TESTING OF SEISMIC PROTECTIVE SYSTEM HARDWARE: SIGNIFICANCE, SCALING AND SIMILARITY

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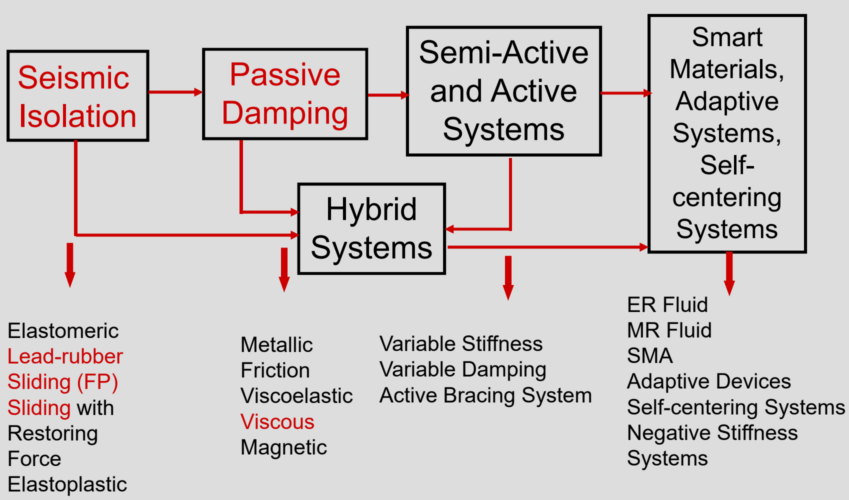
Revised 08/2019 | Civil, Structural & Environmental Eng. , University at Buffalo

SEISMIC PROTECTIVE SYSTEMS



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SCOPE OF PRESENTATION

- Brief description of seismic protective systems and hardware.
- Discussion of qualification, prototype and production testing, and inspection.
- Presentation of examples of significance of testing and inspection of seismic protective systems hardware.
- Presentation of sample testing specifications.
- Discussion of issues of testing of seismic protective system hardware at reduced scale.
- Discussion of issues of testing related to duration of motion effects.
- Presentation of methodologies for scaling and similarity in the testing of seismic protective system hardware.
- Presentation of a sample of projects where testing and inspection were rigorously performed.

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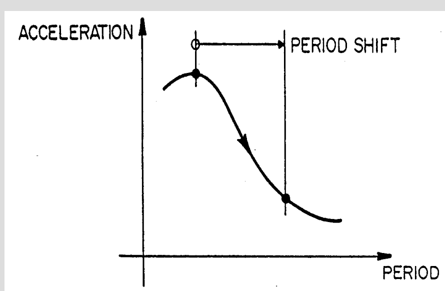
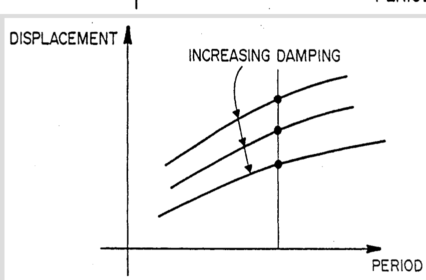
REFERENCES

- Barenblatt, G.I., "SCALING, SELF-SIMILARITY, AMD INTERMEDIATE ASYMPTOTICS", Cambridge University Press, 1996.
- Constantinou, M.C., Tsopelas, P., Kasalanati, A. and Wolff, E.D., "PROPERTY MODIFICATION FACTORS FOR SEISMIC ISOLATION BEARINGS", Report No. MCEER-99-0012, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 1999.
- Kalpakidis, I.V. and Constantinou, M.C., "EFFECTS OF HEATING ON THE BEHAVIOR OF LEAD-RUBBER BEARINGS. I: THEORY," ASCE, J. Structural Engineering, Vol. 135, No.12, 2009, 1440-1449.
- Kalpakidis, I.V. and Constantinou, M.C., "EFFECTS OF HEATING ON THE BEHAVIOR OF LEAD-RUBBER BEARINGS. II: VERIFICATION OF THEORY," ASCE, J. Structural Engineering, Vol. 135, No.12, 2009, 1450-1461.
- Kalpakidis, I.V. and Constantinou, M.C., "PRINCIPLES OF SCALING AND SIMILARITY FOR TESTING OF LEAD-RUBBER BEARINGS," Earthquake Engineering and Structural Dynamics, Vol. 39, No. 13, 2010, 1551-1568.
- Constantinou, M.C., Whittaker, A.S., Kalpakidis, Y., Fenz, D. M. and Warn, G.P.," PERFORMANCE OF SEISMIC ISOLATION HARDWARE UNDER SERVICE AND SEISMIC LOADING", Report No. MCEER-07-0012, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 2007.
- Kalpakidis I.V. and Constantinou, M.C., "EFFECTS OF HEATING AND LOAD HISTORY ON THE BEHAVIOR OF LEAD-RUBBER BEARINGS," Report No. MCEER-08-0027, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 2008.
- Fenz, M.D., Reed, R., Slatnick, S., Steward, H.R., and Constantinou, M.C., "DEVELOPMENT OF PERFORMANCE-BASED TESTING SPECIFICATIONS FOR THE ARKUTUN-DAGI FRICTION PENDULUM BEARINGS", Offshore Technology Conference, Paper OTC 22160, Houston, 2011.
- Sarlis, A.A. and Constantinou, M.C., "MODEL OF TRIPLE FRICTION PENDULUM BEARING FOR GENERAL GEOMETRIC AND FRICTIONAL PARAMETERS AND FOR UPLIFT CONDITIONS," Report No. MCEER-13-0005, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 2013.
- Chandramohan R., Baker J.W. and Deierlein G.G., "QUANTIFYING THE INFLUENCE OF GROUND MOTION DURATION ON STRUCTURAL COLLAPSE CAPACITY USING SPECTRALLY EQUIVALENT RECORDS". Earthquake Spectra, 32 (2), 927-950, 2016.
- Kitayama, S. and Constantinou, M.C., "EFFECT OF STRONG EARTHQUAKE GROUND MOTION DURATION ON DISPLACEMENT, FORCE AND ENERGY DISSIPATED IN SEISMIC ISOLATION SYSTEMS", in review, 2019.

SEISMIC ISOLATION





A method of construction and a technology in which a system is used to provide period lengthening and ability to absorb energy

- Isolator flexibility
- Force/acceleration reduction
- Displacement increase
  - Isolator displacement capacities of 500 to over 1000mm -need for damping
  - Displacement concentrated in isolation system-small structural drift

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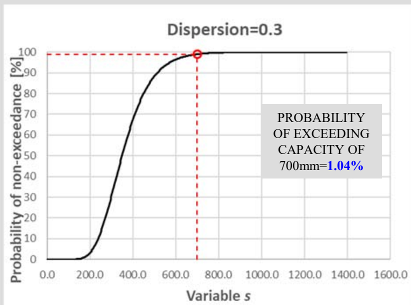
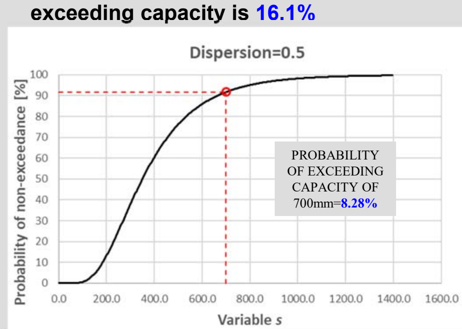
SEISMIC ISOLATION

- **Typically, seven spectrally matched ground motion triplets are used to estimate isolator displacements. Good at estimating median or average values.**
- **Say median isolator displacement m=350mm. Say displacement capacity is 700mm.**

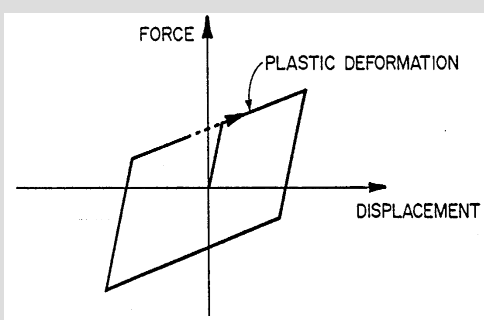
- **Isolator displacement capacities of 500 to over 1000mm?**
- **Uncertainty in response** (mostly due to record-to-record variability, and other uncertainties in material properties, modeling accuracy, etc.) **and acceptable isolator collapse risk determine isolator displacement capacity.**
- **For dispersion of 0.7, probability of exceeding capacity is 16.1%**





$$P(X < x) = \int_0^x \frac{1}{s\beta\sqrt{2\pi}} \exp\left[\frac{(\ln s - \ln m)^2}{2\beta^2}\right] ds$$

SEISMIC ISOLATION

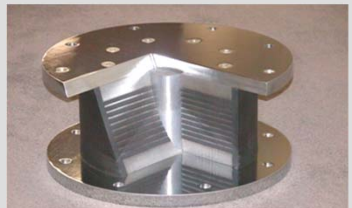


Energy dissipation

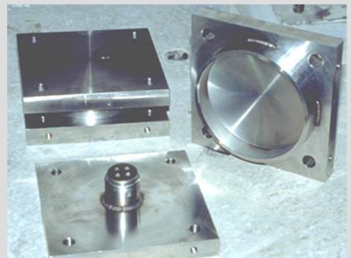
- hysteretic
  - high-damping rubber
  - yielding of lead
  - sliding friction
- viscous
  - external hardware-fluid viscous dampers

ISOLATION HARDWARE

- Isolation bearings
  - Elastomeric
    - Low-damping rubber
    - High-damping rubber
    - Lead-rubber
  - Sliding
    - Friction Pendulum
    - Sliding with Restoring Force
    - Sliding with Yielding Devices (Elastoplastic)
- Energy dissipation devices
  - Viscous dampers



COURTESY DIS



UNIVERSITY AT BUFFALO, 1988

ISOLATION HARDWARE

- Lead Rubber bearing

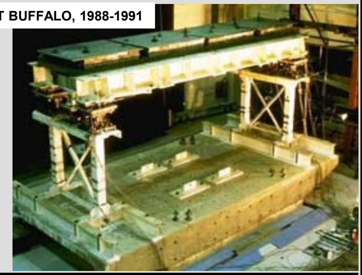
ENGINEER: SULEYMAN HOCA, ANKARA

COURTESY: DIS

ERZURUM HOSPITAL, TURKEY, 2007

QUALIFICATION TESTING

- Conducted to qualify a new technology
  - Material testing.
  - Component testing.
  - Shake table testing.
- Used to
  - Acquire data for use in model validation.
  - Observe behavior under extreme conditions.
  - Develop database of properties for supporting bounding analysis considerations.

UNIVERSITY AT BUFFALO, 1988-1991

UNIVERSITY AT BUFFALO, 2016

QUALIFICATION TESTING

- Conducted to qualify a new technology
  - Double and Triple FP isolators
- Used to
  - Acquire data for use in model validation.
  - Observe behavior under extreme conditions.

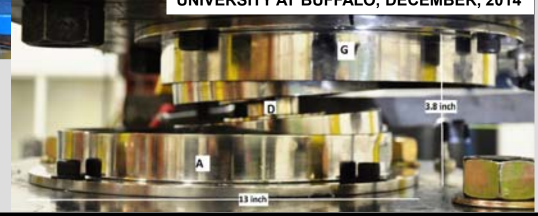
UNIVERSITY AT BUFFALO, 2004

QUINTUPLE FP BEARING

ENGINEER: SOM, LOS ANGELES

- Los Angeles County Museum of Art.
- Quintuple FP isolators.
- 1775mm displacement capacity.
- 20000kN gravity load.
- Full-scale qualification testing, June 5, 2019.

UNIVERSITY AT BUFFALO, DECEMBER, 2014

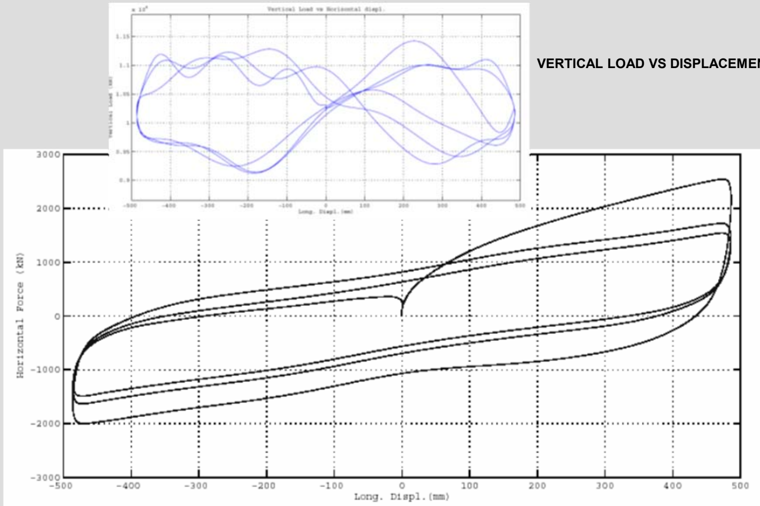


PROTOTYPE DYNAMIC TESTING

- For each type of isolator used, two are tested under actual load and real dynamic conditions.
- Testing reveals properties for use in analysis and design, and in quality control.
- Done under the supervision of peer review panel.
- SRMD Test Machine/UCSD
  - Horizontal capacity
    - 2500mm stroke
    - 1.8m/sec
  - Vertical capacity
    - 72000kN
  - Lead-rubber isolators for Erzurum Hospital tested at SRMD, 2007

COURTESY: DIS

LEAD-RUBBER BEARING



VERTICAL LOAD VS DISPLACEMENT

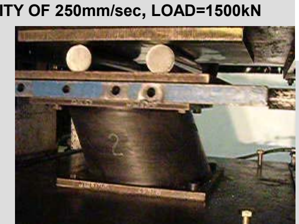
ERZURUM HOSPITAL, TURKEY, 2007
SRMD TEST MACHINE, UC SAN DIEGO
LOAD=10260kN, DISPLACEMENT=480mm, VELOCITY=1m/sec

PROTOTYPE DYNAMIC TESTING

LEAD RUBBER BEARING
WEAR TESTING
AT VELOCITY OF 3mm/sec, LOAD=2000kN
16,000 CYCLES, TOTAL TRAVEL 1600m

LEAD RUBBER BEARING
DYNAMIC TESTING
AT VELOCITY OF 250mm/sec, LOAD=1500kN

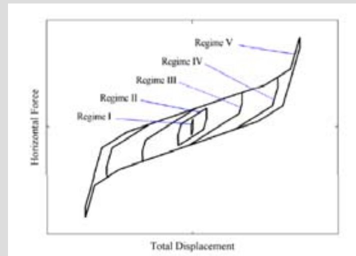
WOODROW WILSON BRIDGE BEARINGS
QUALIFICATION-PROTOTYPE TESTING AT UNIVERSITY AT BUFFALO, 2003

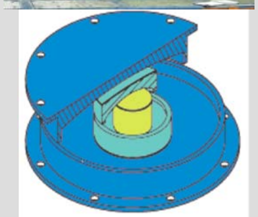


ENGINEER: PARSONS, NYC

PROTOTYPE DYNAMIC TESTING
TRIPLE FP ISOLATORS

UNIVERSITY AT BUFFALO, 2007





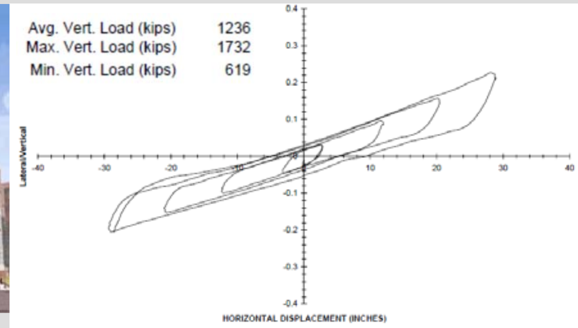
PROTOTYPE DYNAMIC TESTING

ENGINEER: SOM, SAN FRANSISCO

TRIPLE FP ISOLATOR TESTING FOR
SAN BERNARDINO COUNTY COURTHOUSE
PROTOTYPE TESTING
NOVEMBER 2010

EPS BEARING TESTING MACHINE
LOAD=6600kN
AMPLITUDE=1000mm
PEAK VELOCITY=1080mm/sec

PROTOTYPE DYNAMIC TESTING



ENGINEER: ARUP, SAN FRANSISCO
COURTESY: SAN FRANCISCO DEPARTMENT OF PUBLIC HEALTH

SAN FRANCISCO GENERAL HOSPITAL PROTOTYPE TESTING,
LOAD=5500kN, DISPLACEMENT=740mm, VELOCITY=1.2 m/sec
EPS BEARING TESTING MACHINE, OCTOBER 2008

PRODUCTION (QUALITY CONTROL) TESTING

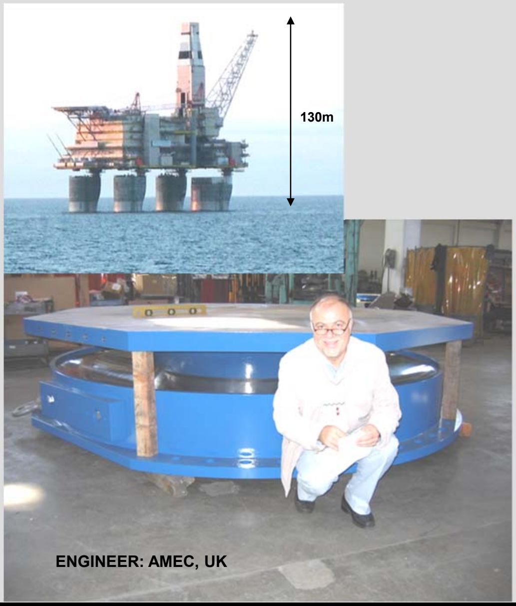
- All isolators tested under (preferably) dynamic conditions.
- Quality of production isolators revealed. Need to meet performance criteria.
- Properties of production isolators verified.
- Record of isolator properties established for future evaluation.
- For hospitals in California done under continuous inspection.

IKITELLI INTEGRATED HEALTH CAMPUS, ISTANBUL

2059 TRIPLE FP PRODUCTION ISOLATORS TESTED, 2017

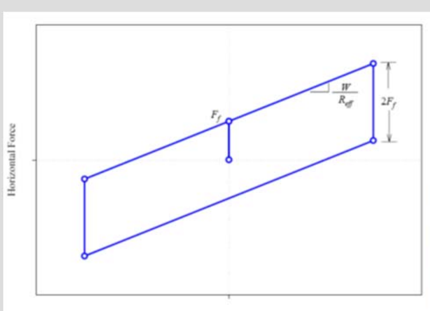
ENGINEER: ARUP, LOS ANGELES

SINGLE FP BEARING

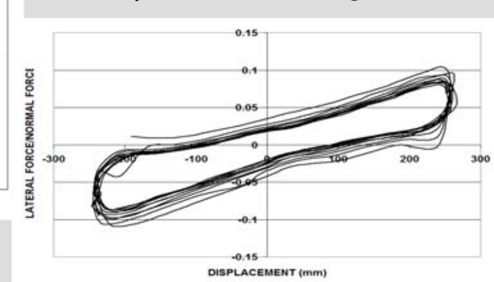


- Piltun and Lunskoye Oil and Gas Platforms, Russia.
- Largest seismic isolators by load.
- 700mm displacement capacity.
- 88MN gravity load
  - Another application carries 103MN
- 130MN max load.
- Full-scale testing.
- Reduced scale dynamic testing.

SINGLE FP BEARING



- W=axial load on bearing
- R_{eff}=effective radius of curvature
- F_f=friction force at sliding interface



SAKHALIN II PLATFORMS PROTOTYPE BEARING PR1,
LOAD=6925kN, DISPLACEMENT=240mm, VELOCITY=0.9 m/sec
EPS BEARING TESTING MACHINE, OCTOBER 2005

FLUID VISCOUS DAMPERS

XIHOUMEN BRIDGE, CHINA
8.8m LONG WHEN EXTENDED
+/-1.2m DISPLACEMENT CAPACITY
1000kN RATED LOAD CAPACITY

FLUID VISCOUS DAMPERS

COURTESY: WASHINGTON HOSPITAL
ENGINEER: THORNTON TOMASETTI, SAN FRANCISCO

WASHINGTON HOSPITAL PROTOTYPE TESTING
PEAK FORCE=2050kN, DISPLACEMENT=500mm, VELOCITY=2400mm/sec
TAYLOR DEVICES TESTING MACHINE, MAY 2013

FLUID VISCOUS DAMPERS

COURTESY: TAYLOR DEVICES

MILLENIUM BRIDGE, LONDON.
SUSPENSION BRIDGE WITH LATERAL CABLES.
OPENED JUNE 10, 2000, CLOSED IN TWO DAYS.
EXCESSIVE BRIDGE SWAY WITH MORE THAN 1000 PEOPLE ON BRIDGE.

ENGINEER: ARUP, LONDON

37 HERMETICALLY-SEALED VISCOUS DAMPERS, 1.3 BILLION CYCLES.
50 TUNED MASS DAMPERS.
OPENED TO PUBLIC JANUARY 2002

PEER REVIEW AND INSPECTION

- **PEER REVIEW**
  - Conducted by a committee of one to three individuals knowledgeable in seismic hazard analysis, structural design and seismic protective systems.
  - Committee hired by Owner, works with Engineer during design and reports to Building Officials.
  - Examples
    - Stanford University Hospital: Asher, Constantinou, Mejia.
    - Apple Campus: Mahin, Constantinou, Baker.
    - Washington Hospital: Constantinou.
    - Giant Magellan Telescope: Kircher, Abrahamson.
    - Loma Linda University Medical Center: Lizundia, Constantinou, GeoPentech
- **INSPECTION**
  - Prototype testing always observed and independently reported by representative of peer review panel.
  - For hospitals in California, prototype testing is required to be continuously observed by:
    - Inspector of Record
    - Independent Engineer
    - State Agency OSHPD
    - Engineer of Record
  - For hospitals in California, production testing is required to be continuously observed and certified by:
    - Inspector of Record
    - Independent Engineer

SIGNIFICANCE OF TESTING

- **Prototype bearings and dampers need to be tested under a variety of conditions to determine their properties.**
- **All production bearings and dampers need to be tested to verify properties and reveal problems (quality control).**
- **All testing should be performed at full scale-otherwise complex scaling principles need to be used. Should be used only for hardware that is impossible to test anywhere.**
- **All testing should be dynamic. This is absolutely necessary for the prototype bearings and dampers.**
- **Observation of testing and certification of authenticity of results is becoming increasingly important.**

SIGNIFICANCE OF TESTING, INSPECTION AND PEER REVIEW

- **Example of problems when bearings were not tested.**
- **Kunming Airport, China, 2011.**
- **Bearings not tested.**
- **Bearings failed during construction.**
- **Hundreds of bearings replaced.**

COURTESY: DR. YONGI CHEN

- **Lack of Peer Review.**

SIGNIFICANCE OF TESTING

- Bolu Viaduct, Turkey, 1999
- Bearings were too small (lack of peer review).
- Bearings not tested.
- All 1638 bearings failed during construction in earthquake of November 1999.

SIGNIFICANCE OF TESTING

- Example of problems when dampers were not tested.
- California State Office Buildings 8 & 9, 2007.
- Specifications called for production testing of only 25% of dampers.
- 75% of dampers installed without testing and then testing started.
- Dampers showed abnormal behavior.
- 256 dampers removed from structure and re-built.

SIGNIFICANCE OF PROPER TESTING

30% OF APARTMENTS WITH BASE ISOLATION SYSTEMS SUFFERED DAMAGE IN EARTHQUAKE

JAPAN PROPERTY CENTRAL

Fully licensed real estate brokerage in central Tokyo

Posted on January 27, 2012

A survey by the Japan Society of Seismic Isolation found that 30% of buildings constructed with base isolation (*menshin*) systems suffered damage to the building dampers during the March 11 Tohoku earthquake.

The Society sent out a survey to 327 menshin buildings across Japan. While the majority reported no damage, 28% (90 properties) did report some kind of damage resulting from the dampers or moving parts not functioning properly. The majority of the buildings with damage were in greater Tokyo and Miyagi Prefecture. There was also one case reported in Osaka, which was a long way from the epicenter. The failure of the base isolation structure in some buildings is of concern to the Society.

There are a total of 2600 *menshin* buildings across Japan. This is the first investigation on the actual efficiency of this construction method following a major quake.

http://japanpropertycentral.com/2012/01/30-of-apartments-with-base-isolation-systems-suffered-damage-in-earthquake/

SIGNIFICANCE OF INSPECTION, OBSERVATION OF TESTING AND CERTIFICATION OF AUTHENTICITY

- **In 2018 the Japanese Ministry of Land, Infrastructure, Transport and Tourism determined that a manufacturer of oil dampers, Kayaba System Machinery, a subsidiary of KYB Corporation, falsified test data for dampers in hundreds of buildings (over 30,000 dampers) over a period of more than 15 years. The company must replace all dampers by 2020.**

		Nonconforming products *1		③Unknown (including those for which surveying is continuing)*2	① - ③ Total	Total No. of products shipped (reference) *3
		① Nonconforming to certification by Minister	② Out of customer standards			
Seismic isolation oil damper	No. of properties	128	256	519	903	1,052
	No. of products	499	1,914	5,137	7,550	10,369
Seismic mitigation oil damper	No. of properties		26	57	83	358
	No. of products		146	3,232	3,378	20,779

KYB CORPORATION, OCTOBER 16, 2018

SAMPLE TESTING SPECIFICATIONS

Sample tests to determine properties and verify capacities per ASCE 7-10 (also ASCE 7-16) but using only D_M (AVERAGE DISPLACEMENT CALCULATED FOR THE MAXIMUM EARTHQUAKE)

Test	ASCE 7-10 Reference	Vertical Load	Amplitude of Lateral Displacement or Load	Peak Cyclic Velocity or Load Rate	Cycles	Acceptance Criteria
1	17.8.2.2, item 1	P_{nom}	P_W	1Hz	20	No motion
2	17.8.2.2, item 2	P_{nom}	$0.25D_M$	>125mm/s	3	1, 2, 3, 4
3	17.8.2.2, item 2	P_{nom}	$0.5D_M$	>125mm/s	3	1, 2, 3, 4
4	17.8.2.2, item 2	P_{nom}	$0.67D_M$	>125mm/s	3	1, 2, 3, 4
5	17.8.2.2, item 2	P_{nom}	D_M	>125mm/s	3	1, 2, 3, 4
6	17.8.2.2, item 2	P_{min}	$0.25D_M$	>125mm/s	3	1, 2, 3, 4
7	17.8.2.2, item 2	P_{min}	$0.5D_M$	>125mm/s	3	1, 2, 3, 4
8	17.8.2.2, item 2	P_{min}	$0.67D_M$	>125mm/s	3	1, 2, 3, 4
9	17.8.2.2, item 2	P_{min}	D_M	>125mm/s	3	1, 2, 3, 4
10	17.8.2.2, item 2	P_{max}	$0.25D_M$	>125mm/s	3	1, 2, 3, 4
11	17.8.2.2, item 2	P_{max}	$0.5D_M$	>125mm/s	3	1, 2, 3, 4
12	17.8.2.2, item 2	P_{max}	$0.67D_M$	>125mm/s	3	1, 2, 3, 4
13	17.8.2.2, item 2	P_{max}	D_M	>125mm/s	3	1, 2, 3, 4
14	17.8.2.2, Item 3	P_{nom}	D_{TM}	>125mm/s	3	1, 4
15	17.8.2.2., Item 4	P_{nom}	$0.75D_M$	>125mm/s	20	1, 4
16	17.8.2.5	P_{min}	D_{TM}	>125mm/s	1	1, 4, 5, 6
17	17.8.2.5	P_{max}	D_{TM}	>125mm/s	1	1, 4
Acceptance criteria per Section 3.3.4						

SAMPLE TESTING SPECIFICATIONS

Sample tests to determine properties and verify capacities per ASCE 7-10 (also ASCE 7-16) but using only D_M

P_{nom} (kN)	P_{min} (kN)	P_{max} (kN)	D_M (mm)	D_{TM} (mm)	T_M (sec)	Number of Cycles N in Ultimate Capacity Test
2300	500	4000	500	575	4.0	10

Acceptance Criteria for Prototype Tests

1. The load-displacement plots of all tests have a positive incremental force-carrying capacity.
2. For each increment of displacement, under each vertical load case, the difference between the effective stiffness at each of the three cycles of test and the average value of effective stiffness is no greater than 15 percent.
3. For each increment of displacement, under each vertical load case, and for each cycle of test, the difference between effective stiffness of the two test specimens of a common type and size of the isolator unit and the average effective stiffness is no greater than 15 percent.
4. Bearing shall remain stable.
5. No greater than a 20% change between k_{eff} in the initial cycle and k_{eff} in the last cycle.
6. No greater than a 20% decrease from β_{eff} in the initial cycle and β_{eff} in the last cycle.

SAMPLE TESTING SPECIFICATIONS

Sample tests to determine properties and verify capacities in addition to ASCE 7-10

Test	Purpose	Vertical Load	Amplitude of Lateral Displacement	Frequency	Cycles	Acceptance Criteria
QC	Quality Control	P_{nom}	$0.75D_M$	$1/T_M$	3	1, 4
P1	Seismic Properties	P_{min}	D_M	$1/T_M$	5	1, 4
P2	Seismic Properties	P_{nom}	D_M	$1/T_M$	5	1, 4
P3	Seismic Properties	P_{max}	D_M	$1/T_M$	5	1, 4
Acceptance criteria per Section 3.3.4						

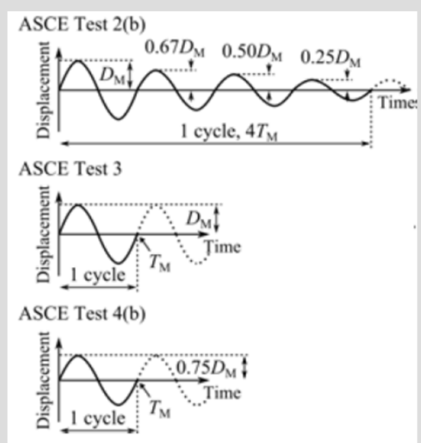
Real Time Dynamic Tests

Test	Vertical Load (kN)	Lateral Displacement (mm)	Min. Peak Velocity (mm/s)	Test Procedure
Vertical Load Capacity Test	10,000	D_M	> 2	Apply vertical test load at the lateral displacement. Maintain the load for 1 minute.
Shear Load Capacity Test	10,000	700	> 2	Apply vertical test load and shear bearing to minimum of 700 mm displacement.

Capacity Tests

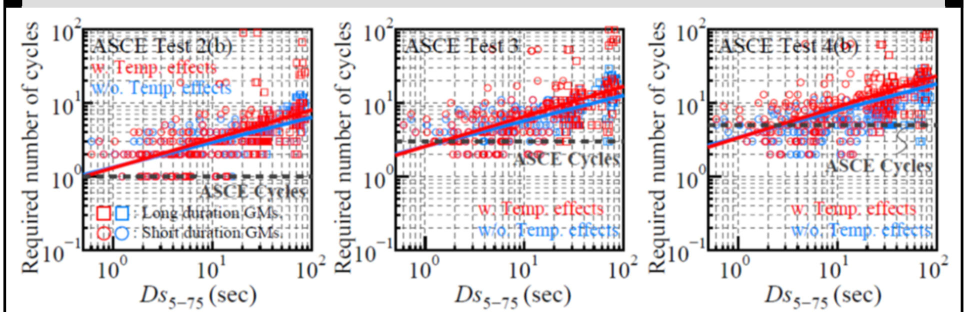
ASCE/SEI 7-16 TESTING SPECIFICATIONS

- Section 17.8.2.2 of ASCE/SEI 7-16
- Test 2(b) consists of four continuous cycles under dynamic conditions with one at each of amplitudes D_M, $0.67D_M$, $0.5D_M$ and $0.25D_M$.
- Test 3 consisting of three cycles at amplitude D_M. The test is not specified as dynamic but is evaluated as a dynamic test.
- Test 4(b) consisting of five cycles at amplitude $0.75D_M$ (the test is followed by one or more sequences of five cycles but with idle time between tests). It is presumed that five cycles at this amplitude are representative of one MCE_R event.



ASCE 7-16
TESTING SPECIFICATIONS

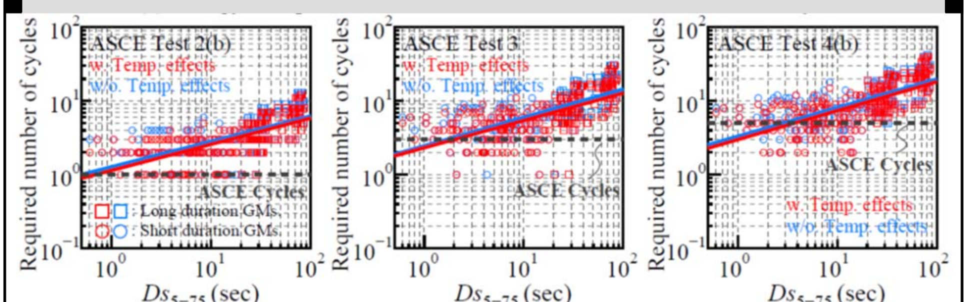
- **Section 17.8.2.2 of ASCE/SEI 7-16**



Required number of cycles such that the calculated energy dissipated in bi-directional analysis equals that in the test.
Elastomeric isolation system, lower bound analysis

ASCE 7-16
TESTING SPECIFICATIONS

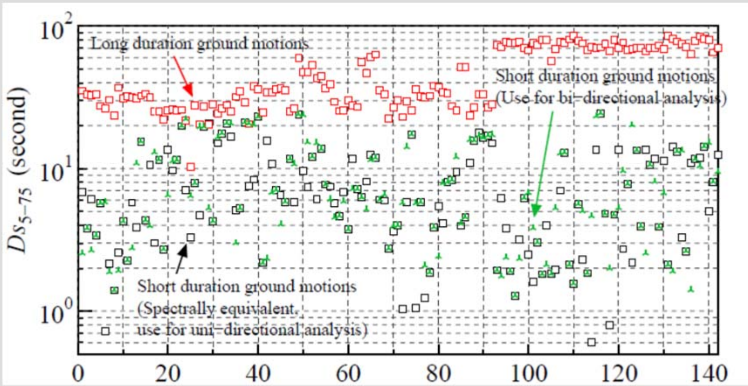
- **Section 17.8.2.2 of ASCE/SEI 7-16**



Required number of cycles such that the calculated energy dissipated in bi-directional analysis equals that in the test.
Single FP isolation system, lower bound analysis

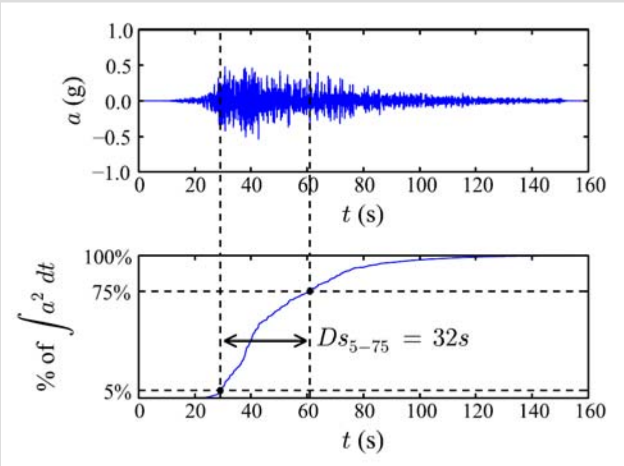
ASCE 7-16
TESTING SPECIFICATIONS

- **Strong motion duration**



ASCE 7-16
TESTING SPECIFICATIONS

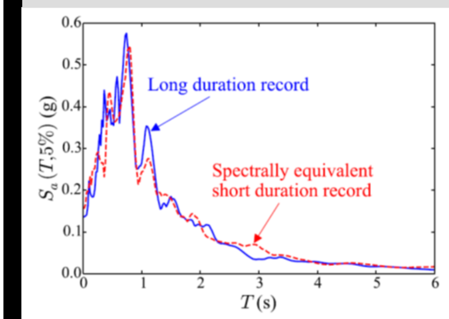
- **Strong motion duration definition**

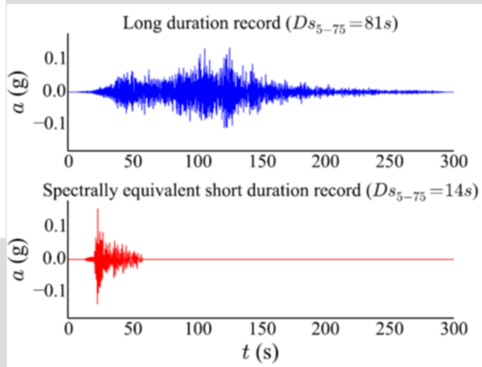


Earthquake Spectra, Volume 32, No. 2, pages 927–950, May 2016

ASCE 7-16
TESTING SPECIFICATIONS

- **Motions used in analysis**





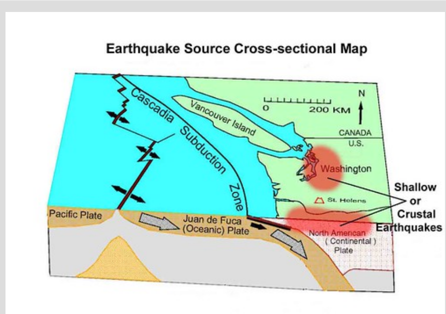
Earthquake Spectra, Volume 32, No. 2, pages 927–950, May 2016

ASCE 7-16
TESTING SPECIFICATIONS

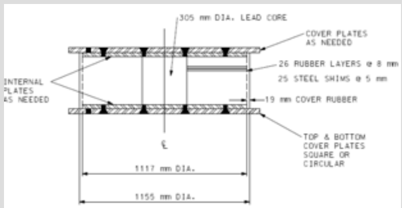
- **Strong Motion Duration Examples**

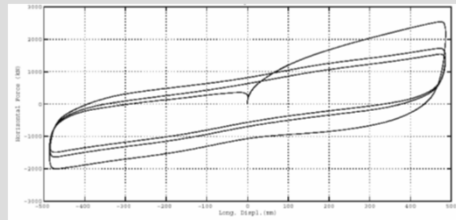
Earthquake Engng Struct. Dyn. 2016; **45**:1357–1379

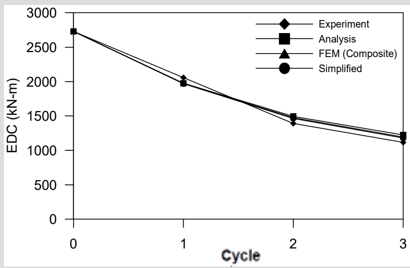
Site	Interface earthquakes	In-slab earthquakes	Crustal earthquakes
Seattle	32 s (35%)	7 s (24%)	5 s (41%)
Eugene	30 s (93%)	8 s (7%)	—
San Francisco	—	—	9 s (100%)

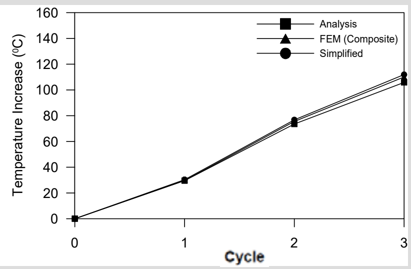


LEAD RUBBER CORE HEATING









ERZURUM HOSPITAL, TURKEY, 2007
LOAD=10260kN, DISPLACEMENT=480mm,
VELOCITY=1m/sec

LEAD RUBBER CORE HEATING

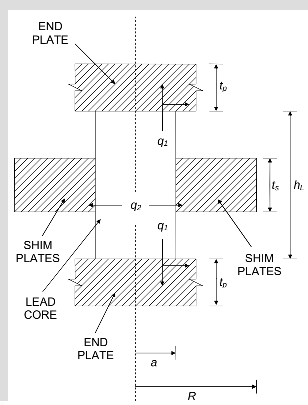
- **Complex heat conduction problem**

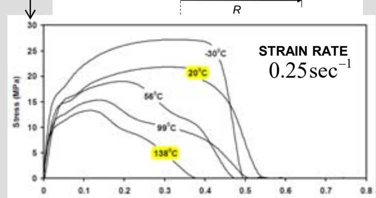
$$\rho_L \cdot c_L \cdot V_L \frac{dT_L}{dt} = q'''(t) \cdot V_L - 2 \cdot q_1(t) - q_2(t)$$

$$q'''(t) = \frac{\left|\sigma_{YL} \cdot A_L \cdot \frac{du}{dt}\right|}{V_L} = \frac{\sigma_{YL} \cdot \left|\frac{du}{dt}\right|}{h_L}$$

$$\sigma_{YL} = \sigma_{YL0} \cdot \exp(-E_2 \cdot T_L)$$

ρ_L **lead density**
c_L **lead specific heat**
q_1 heat flux to top or bottom end plate
q_2 heat flux to shim plates
σ_{YL} **effective yield stress of lead (function of T_L)**
q''' heat production rate (energy per volume per time)
V_L **volume of lead core**
h_L **height of lead core**
A_L **area of lead core**
$\frac{du}{dt}$ **velocity of top of bearing wrt bottom**
T_L **lead core temperature rise**





LEAD RUBBER CORE HEATING

$$\frac{dT_L}{dt} = \frac{\sigma_{YL}(T_L)\cdot v(t)}{\rho_L c_L h_L} - \frac{k_S \cdot T_L}{a\cdot \rho_L c_L h_L}\cdot\left(\frac{1}{F} + 1.274\cdot\left(\frac{t_s}{a}\right)\cdot\left(t^+\right)^{-1/3}\right)$$

Effective Yield Stress

Lead Core Height

Velocity

Lead Core Radius

Total Shim Thickness

Dimensionless Time

$$F = \begin{cases} 2\cdot\left(\frac{t^+}{\pi}\right)^{1/2} - \frac{t^+}{\pi}\cdot\left[2 - \left(\frac{t^+}{4}\right) - \left(\frac{t^+}{4}\right)^2 - \frac{15}{4}\left(\frac{t^+}{4}\right)^3\right], & t^+ \le 0.6 \\ \frac{8}{3\pi} - \frac{1}{2\left(\pi\cdot t^+\right)^{1/2}}\cdot\left[1 - \frac{1}{3\cdot\left(4t^+\right)} + \frac{1}{6\cdot\left(4t^+\right)^2} - \frac{1}{12\cdot\left(4t^+\right)^3}\right], & t^+ > 0.6 \end{cases}$$

$$t^+ = \frac{\alpha_S \cdot t}{a^2}$$

Thermal Diffusivity of Steel

$$\sigma_{YL} = \sigma_{YL0}\cdot\exp(-E_2\cdot T_L)$$

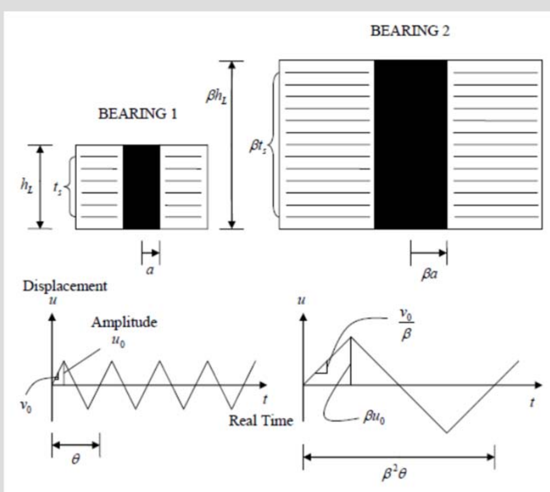
SIMPLIFIED SOLUTION VALID WHEN HEAT CONDUCTION IN STEEL PLATES AND SHIMS IS NEGLECTED

$$T_L' = \frac{1}{E_2}\cdot\ln\left(1 + \frac{E_2\sigma_{YL0}S}{\rho_L c_L h_L}\right)$$

$$S = \int v(t)dt$$

LEAD RUBBER CORE HEATING

- **Scaling of Lead-Rubber Bearings for Testing**



$Q = E_2 T_L$ Temperature

$\left(\frac{\alpha_S t}{a^2}\right)$ Time

$\left(\frac{t_s}{a}\right)$ Shim Thickness

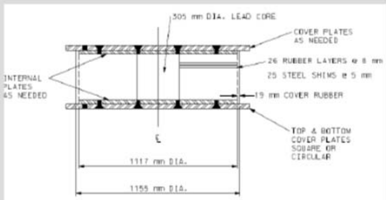
$\left(\frac{a\rho_S c_S}{\rho_L c_L h_L}\right)$ Lead Core Shape

$\left(\frac{E_2\sigma_{YL0} v_0 a^2}{\alpha_S \rho_L c_L h_L}\right)$ Strain Rate

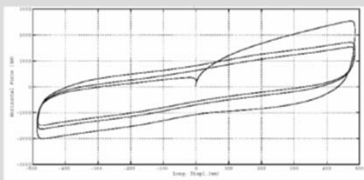
$S_T = S_L^{\,2} = \beta^2$ Thermodynamic Similarity

$S_T = \sqrt{S_L} = \sqrt{\beta}\ldots?$ Gravity Scaling

REDUCED SCALE TESTING OF LEAD-RUBBER BEARINGS



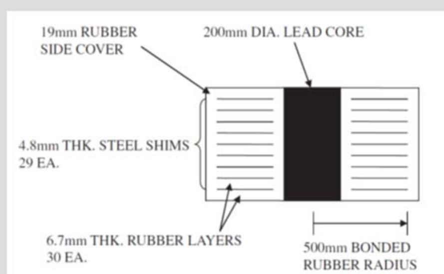
ERZURUM HOSPITAL, TURKEY, 2007
LOAD=10260kN, DISPLACEMENT=480mm, VELOCITY=1m/sec



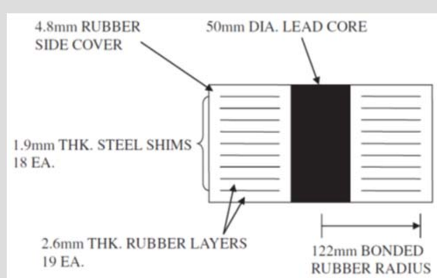
- **REDUCED SCALE BEARING TESTING**
  - LENGTH SCALE 2 (HALF SIZE)
  - LOAD 2565kN
  - DISPLACEMENT AMPLITUDE 240mm
  - VELOCITY 2m/sec
  - CAN CORRECTLY CAPTURE REDUCTION OF STRENGTH PER CYCLE
  - CANNOT PROVIDE RELIABLE INFORMATION ON STARTING VALUE OF STRENGTH
- **SHAKE TABLE TESTING**
  - LENGTH SCALE 4 (QUARTER SIZE)
  - LOAD PER BEARING 640kN
  - FOR REALISTIC TEST WITH AT LEAST 8 BEARINGS CAN ONLY BE DONE AT E-DEFENSE IN JAPAN
  - TO PROPERLY MODEL GRAVITY (UNSCALED), TIME NEEDS TO BE COMPRESSED BY FACTOR $\sqrt{4}=2$. VELOCITY IN THE EXPERIMENTS IS THEN REDUCED BY FACTOR 4/2=2.
  - THERMODYNAMIC SIMILARITY REQUIRES THAT VELOCITY IS INCREASED BY FACTOR 4.
  - IMPOSSIBLE TO OBSERVE HEATING EFFECTS.
  - IS THIS A CASE WHERE HYBRID TESTING IS USEFUL? HOW TO CONDUCT SUCH A TEST?

INCOMPLETE SIMILARITY

- **Most often is impossible to test reduced scale lead-rubber bearings in complete similarity**
- **Incomplete similarity allows for testing at reduced velocity but with increased number of cycles**



FULL SCALE BEARING



QUARTER SCALE BEARING

INCOMPLETE SIMILARITY

- **Test 1-Complete Similarity**

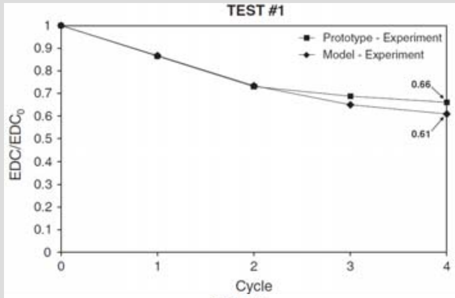
Full size bearing tested at 400mm amplitude, constant velocity of 25mm/sec and 4 cycles

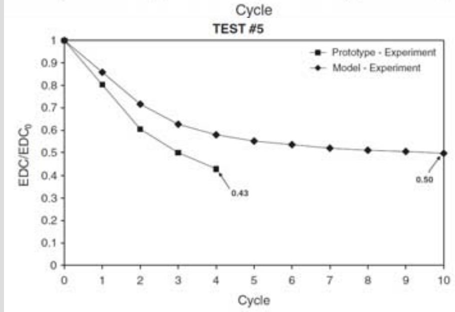
Quarter scale bearing tested at 100mm amplitude, constant velocity of 100mm/sec and 4 cycles

- **Test 5-Incomplete Similarity**

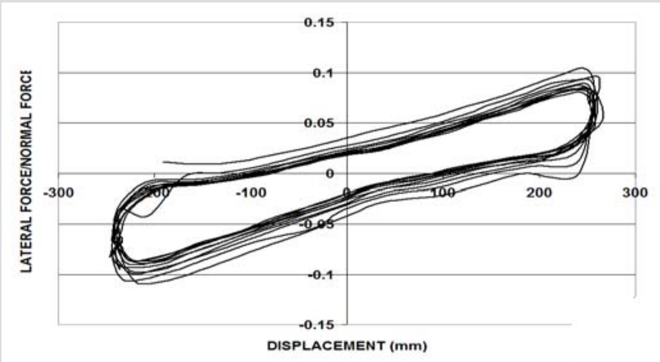
Full size bearing tested at 400mm amplitude, harmonic velocity of 762mm/sec and 4 cycles

Quarter scale bearing tested at 100mm amplitude, harmonic velocity of 190mm/sec and 10 cycles

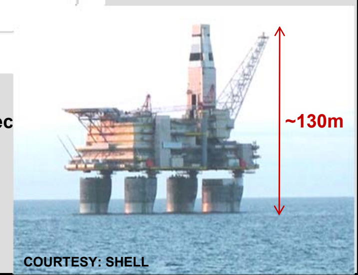




FP BEARING HEATING EFFECTS

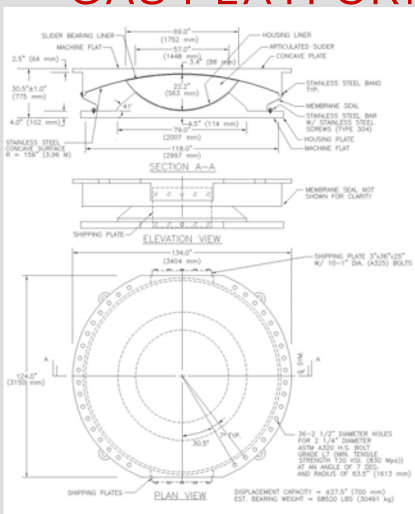


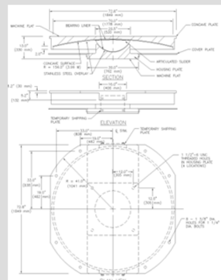
SAKHALIN II PLATFORMS PROTOTYPE BEARING PR1, LOAD=6925kN, DISPLACEMENT=240mm, VELOCITY=0.9 m/sec EPS BEARING TESTING MACHINE, OCTOBER 2005



LUNSKOYE/PILTUN OIL AND GAS PLATFORMS, RUSSIA

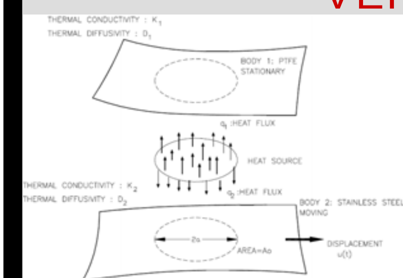
FULL SIZE PRDUCTION BEARING

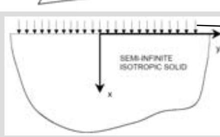




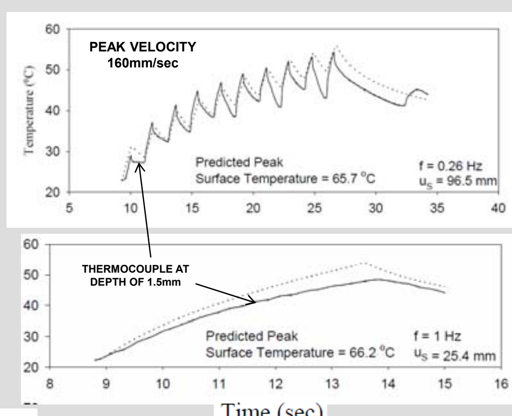
REDUCED SIZE PROTOTYPE BEARING

FRICTIONAL HEATING THEORY VERIFICATION





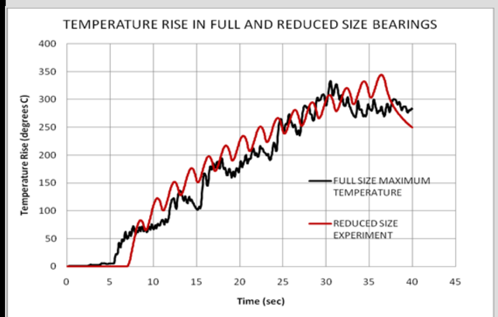
INTERMITTENT HEAT FLUX

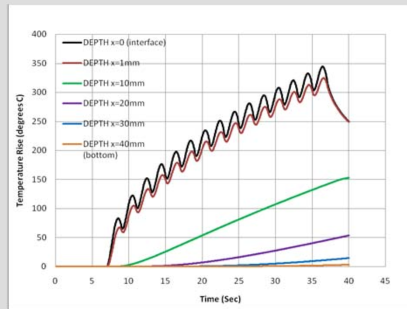


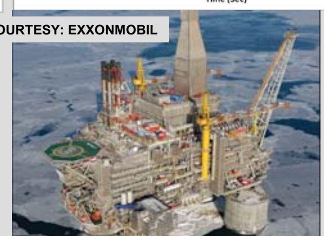
$$T(x,t) = \frac{D^{1/2}}{\pi^{1/2} k} \int_o^t q(t-\tau)\exp\left(-\frac{x^2}{4D\tau}\right)\frac{d\tau}{\tau^{1/2}}$$

k **is the thermal conductivity of stainless steel**
D is the thermal diffusivity of stainless steel
q is the heat flux=μ·p·v

ARKUTUN-DAGI OIL AND GAS PLATFORM, RUSSIA







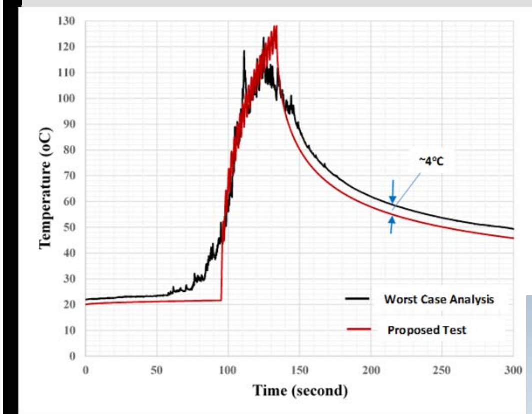
ENGINEER: WORLEY-PARSONS, EXXONMOBIL

PEER REVIEW OF PILTUN, LUNSKOYE AND ARKUTUN-DAGI OIL AND GAS PLATFORMS, RUSSIA

- Performed by a Russian agency under the direction of Professor Yuri Drosdov (Physics and Tribology, Russian Academy of Engineering, Russian Academy of Space, Russian Academy of Science, Lenin Prize).
- Lasted some 10 years.
- Included development and validation of theories based on principles of physics and scaling and similarity (G. I. Barenblatt).

COURTESY: EXXONMOBIL

GIANT MAGELLAN TELESCOPE, CHILE



Test: 10 cycles, 0.25Hz, 145mm amplitude

ENGINEER: M3, TUCSON, AR

COURTESY: M3, TUCSON, AZ

EXAMPLES OF APPLICATIONS OF ISOLATORS WITH PEER REVIEW, INSPECTION AND COMPLETE TESTING REQUIREMENTS

Las Caras Bahia Bridge, Ecuador

ENGINEER: ECUADORIAN ARMY CORPS OF ENGINEERS

Designed with Triple FP system having the following characteristics:

1. Substructure designed to be essentially elastic and with high redundancy.
2. Isolators designed with increased displacement capacity. Capacity was 585mm at full engagement of restraining rings and about 750mm after failure of inner ring and when collapsing.
3. Isolators designed to resist lateral force equal to 50% of vertical load.
4. All isolators tested for enhanced performance.

COURTESY: PROF. L. COLONEL ENRIQUE MORALES

April 16, 2016 M7.8 Earthquake

Bearing displacements varied from about 100 mm to 650 mm.

Four bearings at pier 12 had displacements of about 650mm with the inner rings plastically deformed and fractured.

Bridge was fully functional and used in earthquake recovery.

EXAMPLES OF APPLICATIONS OF ISOLATORS WITH ENHANCED TESTING REQUIREMENTS

Apple Campus, California
Triple FP Bearings

ISOLATOR DISPLACEMENT CAPACITY 1300mm

Engineer: ARUP, SAN FRANCISCO

San Bernardino County Courthouse, California
Triple FP Bearings+ Viscous Dampers
in Superstructure

San Bernardino County Courthouse, California
11-story Tower+3-story Podium

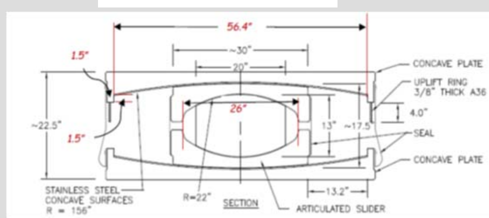
Engineer: SOM, SAN FRANCISCO

EXAMPLES OF APPLICATIONS OF ISOLATORS WITH ENHANCED TESTING REQUIREMENTS

Wrapper Building, Los Angeles, California

COURTESY: ERIC OWEN MOSS ARCHITECTS

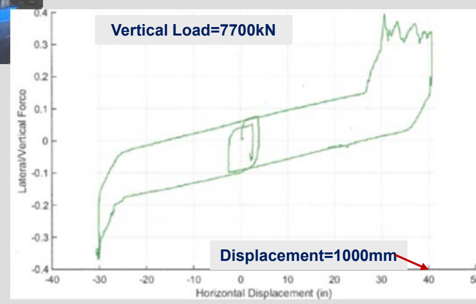
1500mm PLAN DIMENSIONS



ENGINEER: ARUP, LOS ANGELES

EXAMPLES OF APPLICATIONS OF ISOLATORS WITH ENHANCED TESTING REQUIREMENTS

Wrapper Building, Los Angeles, California



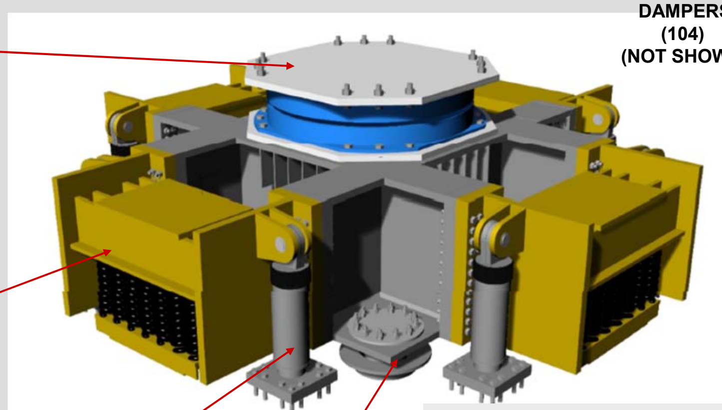
Designed with Triple FP system having the following characteristics:

1. Accommodate 140mm uplift.
2. Prototype isolators tested to loads of 37000kN (average load is 7700kN)
3. Prototype isolators tested to failure of outer ring at a displacement exceeding 1000mm. Designed such that inner ring is stronger than outer ring.

LOMA LINDA UNIVERSITY MEDICAL CENTER UNDER CONSTRUCTION IN 2019 3D SEISMIC ISOLATION SYSTEM

VISCOUS DAMPERS (104) (NOT SHOWN)

TRIPLE FP ISOLATOR (126)



VERTICAL HELICAL SPRINGS (over 50,000 helical springs)

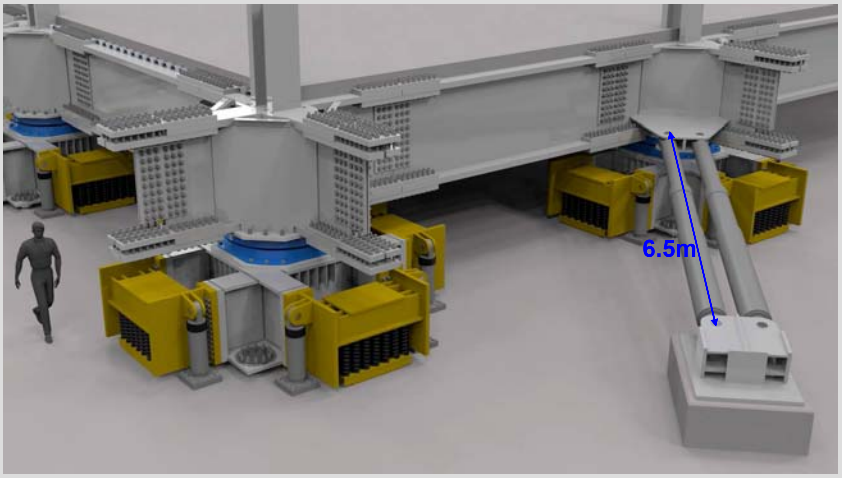
VERTICAL DAMPERS (1008)

VERTICAL SHEAR PINS (508)

126 Isolators, 104 Dampers Tested
508 Vertical Shear Pins under Testing
All components to be tested with continuous inspection

Engineer: ARUP, LOS ANGELES

LOMA LINDA UNIVERSITY MEDICAL CENTER
UNDER CONSTRUCTION IN 2019
3D SEISMIC ISOLATION SYSTEM



Engineer: ARUP LOS ANGELES

Revised 08/2019 Civil, Structural & Environmental Eng. , University at Buffalo

LOMA LINDA UNIVERSITY MEDICAL CENTER
UNDER CONSTRUCTION IN 2019
3D SEISMIC ISOLATION SYSTEM

TRIPLE FP ISOLATOR

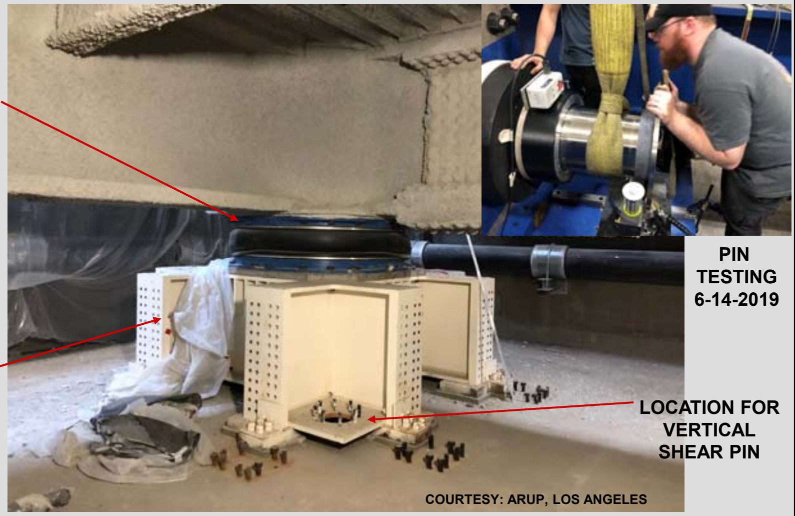
VISCOUS DAMPER

PEDESTAL WITHOUT VERTICAL ISOLATION SYSTEM

Revised 08/2019 Civil, Structural & Environmental Eng. , University at Buffalo

LOMA LINDA UNIVERSITY MEDICAL CENTER UNDER CONSTRUCTION IN 2019 3D SEISMIC ISOLATION SYSTEM

TRIPLE FP ISOLATOR

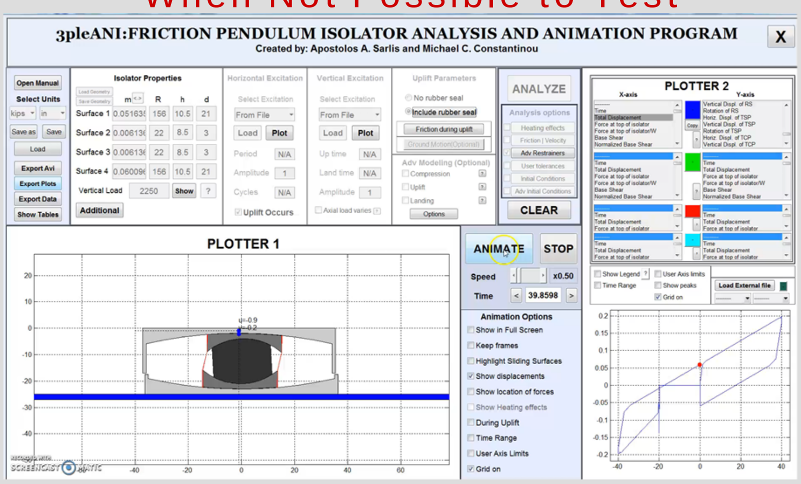


PIN TESTING 6-14-2019

PEDESTAL WITHOUT VERTICAL ISOLATION SYSTEM

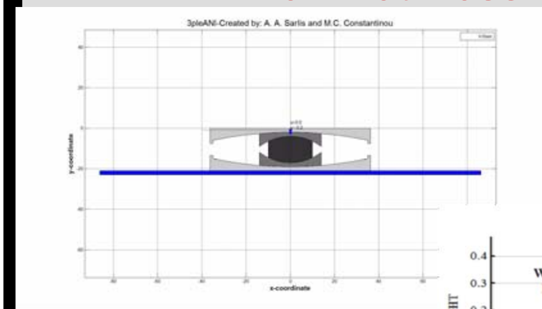
LOCATION FOR VERTICAL SHEAR PIN

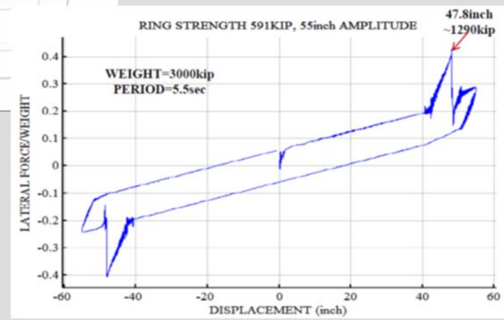
LOMA LINDA UNIVERSITY MEDICAL CENTER When Not Possible to Test



- SOME ISOLATORS HAD UPLIFT DISPLACEMENTS OF 210mm. THEY WERE PROVIDED WITH RESTRAINER RINGS CAPABLE TO ACCOMMODATE UPLIFT OF UP TO 275mm.
- ISOLATORS COULD NOT BE TESTED TO SUCH UPLIFT DISPLACEMENT. ISOLATORS WERE ANALYZED IN SPECIAL SOFTWARE 3pleANI.

LOMA LINDA UNIVERSITY MEDICAL CENTER
When Not Possible to Test





ISOLATORS COULD NOT BE TESTED TO FAILURE OF THE EXTERIOR RING AT DISPLACEMENTS EXCEEDING 1400mm. ISOLATORS WERE ANALYZED IN SPECIAL SOFTWARE 3pleANI.

SUMMARY

- **Seismic isolation and damping hardware require full scale dynamic testing to reveal their mechanical properties. Dynamic testing is essential in the prototype testing program.**
- **Production or quality control testing also requires that all hardware is tested, preferably under dynamic conditions.**
- **As displacement, velocity and force demands increase with seismic isolation applications in demanding environments, dynamic testing at full scale becomes increasingly difficult, time consuming and expensive, and occasionally impossible.**
- **Testing of reduced scale hardware is then the only option but rigorous principles of scaling and similarity are required. These require the development and verification of theories to predict the degrading behavior of the hardware.**
- **Occasionally advanced computational tools may provide supplemental information to testing.**
- **When dynamic full scale testing is not possible and reduced scale dynamic testing is conducted (based on principles of scaling and similarity) or quasi-static full scale testing is conducted, there should be penalties to reflect uncertainties in isolator mechanical properties and capacities.**
- **Testing specifications require revision on the basis of contemporary understanding and considerations of strong ground motion duration.**
- **Inspection, independent observation of testing and certification of authenticity of test results is becoming increasingly important.**