Experimental Testing and Analytical Modelling of Damage-Avoidance Steel Connections using HF2V Damping Devices

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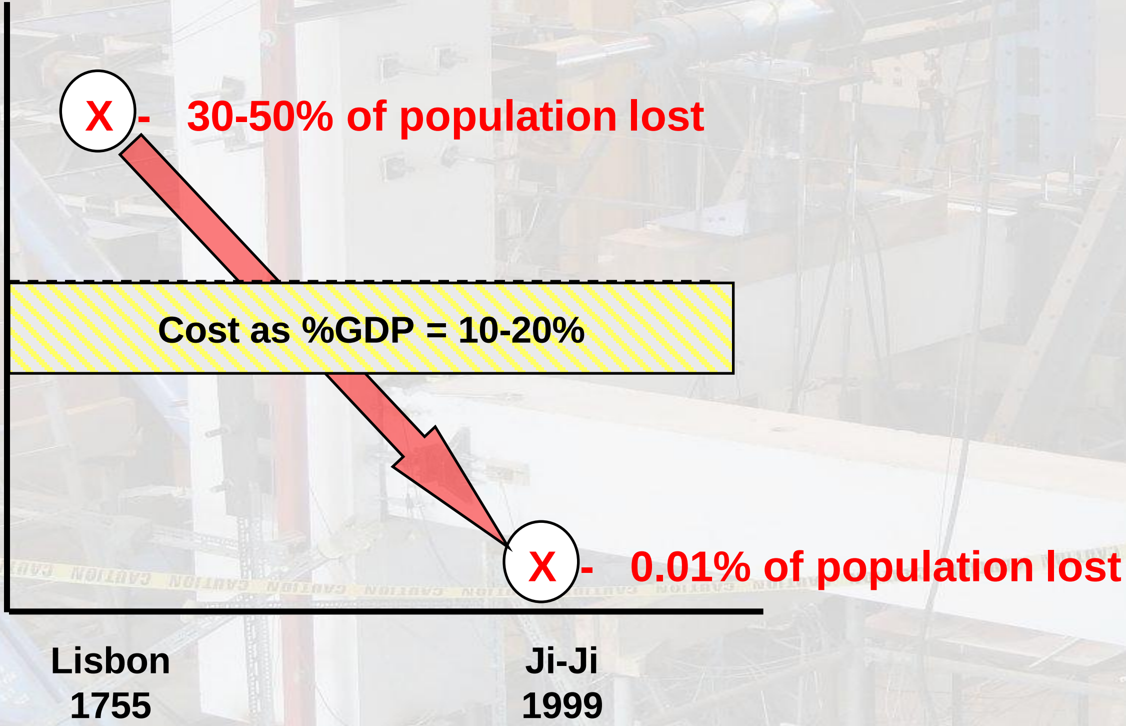
Earthquake Resistance



- For relatively large design events
- Lives lost has gone down to nearly zero in developed countries
- Cost and economic damage has remained largely constant

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Problem

- **Structural design provides energy dissipation through structural damage and the formation of plastic hinges**
- **This approach protects life-safety**
- **Recent research has looked at damage-free rocking connections**
- **By removing the damage mechanism, we also remove the ability to efficiently dissipate energy**
- **Therefore, we need to provide an alternative means of dissipating energy.**
- **Ideally this method will be damage-free, not prone to fatigue, stiffness or strength degradation, and require no maintenance following large response cycles**

Main Goals

- **High force capacity** = High dissipation
  - Only 3-10 large response cycles per big earthquake

- **Small device volume**
  - Tight constraints for typical structural connections - Universal column sections nominally 350mm deep – W14 in American Codes

- **Maximum energy dissipation per cycle**
  - “Square” hysteresis loop = maximum energy removed

- **Goal**: Dissipate energy in the device every cycle rather than by damage to structural connections

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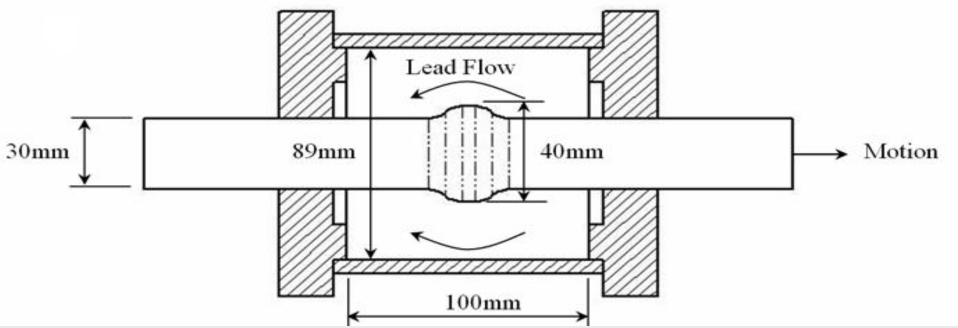
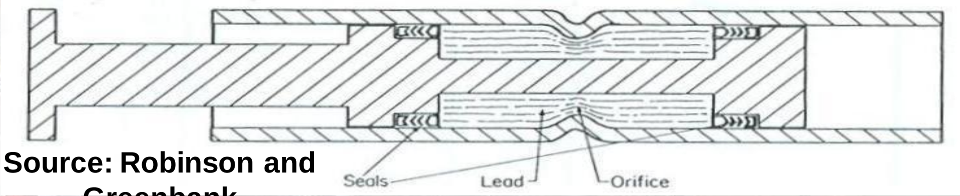
Device Mechanics

Plastic extrusion of working material through an annular restriction

Bulged-shaft type extrusion damper



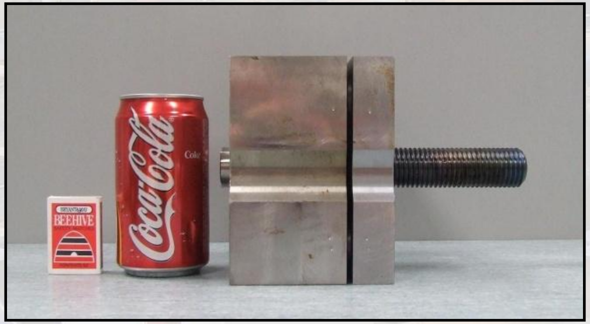
Constricted-tube type extrusion damper

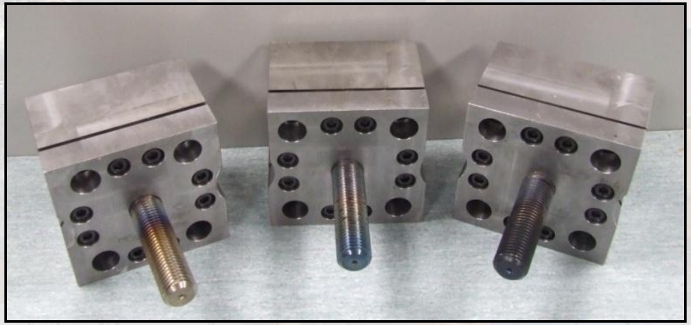


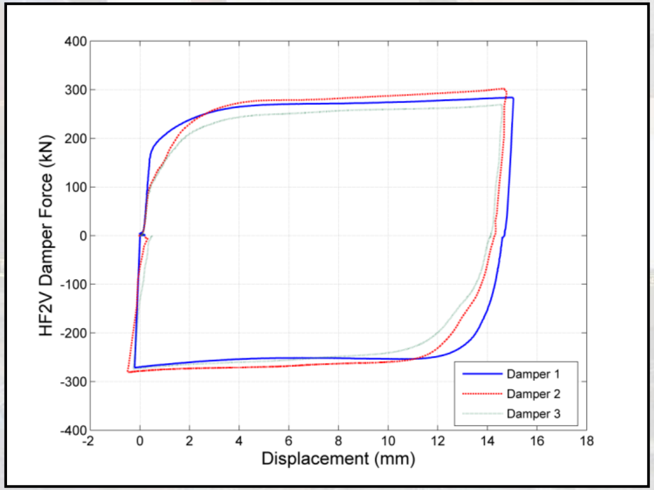
Source: Robinson and Greenbank

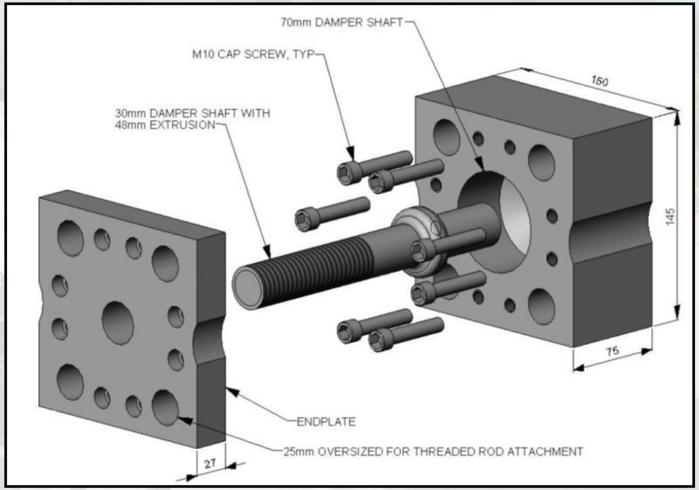
Bulged-shaft design chosen for low manufacturing cost and repeatable results

Constructed Devices

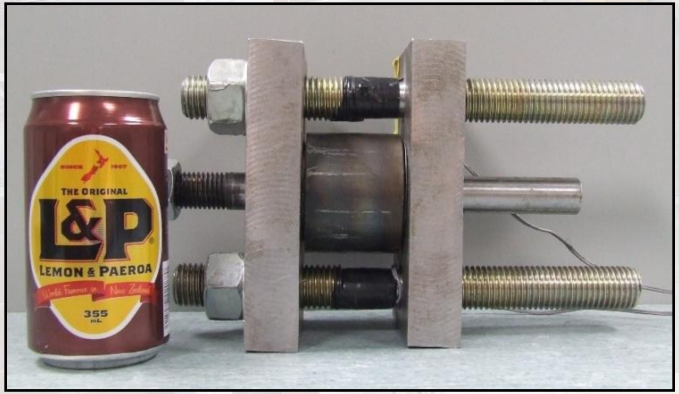


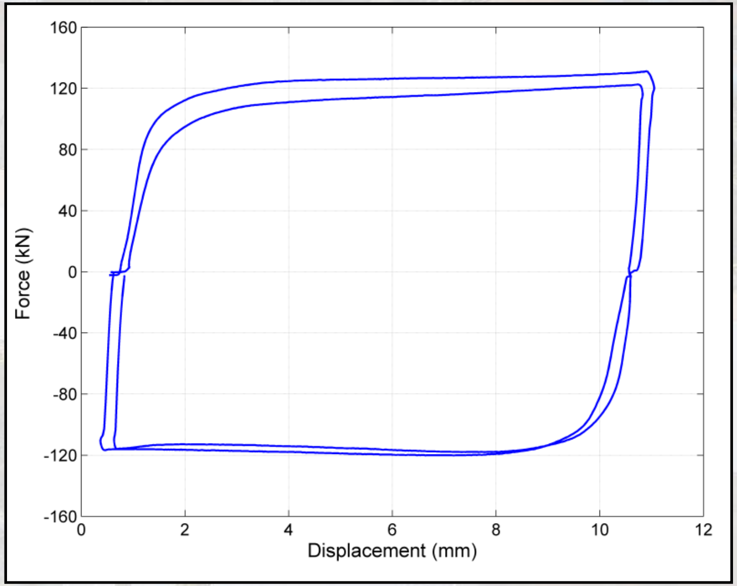






Constructed Devices





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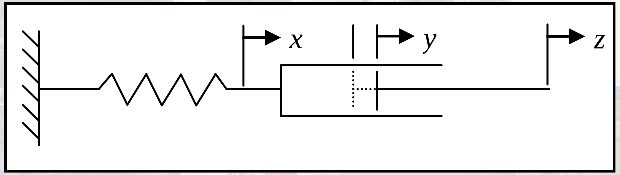
Damper Mechanics

- **Several near full-scale experiments have shown promising results.**
- **Flexibility of the connecting elements has been identified as a key design issue affecting performance <u>and</u> its predictability from models.**
  - **Although careful design can minimise these effects, it will always be present, and have a measurable impact on the results.**

- **So how to model these effects?**



$$x + y = z$$

$$\dot{x} + \dot{y} = \dot{z}$$

$$F_D = Kx = \frac{x}{f_D} = C_\alpha \left|\dot{y}\right|^\alpha \operatorname{sgn}(\dot{y})$$

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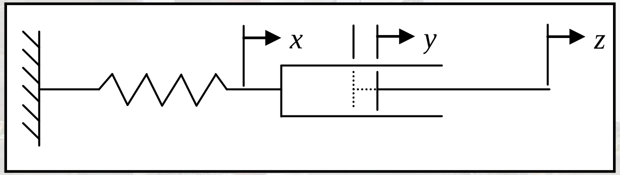
Damper Mechanics

- **Solution to a system of coupled, unstable DEs:**
  - **Apply finite difference approximations and use a predictor-corrector formulation**
  - **For small time-steps, the system can be solved without iteration**
  - **Inner iteration can be used for larger time steps or greater accuracy**

- **Alternatively, root-finding techniques can be used to find the exact solution**
  - **Computation is similar, but less well accepted in the field.**
  - **Does require greater computing ‘nous’**



Predictor: $$F_{i+1} = F_i + \frac{\Delta t}{f_D}\left(2\dot{x}_i - \dot{x}_{i-1}\right)$$

Corrector: $$F_{i+1} = C_\alpha \left|\dot{y}_{i+1}\right|^\alpha \operatorname{sgn}\left(\dot{y}_{i+1}\right)$$

$$\dot{y}_{i+1} = \frac{z_{i+1} - z_i + f_D F_i}{\Delta t + f_D C_\alpha{}^{(1/\alpha)} \left|F_{i+1}\right|^{1-1/\alpha}}$$

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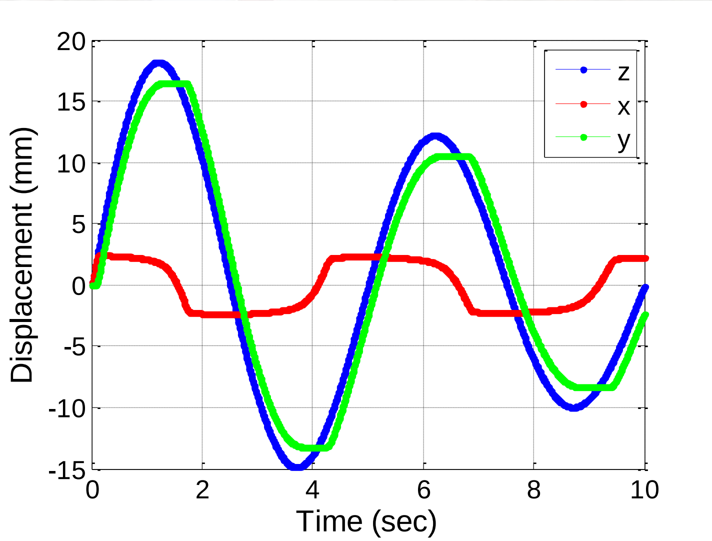
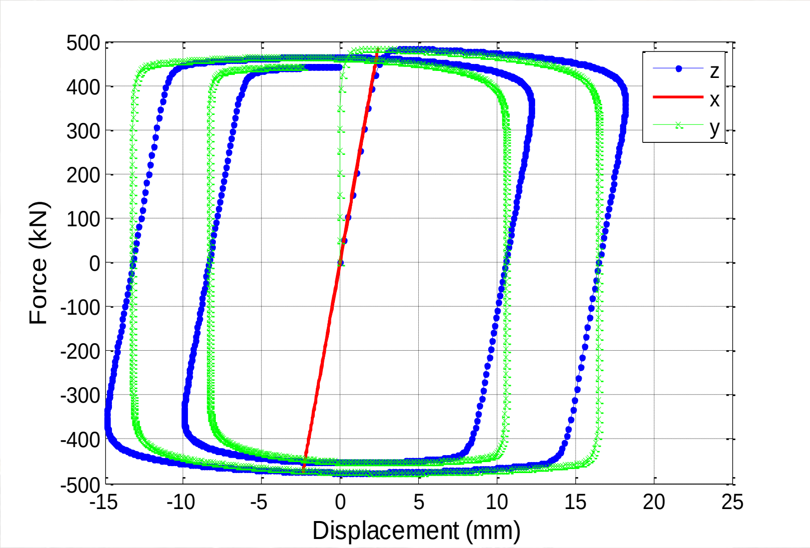
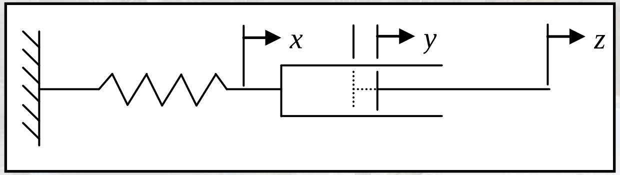
Damper Model Results

- Observed phase lag between input displacement and damper response due to spring flexibility → **Results for α = 0.12**

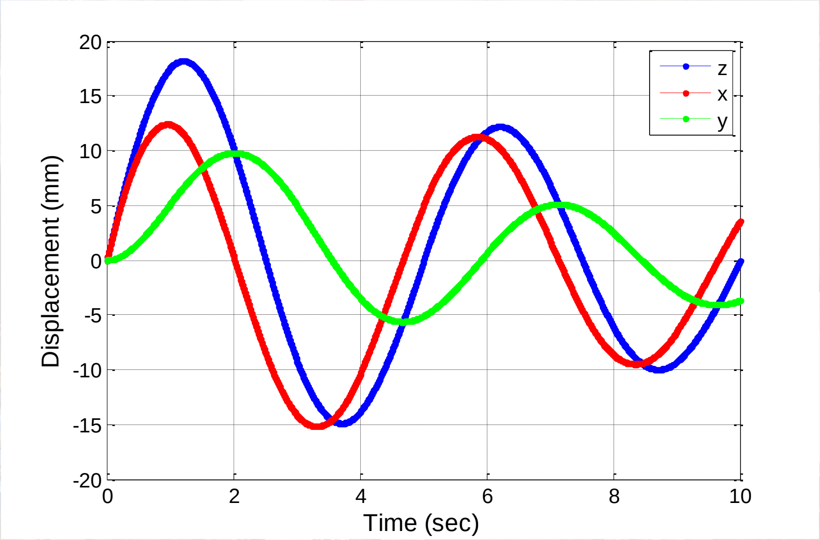


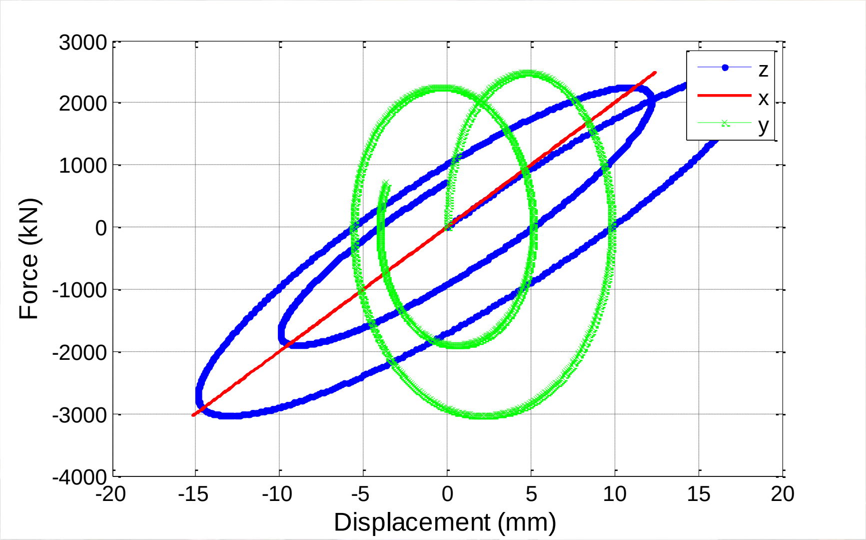


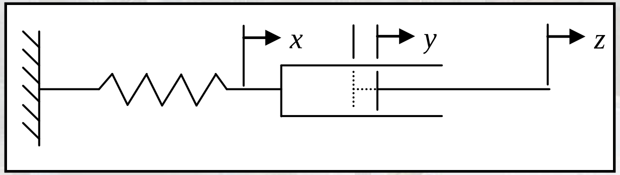


Damper Model Results

- Results for $\alpha = 1.0$ – standard viscous damper







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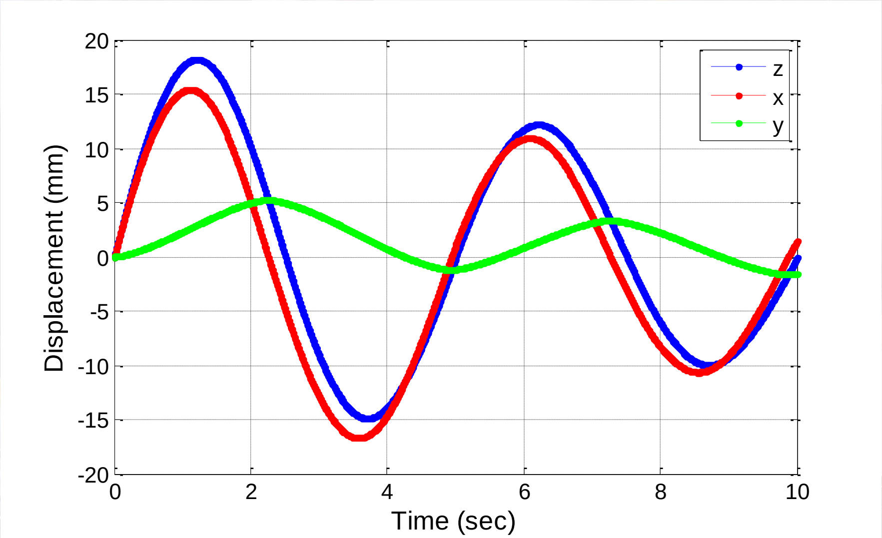
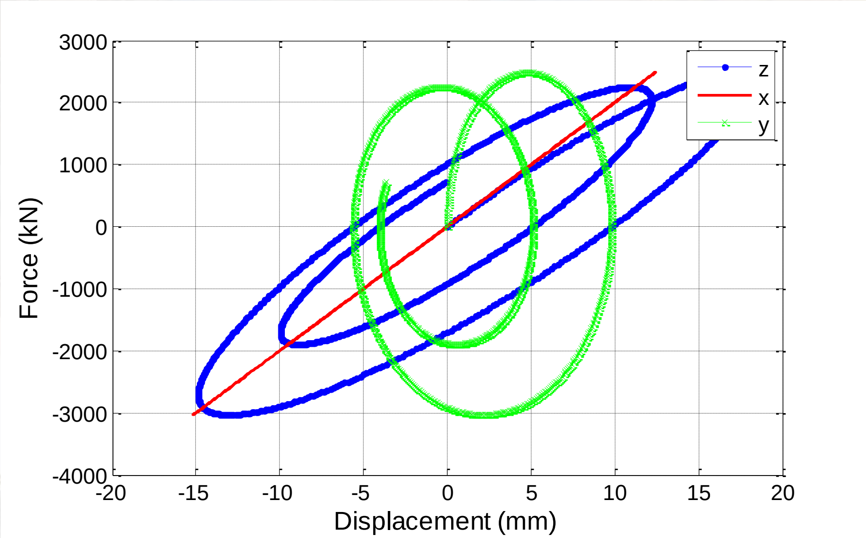
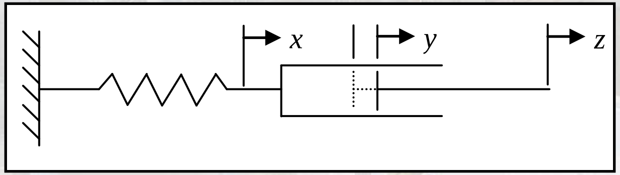
Damper Model Results

- **Results for α = 2.0 – air damper**







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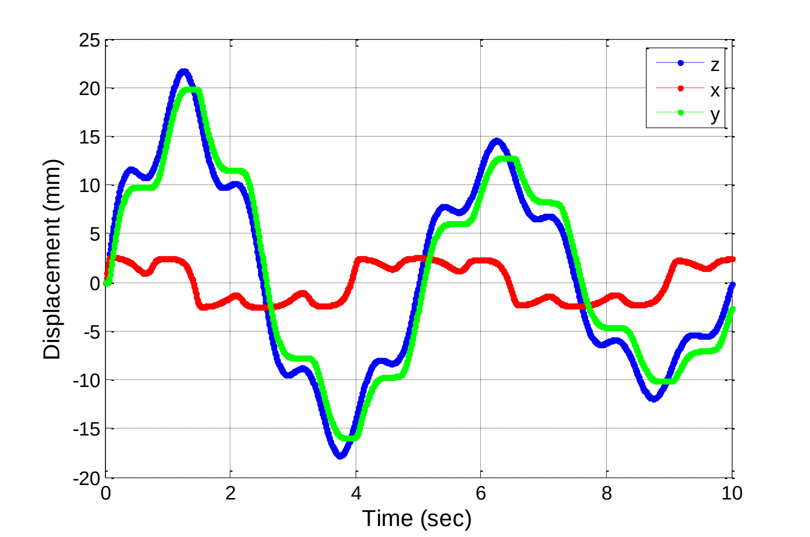
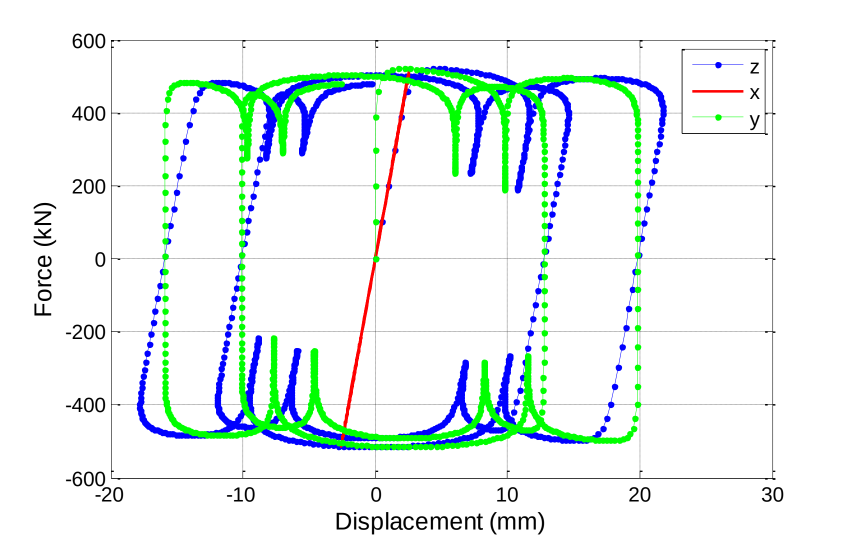
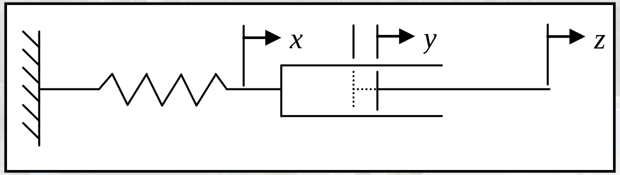
Damper Model Results

- **The results of small reversals in the input displacement – a test of model of model robustness, $\alpha = 0.12$**

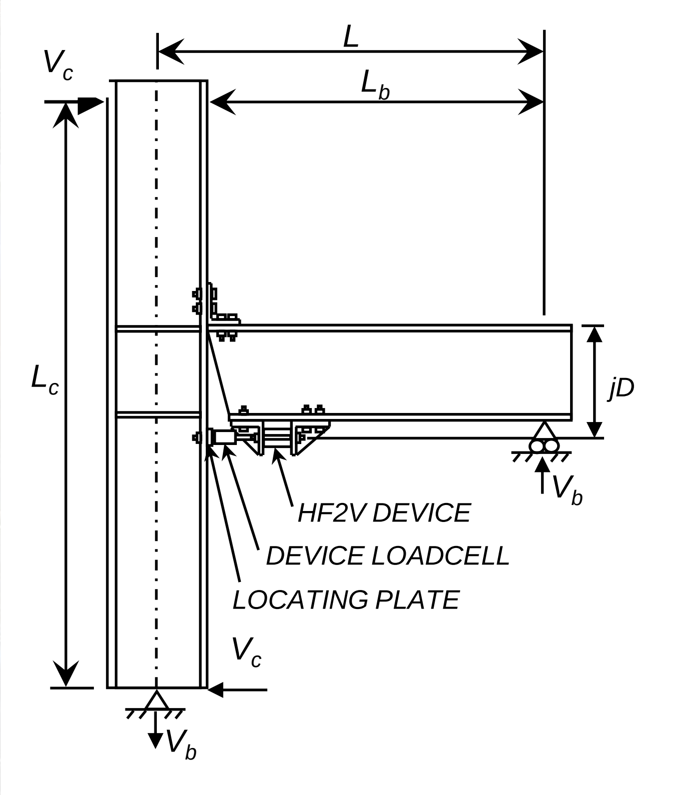






Structural Implementation

- Steel joint implementation



Structural Implementation

- **Steel joint deflection: combination of:**
  - **Rigid body displacements during damper motion (analogous to *y*).**
  - **Elastic member and damper connection bracket/rod/etc deflections (analogous to *x*).**
  - **Can all be calculated from rational mechanics and damper/device model.**

Predictor: $$V_{c,i+1} = V_{c,i} + \frac{\Delta t}{f_\theta}\left(2\dot{\theta}_{S,i} - \dot{\theta}_{S,i-1}\right)$$

Corrector: $$V_{c,i+1} = C_\theta \left|\dot{\theta}_{y,i+1}\right|^\alpha \operatorname{sgn}\left(\dot{\theta}_{y,i+1}\right)$$

where: $$C_\theta = \frac{jDL}{L_b L_C} C_\alpha \left(jD\right)^\alpha$$

$$\dot{\theta}_{y,i} = \frac{\theta_{z,i+1} - \theta_{z,i} + \theta_{S,i}}{\Delta t + f_\theta C_\theta^{1/\alpha} \left|V_{C,i}\right|^{1-1/\alpha}}$$

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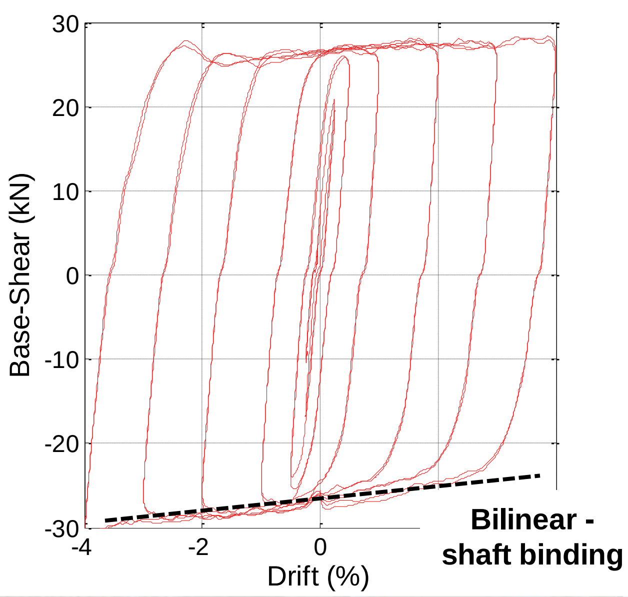
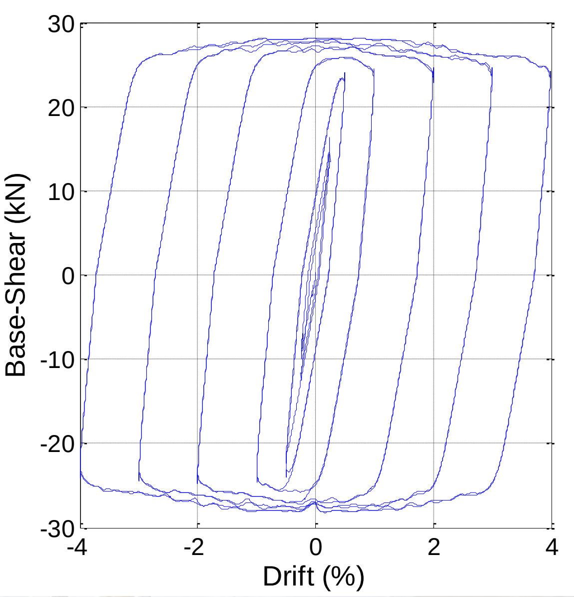
Structural Implementation Results

- Model and Experimental results show good agreement
- Overall response is a function of the damper mechanics, and flexibility of the damper connecting elements and members deflections.

Experiment



Model



Conclusions

- **Flexibility of the damper connecting elements has been identified as a key design issue which will impact on the results.**

- **A simple damper model is developed to include these flexibility effects, and is general so that it can be used for any non-linear viscous damper**

- **The steel DAD connection using any such damper can be modelled by a rotational form of the damper model which incorporates geometric transformations and the flexibilities of the structural members**

- **Overall good agreement is seen between the experimental and model results for both the damper model and connection model**

Conclusions

- Overall damage-avoidance and damper design
  - Initial development of prototype devices
  - Spectral investigation into likely reductions and relation to design guidlines
  - Structural Implementation – concrete and steel connection
  - Model development – both for the dampers, the steel experiment, and the concrete connections

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