Modeling and Model Updating of a Full-Scale Experimental Base-Isolated Building

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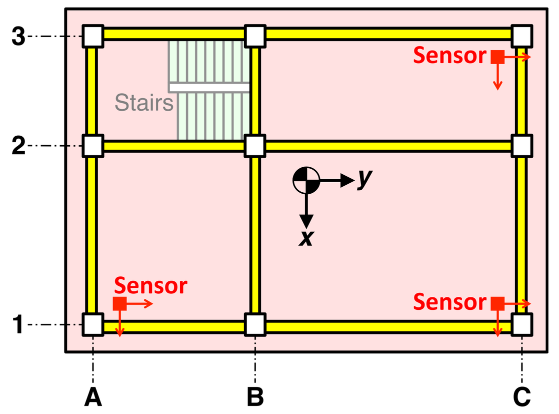
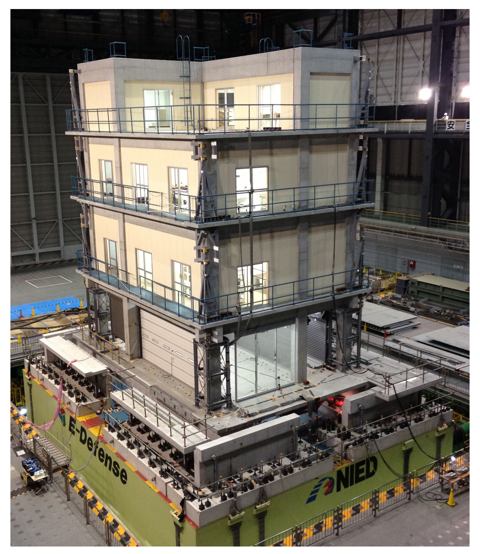
Motivation and Objectives

- Base-isolation and other seismic protective systems mitigate a building's response to seismic input while also ensuring the safety of the building's occupants and contents.
- Full-scale testing of buildings and structures that incorporate these systems is expensive but offers valuable insight into their dynamics and mechanical behavior.
- These systems often behave nonlinearly, creating a notable challenge for modeling and predicting the responses induced by other hazardous natural excitations outside of the testing regime, responses in retrofit design studies, or probabilistic response modeling.
- This study uses experimental response data, model identification, and optimization to update a finite element model to accurately simulate the dynamic response of the base-isolated building.

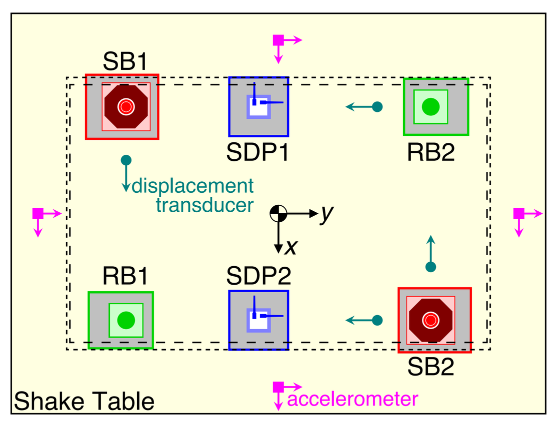
Experimental Set-Up

- A base-isolated test structure at Japan's E-Defense lab underwent initial testing in March 2013 [4] and subsequent testing in August 2013; this study focuses on the first day of testing (8 Aug. 2013)
- The structure was mounted on E-Defense's 6-DOF shake table, the world's largest.
- The structure consists of a four-story, asymmetric, moment frame with a setback and coupled transverse-torsional motion. The 690-ton superstructure is roughly 14 m × 10 m × 15 m.
- The building rested on a passive base-isolation layer composed (on 8 Aug. 2013) of:
  - two rubber bearings (denoted RB1 and RB2 below),
  - two elastic sliding bearings (SB1 and SB2), and
  - two passive U-shaped steel yielding damper pairs (each of which, SDP1 or SDP2, has one steel yielding element in the *x*-direction and the other in the *y*-direction).
- The building was subjected to random excitations along different table axes — *i.e.*, in the *x*-, *y*- and *z*-directions — and scaled versions of historical and synthetic earthquake ground motions.
- Tri-directional accelerometers were at three corners on each floor, and two corners on the roof (the top story is different), for a total of 14 locations and 42 superstructure accelerations.
- 4 tri-directional accelerometers were on the shake table, providing a total of 12 base acceleration channels.

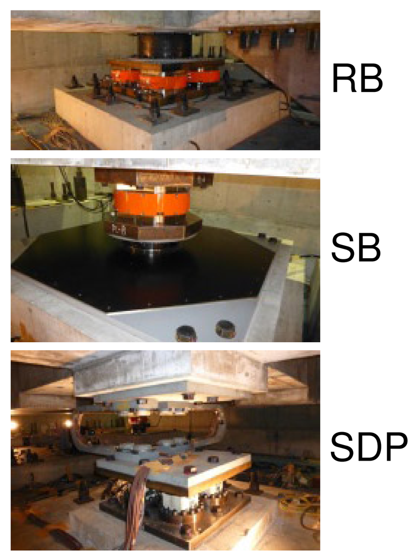




Specimen



Isolation-Layer Plan View



Isolation Devices

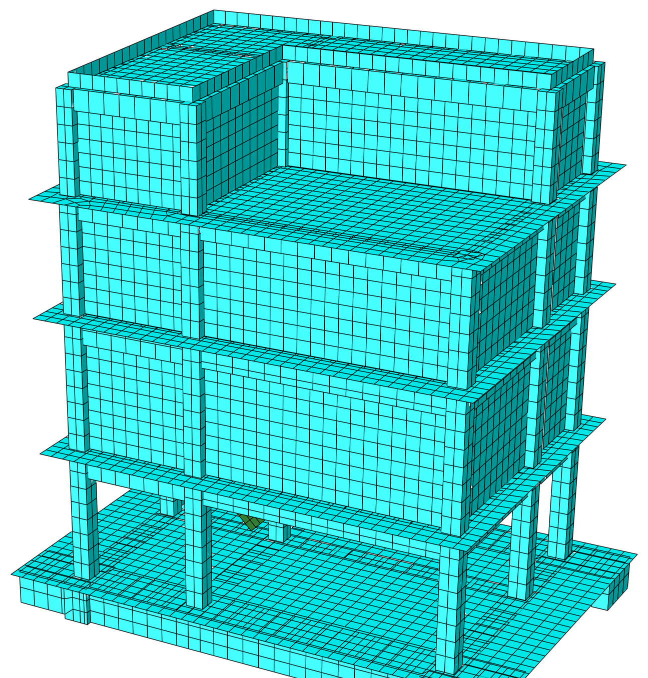
System Identification

- The building linear dynamic characteristics were identified [2] using the 12 table acceleration responses as inputs and the 42 building acceleration responses as outputs.
- The system was identified using Subspace State Space System Identification (N4SID) [3].
- Acceleration responses from Test 010 (random excitation commanded to table in all three directions) were detrended, 30-Hz low-pass filtered, and decimated to 100 Hz.

- Stabilization diagrams, over 10–90 states, indicated the true modes — *i.e.*, with **(1)** <1% frequency change, **(2)** <5% damping ratio change, and **(3)** mode shapes nearly identical as indicated by modal assurance criterion (MAC) values of at least 0.98. Note: $\mathrm{MAC}(\boldsymbol{\phi},\boldsymbol{\psi}) = \boldsymbol{\phi}^{\mathrm{T}}\boldsymbol{\psi}/\sqrt{\boldsymbol{\phi}^{\mathrm{T}}\boldsymbol{\phi}\boldsymbol{\psi}^{\mathrm{T}}\boldsymbol{\psi}}$.

	N4SID Identified	Original FEM		Updated FEM	
Mode #	Freq. [Hz]	Freq. [Hz]	(% Error)	Freq. [Hz]	(% Error)
1	0.685	0.684	(–0.146)	0.691	(0.876)
2	0.698	0.697	(–0.143)	0.692	(–0.856)
3	0.710	0.721	(1.549)	0.712	(0.282)
4	4.781	5.526	(15.583)	4.582	(–4.162)
5	5.175	6.892	(33.179)	5.223	(0.928)
6	7.293	8.706	(19.375)	7.478	(2.537)

Finite Element Model and Updating



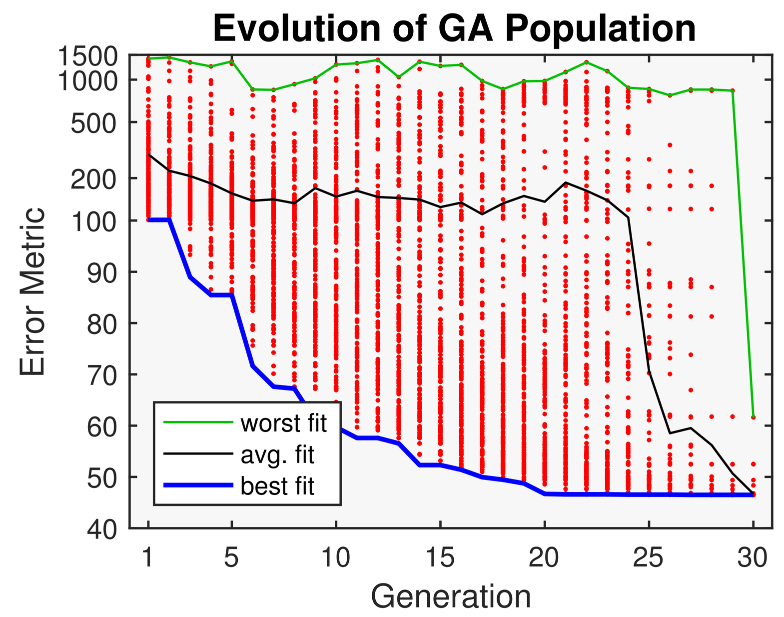
- A finite element model (FEM) was developed in ABAQUS® based on the structure design drawings.
  - The beams, columns, and shear walls were modeled by solid concrete elements and embedded reinforcing steel bars modeled by truss elements; initial material properties are taken from design code.
  - The floor slabs and the nonstructural walls (autoclaved lightweight concrete [ALC] plates) were modeled with shell elements; initial nominal Young's moduli were chosen as typical for these elements.
  - The isolation-layer devices were modeled with spring elements; initial values are from a linear force-displacement regression analysis [1].
- The mass matrix M, the nominal stiffness matrix K_0, and stiffness matrices K_i with unit changes to the i^{th} to-be-optimized parameter θ_i, $i = 1, \ldots, n_{\boldsymbol{\theta}}$, are exported from ABAQUS for further analysis in MATLAB, where modified stiffness $\mathrm{K} = \mathrm{K}_0 + \sum_{i=1}^{n_{\boldsymbol{\theta}}}[\mathrm{K}_i - \mathrm{K}_0](\theta_i - \theta_i^{\text{nominal}})$.
- The parameter vector $\boldsymbol{\theta}$ has $n_{\boldsymbol{\theta}} = 26$ elements, including:
  - the Young's moduli of: the *x*- and *y*-direction beams on floor 1, floors 2–3 and floor 4; the columns in floors 1–3 and floor 4; the nonstructural walls; the shear walls; the floor slabs; and the stairs
  - the *x*- and *y*-direction stiffnesses of: the rubber bearings, rubber sliders, and steel dampers pairs.
- Define an error metric of the differences between the identified frequencies f_i^{ID} and the corresponding FEM frequencies $f_i^{\text{FEM}}(\boldsymbol{\theta})$ and between the corresponding mode shapes $\boldsymbol{\phi}_i^{\text{ID}}$ and $\boldsymbol{\phi}_i^{\text{FEM}}(\boldsymbol{\theta})$:

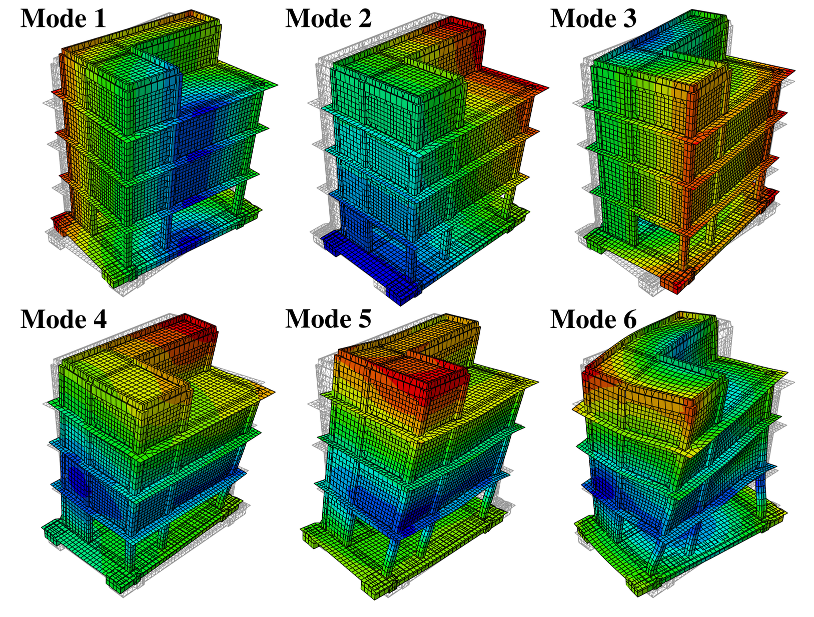
$$J(\boldsymbol{\theta}) = \sum_{i=1}^{6}\left[f_i^{\text{FEM}}(\boldsymbol{\theta}) - f_i^{\text{ID}}\right]^2 + \sum_{i=1}^{6}\left[1 - \mathrm{MAC}\left(\boldsymbol{\phi}_i^{\text{ID}}, \boldsymbol{\phi}_i^{\text{FEM}}(\boldsymbol{\theta})\right)\right]^2 \qquad (1)$$

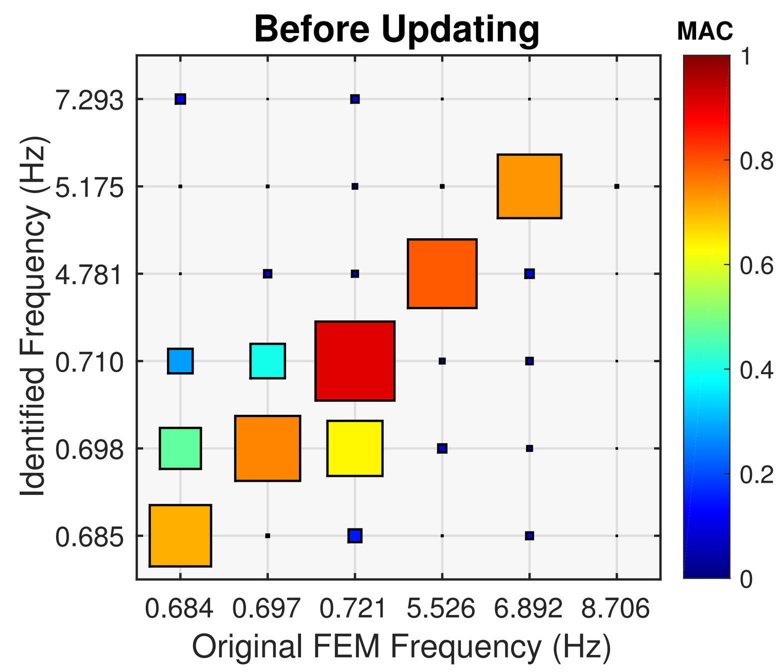
- A genetic algorithm optimization is used to find parameter values that minimize the error metric. (A Nelder-Mead Simplex method has also been studied, but tended to get stuck at local minima.) The GA uses a population of 200 for 30 generations, with defaults for other GA parameters in MATLAB's Global Optimization Toolbox (5% EliteCount, 80% crossover fraction, 1% mutation rate).
- The parameters are allowed to vary within bounds that are about ±10% from the nominal values to eliminate solutions that are clearly nonphysical.

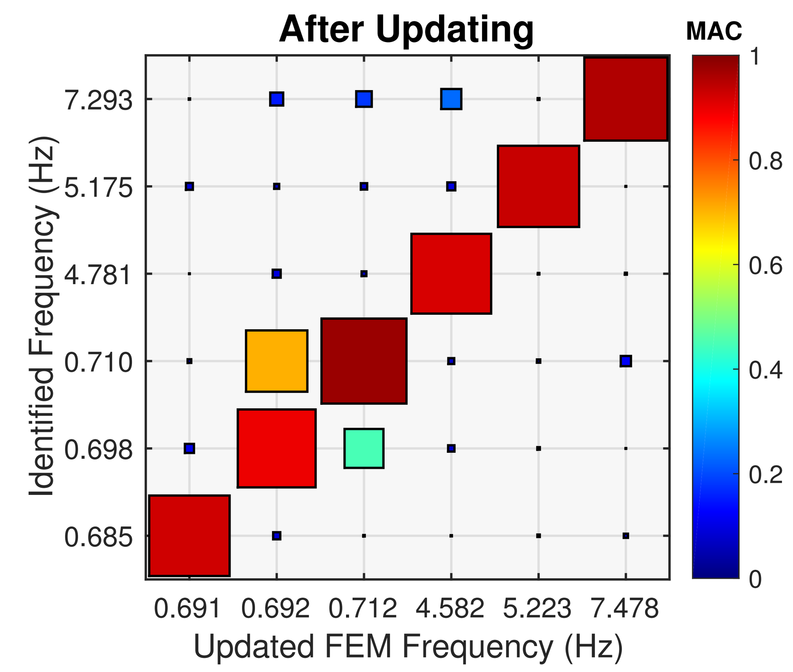
Results

- Among the 200 samples in the first generation, the error metric ranges from about 100 up to almost 1500; the minimum error decreases gradually and converges, such that most of the population has an error metric of about 46 in the 30th generation.
- The first six frequencies (and their percent errors) of the original and updated FEMs are shown in the table above; the maximum frequency error drops by nearly an order of magnitude. The improvement in the mode shape correlation is shown in the MAC graphic.









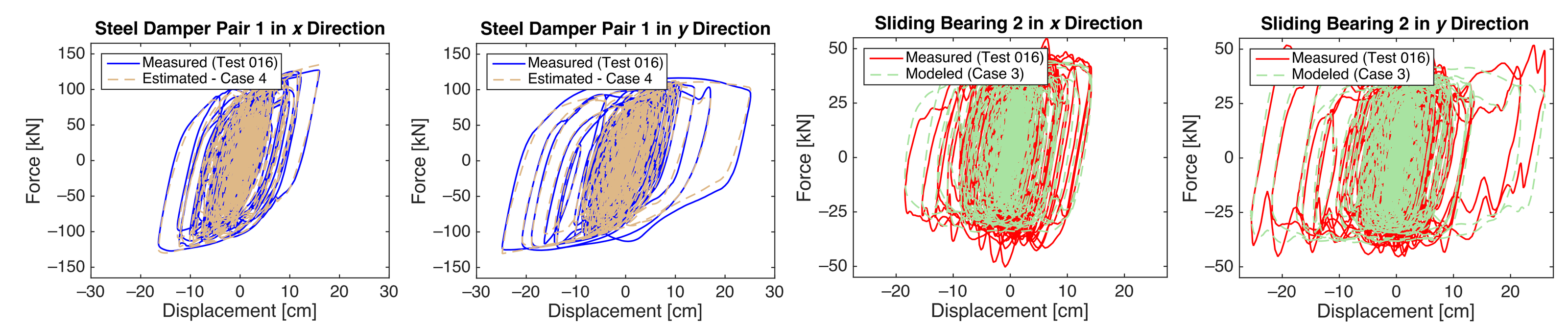
- Summary of parameters changed by the updating:
  - largest change in Young's Modulus: 11.6% (*x*-direction beams in floors 2–3);
  - largest change in the stiffness of rubber bearings: 4.7% (k_y^{RB2}: 1119 kN/m → 1193 kN/m);
  - largest change in the stiffness of rubber sliders: 15.2% (k_y^{SB1}: 1464 kN/m → 1727 kN/m);
  - largest change in the stiffness of steel dampers: 9.1% (k_x^{SDP1}: 3859 kN/m → 4045 kN/m).

Conclusions

- The FEM has been updated to much more closely match the natural frequencies and mode shapes identified from the experimental response data.
- The genetic algorithm does not get stuck at local minima like conventional hill-climbing optimizers.
- Including reinforcing bars, offset beams and the nonstructural walls resulted in reasonable parameter changes (preliminary updates to a simpler model without these features resulted in large non-physical changes in many parameters) with a significantly better match in identified modal characteristics.

Ongoing Research

- The updated MATLAB model is being merged with a set of bidirectionally-coupled Bouc-Wen models already developed [1] to simulate the nonlinear behavior of the isolation-layer devices.



- Controllable damping devices will be added to the isolation layer, and new control strategies will be developed to mitigate the response of this building.

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