Seismic retrofitting of buildings using energy dissipation devices

O. Lavan
Technion – Israel Institute of Technology
Aim of the talk

- Present ongoing research in which the presenter has been involved.
- Various types of energy dissipation devices will be discussed.
- Various structural systems (e.g. frames, walls etc.) are considered.
- How (and if) to use such devices in cultural heritage buildings? \( \Rightarrow \) discussion with the audience (future collaboration?).
Acknowledgement

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- Prof. G.F. Dargush.
- Dr. S. Dogruel.
- Prof. R. Levy.
- Prof. A.M. Reinhorn.
- Prof. A. Rutenberg.
Motivation and introduction

Various energy dissipation devices.

Various design approaches (as time allows).

Conclusions
Motivation

- Codes were aimed at preventing loss of human life while permitting a heavy damage to structures and property under strong earthquakes.
- Heavy damage was caused by the 1994 Northridge and the 1995 Kobe earthquakes.
- Performance-Based-Design.
- Retrofitting of existing structures:
  - Passive control devices

- Goal: develop optimal design methodologies
Energy dissipation devices

Figure 3.20 Force-Displacement Response of X-shaped Device (Bergman and Goel, 1987); Displacement Amplitude a) 0.42in, b) 1.04in, c) 1.56in

Figure 5.6 Typical Hysteresis Loop Results from a Sinusoidal Test

Figure 6.15 Oil/Fluid Dumper Force-Displacement Response (Constantinou and Symans, 1993b)
Energy dissipation devices
Tuned Mass Dampers - TMDs

Fig. 3.12. Amplitudes of the main mass of Fig. 3.6 for various values of absorber damping. The absorber is twenty times as small as the main machine and is tuned to the same frequency. All curves pass through the fixed points $P$ and $Q$.

Fig. 3.13. Resonance curves for the motion of the main mass fitted with the most favorably tuned vibration-absorber system of one-fourth of the size of the main machine.
Weakening

- Accelerations (forces) are reduced
- Inter-story drifts are increased
- Combination with viscous dampers

\[ f = ma \]
**Gap and objective**

- The design process has become increasingly complex.
  - What type of damper is good for what purpose (hazard, type of damage to be controlled, type of structural system)?
  - Once a type of damper is chosen, how can one come up with an efficient design?

  - Most design methodologies lead to “expensive” designs.
  - Optimal design methodologies require understanding of concepts and tools from optimization theory.

- **Develop practical optimal design methodologies.**
Requirements from the design methodology

- Assist in choosing the right type of device
- General for all types of devices and objectives
- Lead to an efficient (optimal?) performance-based solution
- Small computational effort
- Simple and transparent to practicing engineers: Make use of tools familiar to the engineering community
- Lead to understanding of the behavior of the optimal designs
- Unfortunately, there is no single method that can satisfy all requirements.
**Strategy – levels of optimization**

- Identify what retrofitting technique is advantageous for what purpose and what characteristics optimal designs have.
  - Experience.

  I
  ⇒ Multi-objective zero order optimization scheme (GA).

- Identify what characteristics optimal designs of specific problems have.
  - Gradient based approach
  ⇒ Multi-objective zero order optimization scheme (GA).

II
- Taylor simple design methods for specific problems considering insight from the results attained.
  ⇒ Simple iterative approach
Single objective gradient based approach


Problem Formulation

Minimize the total added damping

subject to:

Various inter-story performance indices at each story

Equations of motion

Size limitations

• Gradient Based Opt
**Characteristic results**

<table>
<thead>
<tr>
<th>Floor number</th>
<th>Optimum damping [kN<em>sec/m</em>10^4]</th>
<th>Maximal drifts [%]</th>
<th>Allowable</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>2</td>
<td>2</td>
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<tr>
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<tr>
<td>9</td>
<td>5.5</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Dampers are assigned only where the performance index is full.

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**O. Lavan**

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Jan. 19-20, 2014
Jerusalem, Israel

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**Single objective simple iterative approach**

**Viscous dampers**


**Hysteretic dampers**

Single objective simple iterative approach

Multiple Tuned Mass dampers


Lavan, O., Daniel, Y. (2013) "Full resources utilization seismic design of irregular structures using multiple tuned mass dampers." Structural and Multidisciplinary Optimization, 48(3), 517-532

Weakening and damping

1. Perform time-history analysis.

2. Design new damping using the recurrence formula.

\[ c_{d_i}^{(k+1)} = c_{d_i}^{(k)} \left( p_i^{(k)} \right)^{\frac{1}{q}} \]

3. Return to stage 1 if the results are not satisfying.

**dampers are assigned only where the performance index is full**
Convergence

Objective function [kN*sec/m] vs. Iteration number

Constraint error vs. Iteration number

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Convergence - hysteretic dampers

\[ \text{ratio} = \frac{\text{sum}(k_0)}{\text{sum}(k_0 \text{ final})} \]

\[ \text{drift}_{\text{max}} / \text{drift}_{\text{allowable}} \]
Convergence - MTMDs

After the third modification, the added mass of TMDs increased to 4.6%. Upon convergence, the properties of each TMD were:

<table>
<thead>
<tr>
<th>Frame</th>
<th>Floor</th>
<th>Mode to dampen</th>
<th>Final mass (ton)</th>
<th>Final stiffness (kN/m)</th>
<th>Final damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
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<td>2</td>
<td>78.08</td>
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</tr>
</tbody>
</table>

TIME domain

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Convergence \( W+D \)

![Graph showing normalized values for max drift, max acceleration, total damping, and total capping force over iteration number.](image)

- \( K_1 = 2368.7 \text{kN/m} \)
- \( F_y_1 = 22.23 \text{kN} \)
- \( K_2 = 2210.8 \text{kN/m} \)
- \( F_y_2 = 21.20 \text{kN} \)
- \( K_3 = 1895.0 \text{kN/m} \)
- \( F_y_3 = 18.24 \text{kN} \)
- \( K_4 = 1421.2 \text{kN/m} \)
- \( F_y_4 = 13.46 \text{kN} \)
- \( K_5 = 789.6 \text{kN/m} \)
- \( F_y_5 = 7.29 \text{kN} \)

\( m = 1.0 \text{ ton} \)
Multi-objective optimal seismic retrofitting of buildings


Optimization objectives

- Maximal normalized inter-story drift of all selected locations.
- Maximal normalized total acceleration of all selected locations.
- Cost
Multi-objective opt. – why?

Drifts

Acc.

Cost
Multi-objective opt. – why?

- Traditional optimization

- A small compromise on the performance may lead to a much cheaper solution.
Pareto front

- A design is Pareto optimal if there exists no feasible design which would decrease some objective without causing a simultaneous increase in at least one other objective.

- Decision is made when the whole picture is at hand (choose best compromise).

- Large computational effort
Example

- With the right design all types of dampers can reduce both objectives.
- Viscous dampers are more efficient in reducing both objectives simultaneously.
- There is a wide region where a large reduction of drifts is accompanied with only a small increase in accelerations.
The weakening and damping approach is more efficient in reducing both objectives simultaneously.

Example

Figure 17
**EDDs in wall structures**


- A single parameter controls the response of VCSW.
- It does not depend on the height of the structure. Hence, this system is also efficient for low rise buildings.
- Based on the example, such a reduction is feasible using "off-the-shelf" dampers.
Open questions

- The research done by the author so far focuses on “modern” buildings.
- How to use such devices in cultural heritage buildings?
- Some research on that has been done by others.
- (Maybe) There is more room for research on that topic.

Thank you!