of devices' performance. The experimental approach is somehow still evolving from what was traditionally required for elastomeric bearings, with the attempt to "adapt" requirements to devices of completely different concepts. Acceptance criteria enforced by codes often show lack of consistency with design approaches and goals. Examples will be proposed to support the need for ad-hoc designed testing protocols that can provide clear inputs to improved analytical tools.

Keywords: Keyword1; Keyword2; Keywords should use Times New Roman 10 pt. font, Italic; separated by semicolon; Maximum 5

1. INTRODUCTION

Device testing has played a major role in the development, design, and acceptance of seismic isolation since the time of implementation of earliest systems. The first building code incorporating regulatory requirements for seismic isolation is the 1991 Uniform Building Code (UBC) (ICBO 1991). Prototype testing were specified in the code to assess the isolation devices' performance in regards of the expected maximum seismic demand. The original prototype testing were based upon elastomeric isolators, the most common technology available at that time. Since then, a number of isolation devices have been proposed, relying on different functional mechanisms, with the most common being today elastomeric bearings and friction isolators. On a parallel effort, several facilities with extensive testing capabilities have been instrumented, in order to test actual devices to be used in construction under the excepted seismic rates of loading. The availability of extensive experimental evidence from full scale testing on seismic isolators determined the evolution in the design of modern seismic isolation systems.

The experimental variability of the mechanical performance of seismic isolation devices was early recognized. This evidence was found so relevant that upper and lower bound values of the isolators' properties were soon required to be used when analyzing such systems in an attempt of allowing the use of simplified structural analysis based on nominal viscoelastic property, or simplified bilinear plastic models, rather than complex nonlinear models. The 2nd Edition of the AASHTO Guide Specification for Seismic Isolation Design (AASHTO 1999) introduced the use of property modification factors (λ) to account for this variability in the structural analysis of seismic isolation systems. Cyclic motion, loading rate, variability in production, temperature, aging, environmental

---

[1] MS Civil Engineering, California State Polytechnic University, Pomona, USA, arsenadzhemyan@yandex.ru

[2] Research Scientist, Structural Engineering, University of California, San Diego, USA, benzoni@ucsd.edu

[3] Contacting author: Asst. Professor, Civil Engineering, California State Polytechnic University, Pomona, USA, glomiento@cpp.edu

exposure and contamination were all considered as significant source of performance variability. According to the AASHTO, nominal properties in the design process of typical isolation systems needed to be based on prior prototype test results provided by manufacturers, while lower and upper bound values of the same properties are then obtained by multiplying nominal values by minimum (λ_{min}) and maximum (λ_{max}) isolator-dependent property modification factors. Structural simulations are finally performed with lower and upper bound values to encompass the entire expected performance variability with simplified numerical models.

When the International Building Code (IBC) (ICC 2000) replaced the UBC, seismic isolation provisions were almost identical to those of the latest UBC edition (ICBO 1997). Starting from 2003, however, the IBC refers to the ASCE-7 for seismic isolation design and testing requirements, and the latest version of the ASCE 7 (ASCE 7-16) introduces the use of property modification factors to account for the isolator performance variability in the design process. The European PrEN 15129 (CEN 2008) adopts a similar approach, based on lower and upper bound representative values of the isolators' performance, accounting for manufacturing, temperature, and aging variations.

Despite the recognized difference in terms of performance variability for isolators of different types, testing procedures remained almost unchanged in the years to follow. Most of the current standards addressing seismic isolation recommend the use of lower and upper bound model parameters to account for all the sources of performance variability. However, the types of prototype tests didn't show the same level of evolution over time, and remain mostly unchanged from 1991 to nowadays. Changes were instead proposed from each individual regulatory agency in terms of number of tests and criteria used for acceptance of the isolation devices, which resulted in notable differences among current standards. The lack of significant updates in terms of types of prototype tests caused current testing protocols being difficult to relate to the recently observed sources of performance variability for different types of isolators. For friction isolators, for instance, each single prototype test triggers different sources of variability that simultaneously affect the mechanical properties of isolators (Benzoni and Lomiento 2016, Lomiento and Benzoni 2017), in ways that make the interpretation of experimental data debatable. At the same time, since all the simultaneous sources of variability cause difficult to predict variations in the mechanical properties, adequacy criteria are mostly used to avoid that those variations exceed predetermined limits during prototype tests, rather than requiring that the observed variation is properly implemented in the structural analysis.

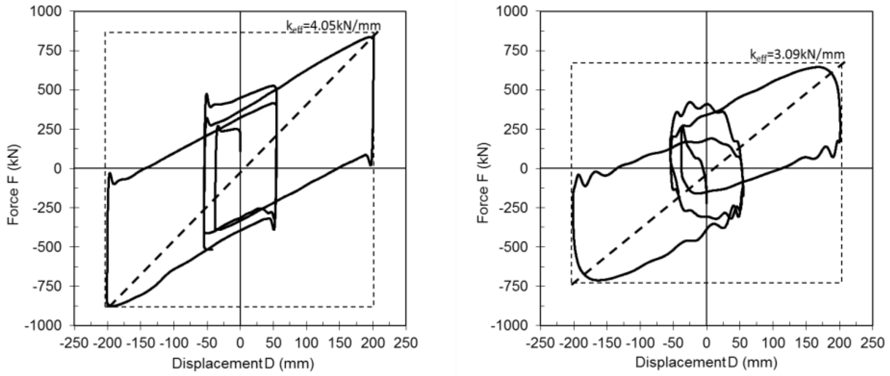
This study is aimed at analyzing and comparing testing protocols and acceptance criteria from their original formulation to some of the current regulations in use in US and Europe. Friction isolators are used as reference devices. Experimental data from recently tested double-concave sliding isolators are used to support the comparison between the testing protocols. A recent friction coefficient model (Lomiento et al. 2013) is used in order to simulate the isolators' performance for different prototype tests. The prototype testing protocols of the original 1991 UBC, and the current AASHTO, ASCE-7, and PrEN 15129 are presented and discussed in terms of similarities and ability to capture the actual performance of friction isolation devices. Acceptance criteria are finally discussed on the basis of the expected experimental behavior of friction isolators, in reason of their consequences on the structural analysis of such isolation systems.

2. EXPERIMENTAL EVIDENCE AND MODEL FOR FRICTION ISOLATORS

A set of experimental data on double pendulum isolator is used to provide evidence of the expected variability of sliding isolators' performance for different prototype testing protocols. Experimental tests on full scale pendulum isolators show that the restoring forces developed at the curved sliding interfaces are mainly affected by the applied vertical force, while the main changes in performance are related to variations of the coefficient of friction (Lomiento et al. 2013a). The four main effects affecting the coefficient of friction μ of typical steel-polymer interfaces, are:

1. "Breakaway effect", (sudden increase of μ at each motion beginning/reversal);
2. "Load effect", (reduction of μ for increasing vertical compression load);
3. "Cycling effect", (reduction of μ due to temperature increase for cyclic sliding);
4. "Velocity effect", (increase of μ with increasing sliding velocity).

The performance of friction isolator is considered rate dependent due to the increase of the coefficient of friction with the sliding velocity, which requires presudo-dynamic testing. Moreover, friction isolator are sensitive to the bi-directional sliding. Due to the different direction of friction and restoring forces (Lomiento et al. 2012, 2013b), the slope of the force-displacement loop, the effective stiffness, and the damping all depend on the bi-directional displacement pattern. The effect of the bi-directional motion on the effective stiffness is shown in Fig. 1 for a sample cloverleaf test. Fig. 1b shows the force-displacement loop a cloverleaf test with longitudinal displacement component identical to the displacement component used for the mono-directional test of Fig 1a. The reduction in effective stiffness caused by the lateral displacement component in the bi-directional cloverleaf test is 24% (from 4.09 kN/mm to 3.05 kN/mm), which qualifies the device as having a direction-dependent behavior (>10% difference for UBC, >15% difference for ASCE 7 and AASHTO).



(a) (b

Fig. 1 – Force-displacement loops for (a) mono-directional (a) and bi-directional cloverleaf test.

A detailed experimental model for the variation of the frictional properties was demonstrated 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 double-concave friction isolators under a wide range of vertical loads and velocity (Adzhemyan 2017). The proposed friction model accounts for load, velocity, and cycling effects through the independent functions $f_N(N)$, $f_v(v)$, and $f_C(C)$, respectively:

Friction model $\mu(N,C,v) = f_N(N)\cdot f_C(C)\cdot f_v(v)$ (1)

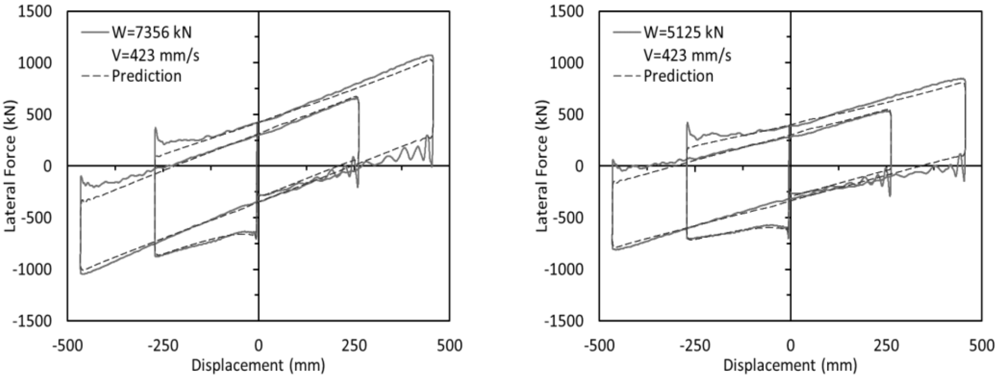
Vertical load function $f_N(N) = \mu_{s0}\cdot e^{-N/N_{ref}}$ (2)

Vertical load function $f_v(v) = \gamma + (1-\gamma)\cdot e^{-|v|/v_{ref}}$ (3)

Vertical load function $f_C(C) = e^{-(C/C_{ref})^{\beta}}$ (4)

Cycling variable $C(t) = \frac{2}{a\pi}\int_{t_0}^{t} N v^2 dt$ (5)

where μ_{s0} = zero-load static coefficient of friction, N>0 vertical compression load on the isolator, N_{ref} = load associated to a 63% friction reduction, a = in-plane radius of the slider, v = sliding velocity, γ = fast / slow friction coefficient ratio, v_{ref} = experimental value of v related to a 63% increment of the coefficient of friction, β = exponential rate of the friction degradation determined from experimental data, C_{ref} = value of the variable C associated with a 63% friction reduction for cycling effects, A = in-plane radius of the concave surface. In this study, values of a specific tested bearing are used, as follows: R = 5000 mm, a = 323.1 mm, A = 802.4 mm μ_{s0} = 0.14, N_{ref} = 8600 kN, γ = 1.9, v_{ref} = 23 mm/s, C_{ref} = 6 kN/mm/s, β = 0.2. Exemplificative experimental and predicted force-displacement loops are presented in Fig. 2 for two different levels of vertical load (i.e. pressure p).



(a) (b

Fig. 2 – Exemplificative experimental and predicted force-displacement loops.

3. PROTOTYPE TESTING

The evolution of the prototype testing from the 1991 UBC to the current AASHTO, ASCE 7, and PrEN is presented hereafter. The number of tests was greatly reduced over the years, and differences and similarities between the testing protocols are analyzed for application to sliding isolation devices. Despite the differences between the testing protocols, 8 categories of tests are commonly used in the different standards, and specifically:

C1. Service (for wind loads or max non-seismic displacement)
C2. Benchmark (for reference values before degradation tests are performed)
C3. Lateral range (for change in lateral performance at different levels of seismic displacement)
C4. Degradation (for degradation of lateral performance due to repeated cycling: ≥10 cycles)
C5. Integrity (for verification of the integrity, after degradation tests are performed)
C6. Vertical range (for change of lateral performance under max and min vertical seismic loads)
C7. Bidirectional (for verification of the directional performance)
C8. Verification (for property verification at the end of the testing protocol)

The tests from each regulatory standard are here attributed to these 8 test categories. Prototype tests are performed separately on two full-size specimens of each type and size of isolator unit of the isolation system. The following notation and notes apply to all the testing protocols.

Legend:

DL, LL	are Dead and Live loads
E, E_M	is the Seismic load, at the design and maximum level earthquake
W	is the Wind load
ψ	is the seismic combination factor for live loads
V	is the peak velocity
D, D_M, D_{TM}	is the total design displacement (design-level, maximum-level, and maximum-total including torsion)
S_{MS}, S_{M1}	is the MCE spectral acceleration values at short periods, and 1 sec period
S_I	is a numerical coefficient for site-soil profile as set forth in Table No. A-23-U of 1991 UBC for seismically-isolated structures
B_M	is the spectrum reduction factor that accounts for the effective damping of the isolation system.
B	is a numerical coefficient related to the effective damping of the isolation system as set forth in Table No. A-23-W of 1991 UBC
f_I	is the inverse of the isolation period T_I

Notes:

(1) Applicable only to vertical load carrying devices.
(2) Applicable only if the force-deflection properties of the isolator units are dependent on the rate of loading. Properly documented dynamic tests of scaled specimens may be used to quantify the properties of rate-dependent systems.

(3) Bi-lateral tests to be carried out only if the force-deflection properties of the isolator units are dependent on bilateral load. Properly documented dynamic tests of scaled specimens may be used to quantify the properties of direction dependent systems.

(4) The bi-directional test shall be performed with a "clover-leaf" pattern. If testing equipment is unable to perform test B, the test can be completed after a rotation of 90 degree of the bearing in order to involve a displacement path perpendicular to the one verified with previous tests.

3.1 UBC (1991)

The first regulatory standard incorporating prototype testing requirements for seismic isolators was the 1991 UBC. Prototype tests were used for establishing and validating the design properties of the isolation system, and complement manufacturing quality control tests. Three types of tests were specifically required, namely A, B, and C, as summarized in Table 1. The number of test per specimen ranges from a minimum of 8 tests, in case of a non-vertical load carrying device with not rate-dependent and not direction-dependent behavior, to a maximum of 48 tests, for vertical load carrying device with rate dependent behavior. This large variation in number of required tests was originally motivated by the lack of experimental evidence of the behavior of relatively new isolation devices at the time of the publication of the standards. It shall be noted that some of the test requirements, such as the bi-directional testing requirements for large-scale isolators, were unattainable at that time because of lack of suitable equipment.

Table 1 – Sequence and cycles of prototype tests from UBC 1991.

Type	**Test Category**	**Vert Load**	**Lateral Load**	**# of Cycles**	**Max Displacement**	**Rate of loading(2)**
A	C1. Service	DL	W	20	-	½f_I f_I 2f_I
B	C3. Lateral range C7. Bidirectional	DL $1.2DL+1.0LL+\vert E\vert$(1) $0.8DL-\vert E\vert$(1)	-	3	0.25D 0.5D 0.75D 1.0D (0.25, 1.0)D(3) (0.50, 1.0)D(3) (0.75, 1.0)D(3) (1.0, 1.0)D(3)	½f_I f_I 2f_I
C	C4. Degradation	DL	-	$15S_I/B \geq 10$	1.0D	½f_I f_I 2f_I
Static	C6. Vertical range	$1.2DL+1.0LL+\vert E\vert$ $0.8DL-\vert E\vert$	-	-	$1.0D_M$	-

3.2 AASHTO (2014)

The AASHTO 2014 prototype tests are presented in Table 2. Tests 2, 3, 4 and 7 are replacement of the 1991 UBC tests A, B, C and static. Test 6 is a property verification test, similar to test 3 of the ASCE 7. The number of tests ranges from a minimum of 12 to a maximum of 13 tests, in case of direction-dependent behavior.

3.2 ASCE 7 (2016)

Differently from all the other standards the ASCE 7-16 uses the Maximum Considered Earthquake (MCE) rather than the design earthquake to set load and displacement demand for the tests. Tests 1, 2, 4 and 5 replace the UBC tests A, B, C, and static. A type 3 test is introduced to evaluate the integrity of the isolator at the maximum total displacement. The sequence of tests associated to the test type 2 for four levels of displacement can be replaced by two dynamic tests, where the four levels of displacement are applied dynamically and consecutively in descending and ascending order (one cycle per level of displacement). The number of tests ranges from a minimum of 6 to a maximum of 21 tests, in case of load-carrying devices with direction-dependent behavior.

Table 2 – Sequence and cycles of prototype tests from AASHTO (2014).

Type	**Test Category**	**Vert Load**	**Lateral Load**	**# of Cycles**	**Max Displacement**	**Rate of loading(2)**
1	C1. Service	DL	-	3	Thermal	-
2	C1. Service	DL	W	20	-	≤0.075Hz
3	C2. Benchmark C3. Lateral range	DL	-	3	1.0D 0.25D 0.5D 0.67D 1.0D 1.25D	f_I
4	C4. Degradation	DL	-	20	1.0D	f_I
5	C5. Integrity	DL	W	3	-	≤0.075Hz
6	C5. Integrity C7. Bidirectional	DL	-	3	1.0D (0.71, 0.71)D (3)	f_I
7	C6. Vertical range	1.2DL+1.0LL+$\lvert E\rvert$ 0.8DL-$\lvert E\rvert$	-	1	1.0D	-

Table 3 – Sequence and cycles of prototype tests from ASCE 7-16.

Type	**Cat.**	**Vert Load**	**Lateral Load**	**# of Cycles**	**Max Displacement**	**Rate of loading(2)**
1	C1. Service	DL+0.5LL	W	20	-	f_I
2	C3. Lateral range C7. Bidirectional	DL+0.5LL 1.2DL+0.5LL+$\lvert E_M\rvert$+0.2S (1) 0.9DL-$\lvert E_M\rvert$ (1)	-	3 **or** 1	0.25D_M 0.5D_M 0.67D_M 1.0D_M (0.25, 1.0)D_M (3) (0.50, 1.0)D_M (3) (0.75, 1.0)D_M (3) (1.0, 1.0)D_M (3) **or** [1.0+0.67+ 0.5+0.25] D_M [0.25+0.5+ 0.67+1.0] D_M	f_I
3	C5. Integrity C7. Bidirectional	DL+0.5LL	-	3	1.0D_M (1.0, 1.0)D_M (3)	f_I
4	C4. Degradation	DL+0.5LL	-	$30S_{M1}/(S_{MS}B_M)\geq 10$	0.75D_M	f_I
5	C6. Vertical range	1.2DL+0.5LL+$\lvert E_M\rvert$+0.2S (1) 0.9DL-$\lvert E_M\rvert$ (1)	-	1	1.0D_{TM}	-

3.4 PrEN 15129 (2008)

The PrEN 15129 specifies different prototype tests for different types of isolators. Only the tests for sliding isolators are presented hereafter. The PrEN requires the minimum number of tests in comparison with the other standards, i.e. a total of 9 tests. Service, dynamic and seismic tests are equivalent to the UBC tests type A, B and C, with the exception of the seismic test being dynamic instead of static. Benchmark, integrity and verification tests are additional tests aimed at verifying the performance of the isolator before and after the main tests are performed.

Table 4 – Sequence and cycles of prototype tests from PrEN 15129 (2008) for sliding isolators.

Type	Test Category	Vert Load	Lateral Load	# of Cycles	Max Displacement	Rate of loading
Service	C1. Service	DL**+LL**	-	20	Max non-seismic	V=5mm/s
Benchmark	C2. Benchmark	DL**+LL**	-	3	1.0D	V=50mm/s
Dynamic	C3. Lateral range	DL**+LL**	-	3	0.25D 0.5D 1.0D	f_I
Integrity	C5. Integrity	DL**+LL**	-	3	1.0D	f_I
Seismic	C6. Vertical range	$1DL+\psi LL+\lvert E\rvert$ $1DL+\psi LL-\lvert E\rvert$	-	3	1.0D	f_I
Bi-dir.	C7. Bidirectional	DL**+LL**		3	(1.0D, 1.0D)$^{(4)}$	f_I
Verification	C8. Verification	DL**+LL**		3	1.0D	f_I

2.5 Comparison

The number of tests required for sliding isolators, which have a rate-dependent and direction-dependent behavior, is summarized in Table 5 for all the standards. The larger variety of tests, in terms of different categories, is required by the PrEN 15129 which requires however the minimum number of tests (9), while the larger number of tests (48) is required by the 1991 UBC. Prototype tests significantly diminished in number from the 1991 UBC to the ASCE 7-16 and the AASHTO, which are currently similar, both in terms of required number of tests and of test categories. Service tests, lateral range, vertical range and bidirectional tests are common to all the standards, even if they can vary in number and level of force/displacement.

Table 5 – Comparison between standards in terms of tests for sliding isolators.

Test Category	1991 UBC	AASHTO	ASCE 7	PrEN
C1. Service	3	2	1	1
C2. Benchmark	-	1	-	1
C3. Lateral range	36	5	6-12	3
C4. Degradation	3	1	1	-
C5. Integrity	0	2	1	1
C6. Vertical range	2	2	2	1
C7. Bidirectional	4	1	3-5	1
C8. Verification	-	-	-	1
Total	**48**	**14**	**14-22**	**9**

Despite the similarities in terms of types of test, the acceptance criteria are significantly different, as shown in the next section.

4. ACCEPTANCE CRITERIA

The isolators' adequacy for all the standards is based on checks of the following 10 items:

- Slope $\Delta F/\Delta D$ for the mono-directional force-displacement loop
- Period T_T, based on tangent stiffness of force displacement loop
- Effective stiffness $k_{eff} = (F^+-F^-)/(D^+-D^-)$ where $F=F_{max}$ for $k_{eff,max}$, and $F=F_{min}$ for $k_{eff,min}$
- Effective damping β_{eff} = (Area loop)/($2\pi k_{eff,max}D^2$)
- Max service force $F_{s,max}$

- Max design force F_{max}
- Max service displacement $D_{s,max}$
- Restoring stiffness k_{res} produced by the concavity of the sliding surfaces
- Energy dissipated per cycle EDC
- Coefficient of friction μ

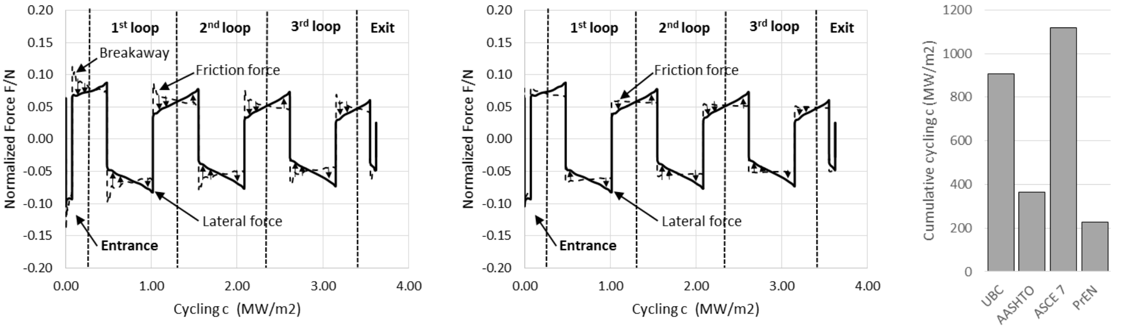
A total of 23 possible checks are performed based on the above 10 items, depending on the standard, as shown in Table 6. It should be noted that the US standards are gradually evolving over time, moving from checks based on linear effective parameters, such as the effective stiffness and damping values, to nonlinear parameters characterizing the isolators' performance, such as the restoring stiffness (referred to as post-yield stiffness), and the coefficient of friction, checked only by the PrEN. The checks in terms of force-displacement slope, stability and deterioration are common to all the standards. Most of the quantitative acceptability checks are performed on lateral range, degradation and integrity tests, even if types of checks might significantly differ from one standard to another one. Moreover the isolators are checked for stability, absence of visible deterioration and vibration.

Table 6 – Comparison between standards in terms of tests for sliding isolators.

Parameter	**Condition**	**UBC**	**AASHTO**	**ASCE 7**	**PrEN**
$\Delta F/\Delta D$	$\Delta F/\Delta D > 0$	All tests	-	All tests	All tests
	$\Delta F/\Delta D \geq W/80$ between 0.5D and 1.0D	-	All tests	-	-
T_T	≤ 6sec	-	All tests	-	-
k_{eff}	≤10% difference from average	C3	C3	-	-
	≤10% difference between 2 specimens	C3	C3	-	-
	≤15% difference from average of 2 specimens	-	-	C3, C5	-
	≤±10% (average) difference from design value	-	C3	-	-
	≤±20% difference from initial value	C4	C4	C4	-
β_{eff}	≤20% decrease from initial value	C4	-	C4	-
	≤30% decrease from initial value	-	C4	-	-
$F_{s,max}$	≤ design value	-	-	-	C1
F_{max}	≤±15% difference from design value	-	-	-	C3, C5, C6
	≤ design value	-	-	-	C7
$D_{s,max}$	≤ design value	-	C1, C5	-	-
k_{res}	$\lambda_{test,min} \leq k_{res}$/nominal $\leq \lambda_{test,max}$ (±30%)	-	-	C3, C4, C5	-
	≤±10% difference between successive cycles	-	-	-	C3, C5, C6
	≤±5% diff. between upper/lower portion of cycle	-	-	-	C3, C5, C6
	≤±15% difference from design value	-	-	-	C3, C5, C6
	≤±15% difference between 2 specimens	-	-	-	C3, C5, C6
EDC	$\lambda_{spec,min}$-5% ≤ EDC/average ≤ $\lambda_{spec,max}$+5% (±20%)	-	-	C5	-
	$\lambda_{test,min}$ ≤ EDC/nominal ≤ $\lambda_{test,max}$ (±30%)	-	-	C4	-
	≥ 85% design value	-	-	-	C3, C5, C6
μ	within design limits	-	-	-	All tests

5. COMPARISON BETWEEN STANDARDS

The sequence of protocol tests from all the standards is simulated by using the experimentally calibrated friction model. Results are presented in the following, showing the variation of some of the performance parameters in regards to the acceptance criteria. The analysis focuses on the following main parameters: (i) effective stiffness k_{eff}, (ii) effective damping β_{eff}, (iii) restoring stiffness k_{res}, and (iv) EDC. The variability of the parameters is presented versus the cycling variable, which is representative of the cumulative heat flux generated by the sliding motion. The experimental variation of the lateral force with the cycling variable is presented in Fig. 3a for a typical 3-cycle prototype test. The test is preceded by an entrance loop, and followed by an exit loop to resolve disturbances of test results at the beginning and the end of the motion. The difference between lateral and friction force is given by the restoring force, whose effect is shown as vertical arrows. The decrease in force throughout the test is due to cycling effects. The force variability predicted by the model is shown in Fig. 3b, which clearly resembles most of the experimental force variability. A notable difference is due to the local breakaway friction force spikes, which are only visible in the experimental data of Fig. 3a, and have limited effects on the above mentioned performance parameters. The cumulative cycling variable for the entire testing protocols is reported in Fig 3c, which shows that the ASCE 7 testing protocol is the one generating the most heat flux, as it involves larger displacements (maximum instead of design levels), while the PrEN is the one generating less heat flux overall.



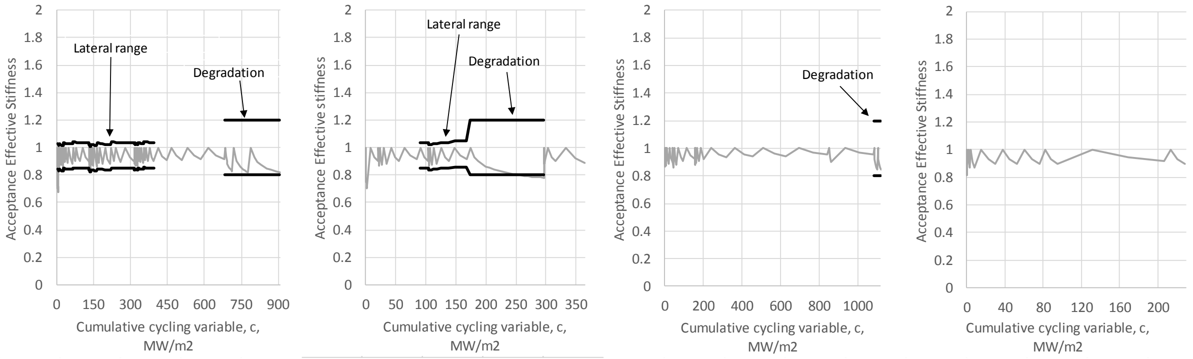
(a) (b) (c)

Fig. 3 – Variation of the normalized force F/N versus the cycling variable c for a typical 3-cycle test: (a) experimental, (b) model prediction; (c) cumulative cycling variable for the testing protocols

For the comparison between the tests of Figs. 4-7, the variation of the four performance parameters is normalized to the value at the beginning of each test, while black lines indicate the acceptance criteria.

5.1 Effective stiffness

The largest variation in effective stiffness is associated with the UBC testing protocol, while the least variation is given by the PrEN. For UBC and AASHTO, service tests show reduction of stiffness up to 32% for service test, while degradation tests show up to 23% reductions. The reductions for ASCE and PrEN are always less than 20%. The effective stiffness is considered important as an acceptance parameter by the UBC and AASHTO. The analyzed isolator would satisfy all the effective stiffness acceptance requirements, except for the one associated to the degradation test of the AASHTO protocol, mostly due to the high cycling effects associated with the test.

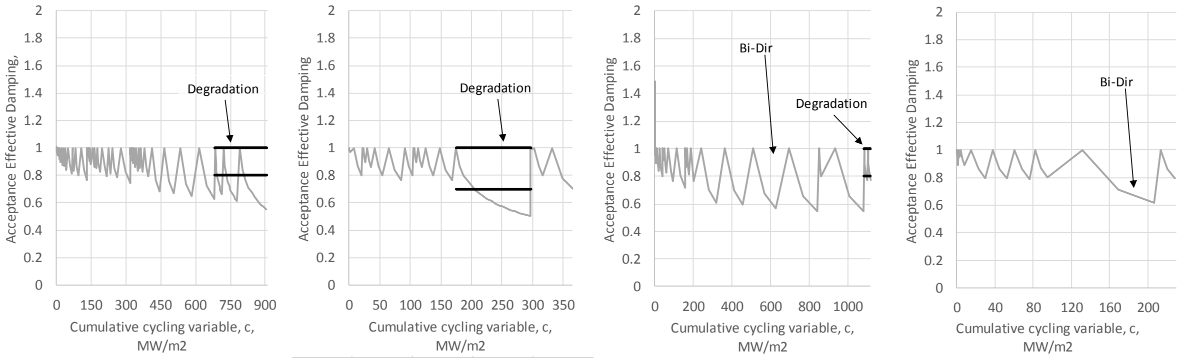


a b c d

Fig. 4 – Effective stiffness and acceptance criteria for: (a) UBC, (b) ASCE 7, (c) AASHTO, (d) PrEN.

5.1 Effective damping

Similarly to the effective stiffness, the largest variation in effective damping is given by the UBC (up to -43%) and AASHTO testing protocol (up to -48%), while the smallest variation comes from the PrEN (-39%). The damping ratio appears more affected by the degradation induced by the cycling effect in comparison with the effective stiffness, which results into non-acceptable results for the UBC, ASCE and AASHTO testing protocols. The highest reduction in damping ratio for the ASCE and the PrEN comes from bi-directional tests, which are not considered for acceptance.

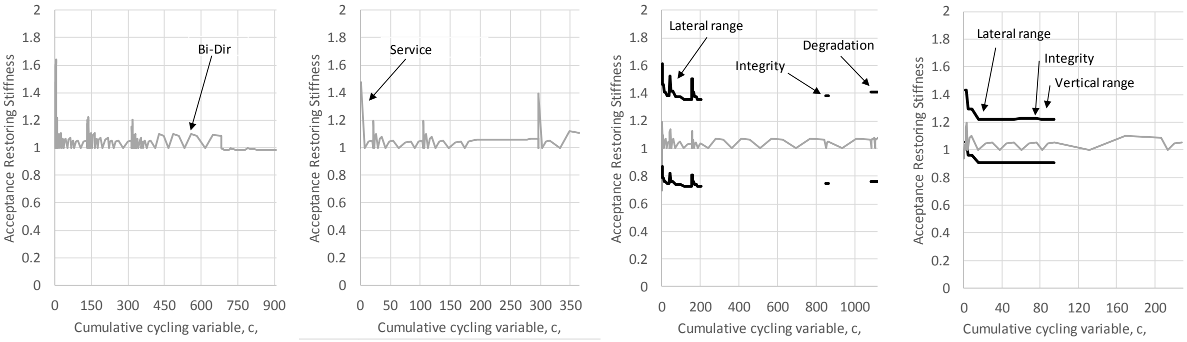


a b c d

Fig. 5 – Effective damping and acceptance criteria for: (a) UBC, (b) ASCE 7, (c) AASHTO, (d) PrEN.

5.1 Restoring stiffness

The cycling effect is again the main source of variation for the restoring stiffness during single tests, as it reduces the slope of the force-displacement loop. The restoring stiffness increases from the 1st to the following loops, due to the friction reduction caused by the cycling effect, which is more significant at the beginning of the test. The restoring stiffness is only considered as an acceptance parameter by the ASCE and PrEn, with the PrEN requirements being more restrictive and resulting in failure of passing the test. The failing condition occurs in the low level (0.25D) displacement test, for which the restoring stiffness suffers a >10% increase from the first to the second loop.

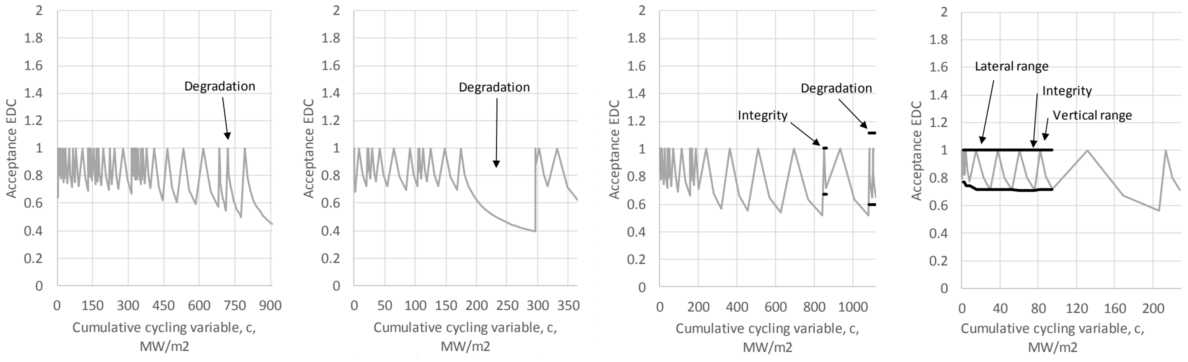


a b c d

Fig. 6 – Restoring stiffness and acceptance criteria for: (a) UBC, (b) ASCE 7, (c) AASHTO, (d) PrEN.

5.1 EDC

Finally, the highest variability in performance parameters is associated with the EDC values. The reduction of the EDC ranges from 52% and 60% throughout all the tests. The variability in EDC was found to be below the acceptance limits of the analyzed standards, even if very close to the lower boundaries for the PrEN requirements.



a b c d

Fig. 7 – Energy dissipated per cycle and acceptance criteria for: (a) UBC, (b) ASCE 7, (c) AASHTO, (d) PrEN.

6. DISCUSSION

From the analysis of the four testing protocols, the performance parameters most subjected to change during tests are the effective damping ratio and the energy dissipated per cycle. Significant variations of these parameters are evidenced in the degradation tests of the UBC and AASHTO standards, and in the bi-directional tests required by the ASCE 7 and PrEN standards. The modification of the degradation test in the ASCE, with respect to the original UBC, reduces the degradation of the dissipation properties in order to match expected reduction from design seismic events. It is advisable that the AASHTO will update testing protocols in a similar manner. Despite showing great reduction in dissipation capability, the bi-directional tests are not considered in any acceptance criteria. When a bi-directional analysis is performed, proper reduction of the dissipation capability shall be considered, in order to account for the augmented cycling effect produced by bi-directional motion.

The effective stiffness of friction isolators appears less affected by all the sources of performance variability. This is partially due to the relative high importance of the restoring force in comparison with the friction force at the design displacement. However, significant variability is identified for service tests, in which the displacement is well below the design displacement. This suggests that appropriate property modification factors shall be defined for serviceability conditions, different in values from what is used for design-level conditions.

The variation of the effective stiffness and damping are considered of secondary importance by the recent ASCE 7 and PrEN. These standards implicitly suggest that nonlinear parameters such as restoring stiffness, EDC, and coefficient of friction are more adequate representation of the performance of sliding isolators. Among these, the restoring stiffness appeared significantly affected by variations during service tests, for which multiple cycles of low-amplitude displacement are performed. Increase in restoring stiffness up to 80% are evidenced for UBC service tests (Fig. 6). This variation shall be also appropriately considered in the analysis, as it can affect the level of displacement expected under service loads.

Overall, a large discrepancy in the acceptance criteria is evidenced among the analyzed standards. Simulations show that the analyzed isolators would not be acceptable for any of the prototype testing protocols, but for different criteria concerning the effective stiffness (AASHTO), the effective damping (UBC, AASHTO, ASCE 7), and the restoring stiffness (PrEN). It is advisable that the testing protocols will go through a standardization process, in order to avoid such discrepancies.

The degradation of the coefficient of friction due to cycling effects has been evidenced as the predominant source of changes in the performance parameters. As already discussed in (Lomiento and Benzoni 2017), a revision of the testing protocols is envisioned in order to determine an equivalence between prototype tests and the expected seismic design conditions not only in terms of force, velocity, and displacement demand, but also in terms of generated heat flux. Finally, the activation of all the sources of friction variability in each test makes interpretation of the variability of the performance parameters hardly predictable. Ad-hoc "property characterization" tests can be effectively introduced in order to isolate each of the sources of variability. This will simplify the understanding of the performance variability, and will allow the calibration of sophisticated predictive models, such as the one used in this study.

7. CONCLUSION

The increased awareness of the changes in friction performance of seismic sliding isolators resulted in modifications of the testing protocols over the years. The number of tests was greatly reduced, and the acceptance criteria were updated to include nonlinear performance parameters along with linear parameters such as effective stiffness and damping. This study compared testing protocols for friction isolators from four regulatory standards: 1991 UBC, ASCE 7, AASHTO, and PrEN 15129. An experimentally validated phenomenological model of the frictional performance of sliding isolators was used to simulate testing protocols and investigate their mutual differences. The comparison showed that there is large discrepancy between acceptance criteria for friction isolators in the different standards, despite the prototype tests being similar in type amongst all the standards, and only slightly different from the original prototype testing protocols of the 1991 UBC. The importance of the bi-directional testing for such isolators has been recognized, and tests have been added in this regards, even if they are not associated with any specific acceptance criteria. The energy dissipation capability was found to be the performance that experienced the largest variations during individual tests. The stiffness properties are instead mostly affected by variations in service test conditions rather than in design test conditions. The simulations proved that the major source of performance variability is the cycling effect, associate to the heat flow generated by the cyclic sliding. A revision of the testing protocols is envisioned in order to make prototype testing representative of seismic design conditions also in terms of heat flux, rather than just considering force, velocity and displacement demand.

8. REFERENCES

AASHTO (1999). *Guide Specifications for Seismic Isolation Design*. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

AASHTO (2014). *Guide Specifications for Seismic Isolation Design, 4th Edition*. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

Adzhemyan A (2017). Experimental Model for Double Concave Sliding Bearings. *Master's Thesis*. Department of Civil Engineering, California State Polytechnic University, Pomona, CA.

ASCE (2016). *Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers (ASCE) ASCE/SEI 7-16, Reston, VA.

Benzoni G, Lomiento G (2016). Experimental assessment of property modification factors for friction isolators. *Proceedings of the 8th World Congress on Joints, Bearings and Seismic Systems for Concrete Structures*. Georgia, Atlanta.

CEN (2008). *PrEN 15129. Anti-seismic devices.* CEN/TC340.

ICBO (1991). *Uniform Building Code, 1991 Edition*. International Conference of Building Officials (ICBO), Whittier, CA.

ICBO (1997). *Uniform Building Code, 1997 Edition*. International Conference of Building Officials (ICBO), Whittier, CA.

ICC (2000). *International Building Code, 2000 Edition*. International Code Council (ICC), Falls Church, VA.

Lomiento G, Benzoni G (2017). Testing protocols and acceptance criteria for performance characterization of pendulum isolators. *Proceedings of the 16th World Conference on Earthquake Engineering*. Santiago, Chile.

Lomiento G, Bonessio N, and Benzoni G (2012): Effects of Loading Characteristics on the Performance of Sliding Isolation Devices. *Proc. of the 15th World Conference on Earthquake Engineering*. Lisbon, Portugal.

Lomiento, G, Bonessio N, and Benzoni G (2013a): Friction model for sliding bearings under seismic excitation, *Journal of Earthquake Engineering*, 17 (8), 1162-91.

Lomiento G, Bonessio N., and Benzoni G (2013b): Concave sliding isolator's performance under multi-directional excitation, Ingegneria Sismica, 30 (3), 17-32.