Force, Switched and Mixed Hybrid Simulation Control in OpenFresco

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Hybrid Simulation

- A dynamic testing method:
  - Complements the shaking table and quasi-static testing methods
- Specimen is a hybrid model of the prototype:
  - Integrates numerical and physical sub-models
- Developed since mid-1970's
  - Almost in parallel with shaking tables!

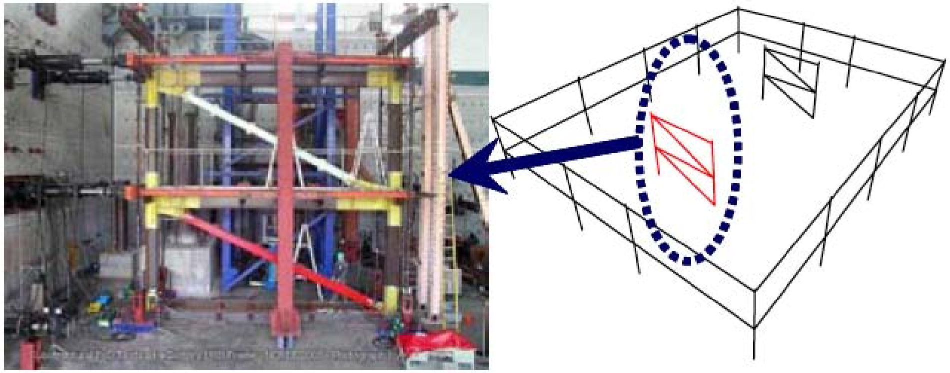
Dynamic Test Methods

Shaking Table

- E-Defense

Hybrid Simulation

- NCREE PISA system



Control in Hybrid Simulation

- Defines how the physical and the numerical sub-structures are integrated:
  - Displacement: enforcing compatibility
  - Forces: enforcing equilibrium
- Defines how the servo-hydraulic system is driven:
  - Displacement/position feedback
  - Force feedback

Displacement Control

- Conventional hybrid simulation is conducted in displacement control
- Advantages:
  - Servo-hydraulic system feedback
  - Numerical model implementation

Displacement Control

- Challenges:
  - Stiff specimens
  - Significant stiffness variations:
    - With direction of loading
    - Degradation due to damage
  - Fast tests:
    - Dynamic effect in the physical sub-model
  - Multiple DOFs

Force Control

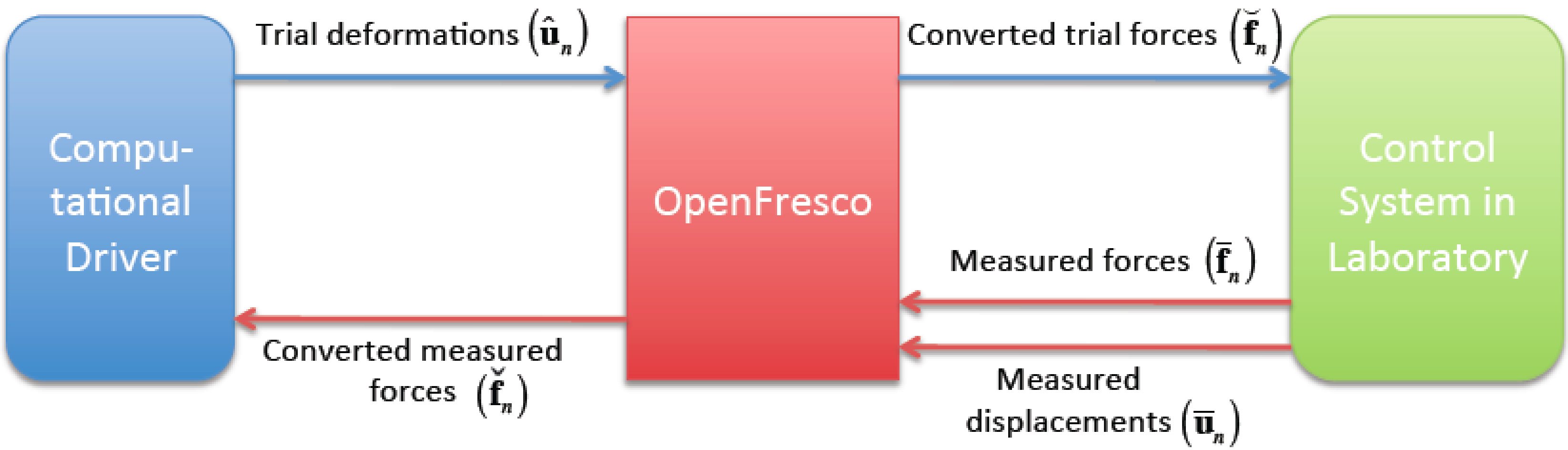
- Control system imposes force on the physical sub-model
- Challenges:
  - Acquiring the force targets:
    - Most numerical models are implemented in “displacement” control
  - Closing the feedback loop:
    - Stiffness of the specimen and loading system impacts the control loop gain
    - Low gain needed for stability: poor tracking
    - Friction and stick/slip behavior affect performance
    - Oscillations in feedback signal from load cells

Force Control: Implementation

- Compatibility (of displ.) methods:
  - Tangent-based:
    - Broyden, BFGS, Intrinsic, Transpose
  - Krylov sub-space
  - Compatible with numerical model implementation methods
- Equilibrium (of forces) methods:
  - Derived from flexibility FEM formulation
  - Require compatible numerical models

Force Control: OpenFresco

- Compatibility methods



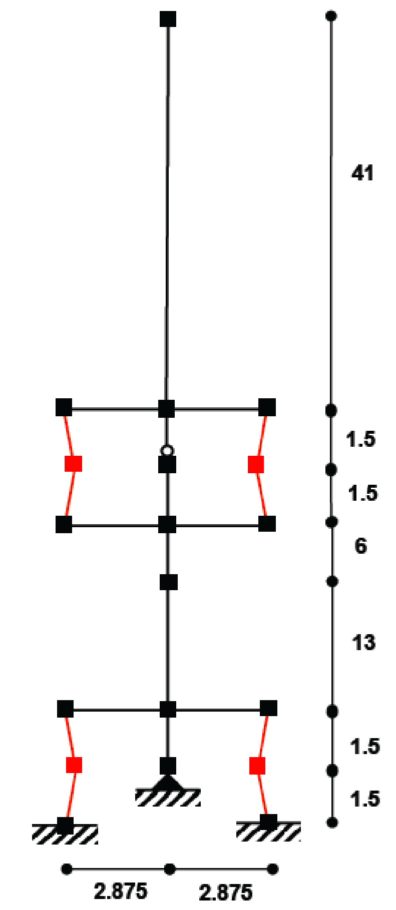
- Conversions implemented in the *ExperimentalSignalFilter* class

Force Control: OpenFresco

- Equilibrium methods
- Implemented in:
  - Flexibility (force) based FEA package in Matlab (based on OpenSees structure)
  - OpenFresco force-based predictor and corrector in Simulink/Stateflow
  - OpenFresco force experimental control sub-class

Force Control:
Validation and Verification

- 2-DOF specimen



$$T_1 = 0.55\text{sec}$$

$$T_2 = 0.20\text{sec}$$

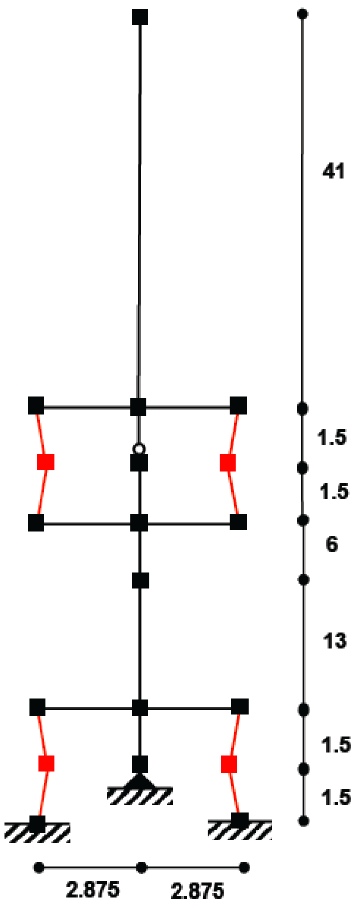
$$m = \begin{bmatrix} 0.01 & 0 \\ 0 & 0.1 \end{bmatrix}$$

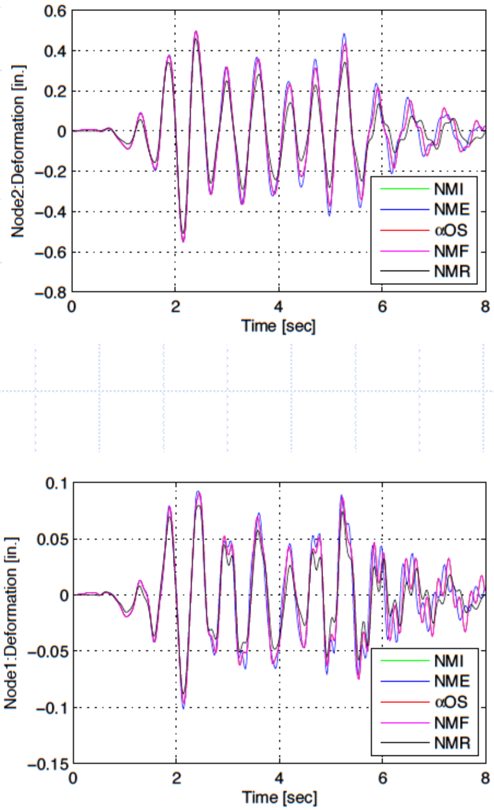
Soft

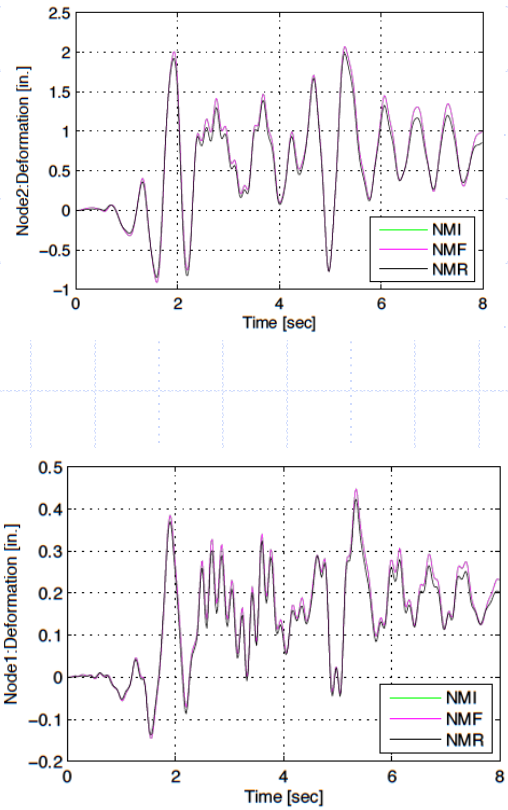
$$k = \begin{bmatrix} 3.4 & -12 \\ -12 & 84 \end{bmatrix}$$

Stiff

Force Control: Validation and Verification







Linear response

Non-linear response

Force Control: Validation and Verification

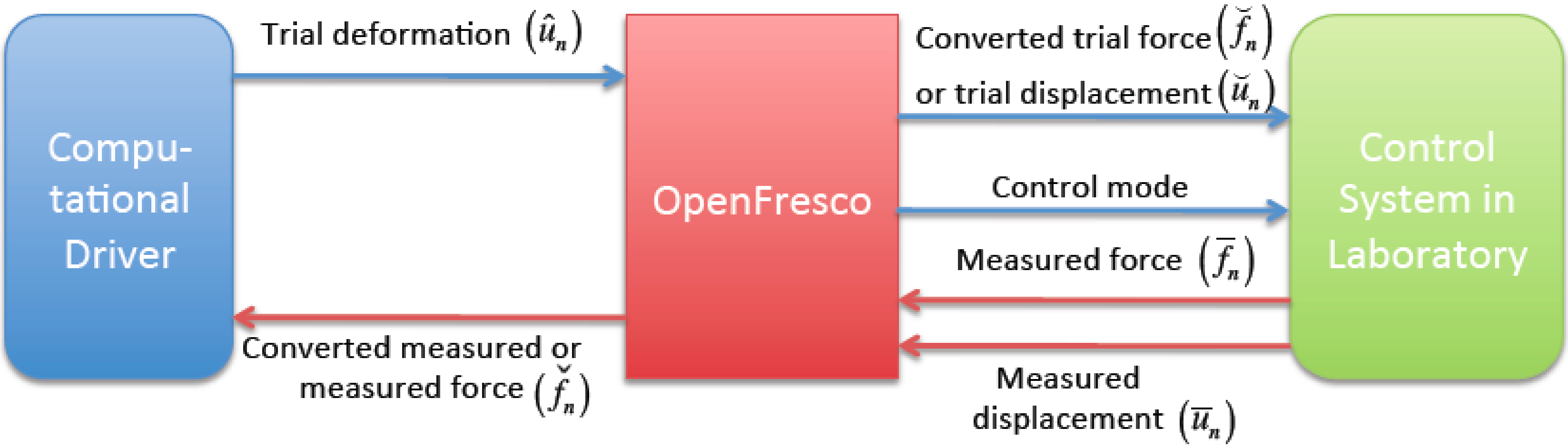
- Node 1 displacement errors

Control method	NME (in.)	αOS (in.)	NMF (in.)	NMR (in.)
DC-Min	2.97×10^{-7}	1.32×10^{-8}	3.90×10^{-6}	2.45×10^{-5}
DC-Mean	0.163	0.147	0.0307	0.379
DC-Max	0.419	0.337	0.153	0.664
CFC:BFGS-Min	3.75×10^{-8}	1.15e-08	4.19×10^{-5}	1.81×10^{-5}
CFC:BFGS-Mean	0.0594	0.0319	0.0519	0.110
CFC:BFGS-Max	0.251	0.166	0.182	0.241
CFC:Intrinsic-Min	N/A	2.92e-08	N/A	8.23×10^{-6}
CFC:Intrinsic-Mean	N/A	0.0527	N/A	0.0750
CFC:Intrinsic-Max	N/A	0.229	N/A	0.191

Switch Control

- Control mode of an actuator changes during hybrid simulation
  - Different specimen stiffness, depending on loading direction
- Challenges:
  - Switch trigger algorithm:
    - Trial force (Point Switching Strategy)
    - Secant stiffness (Secant Switching Strategy)
  - Stable and fast switch
  - Accurate force and displacement control

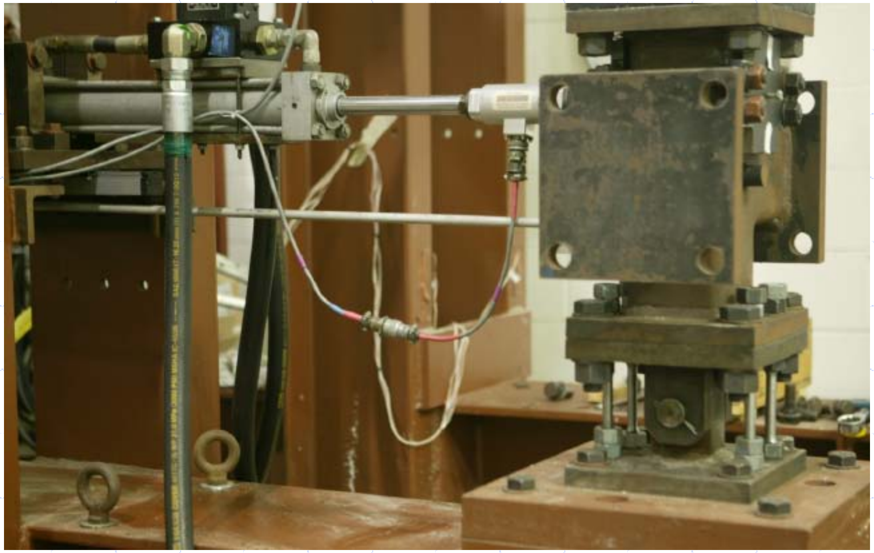
Switch Control: Implementation

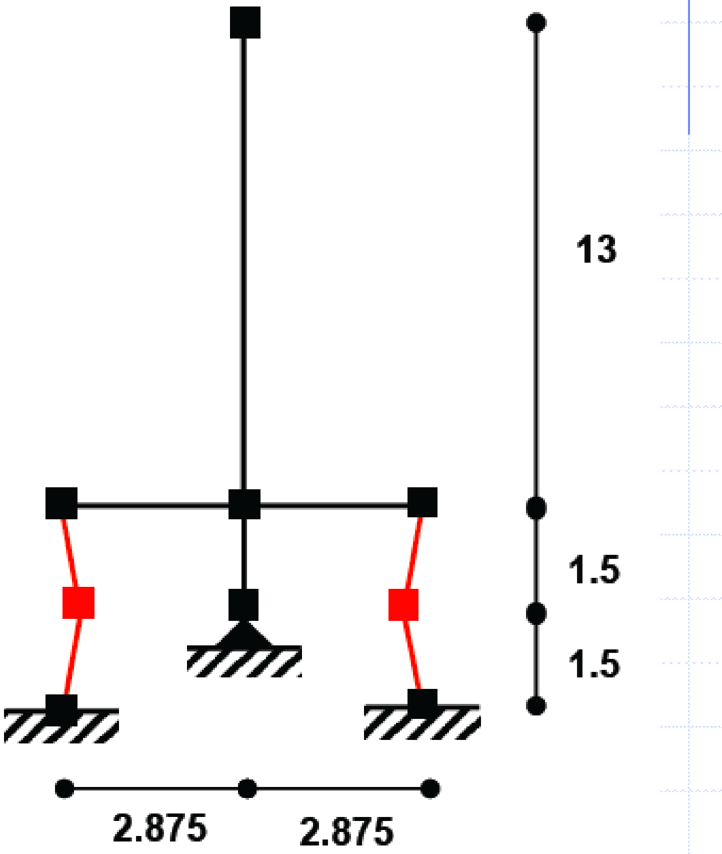


- Compatibility methods:
  - Extended
- Equilibrium methods:
  - Extended

Switch Control: Validation and Verification

- 1-DOF specimen





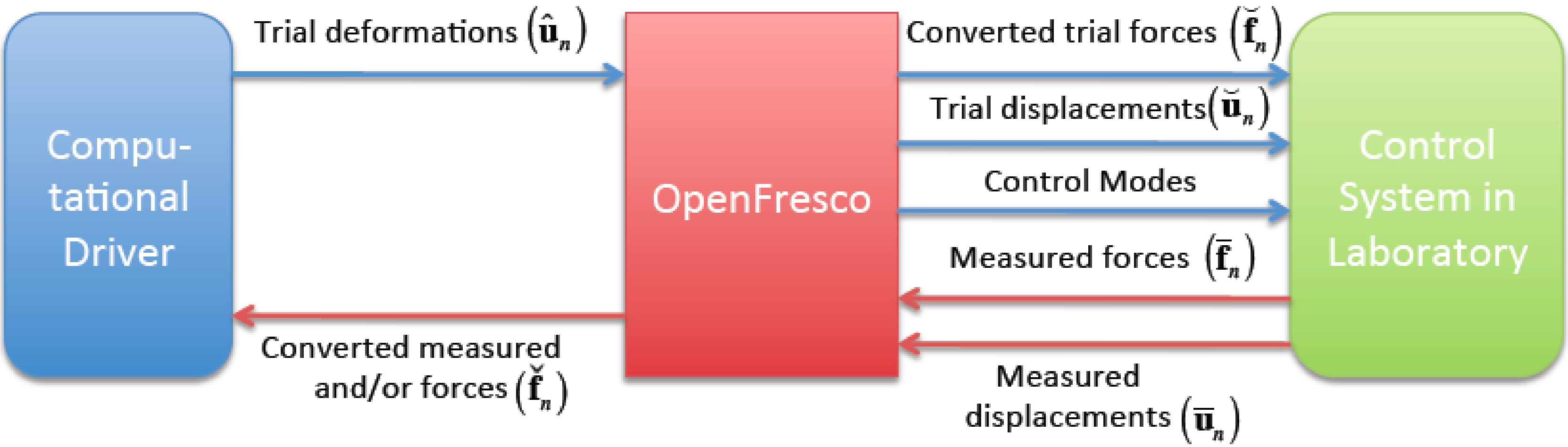
Switch Control: Validation and Verification

Control method	NME (in.)	αOS (in.)	NMF (in.)	NMR (in.)
DC-Min	2.84×10^{-5}	7.30×10^{-7}	1.64×10^{-5}	1.68×10^{-5}
DC-Mean	0.0266	0.0288	0.114	0.0711
DC-Max	0.116	0.118	0.357	0.253
CFC-Min	N/A	N/A	1.14×10^{-5}	N/A
CFC-Mean	N/A	N/A	0.0409	N/A
CFC-Max	N/A	N/A	0.143	N/A
PSC-Min	2.12×10^{-5}	6.34×10^{-6}	2.11×10^{-5}	2.49×10^{-5}
PSC-Mean	0.0410	0.0816	0.0433	0.0422
PSC-Max	0.104	0.300	0.204	0.147
SSC-Min	8.00×10^{-6}	1.40×10^{-5}	6.67×10^{-5}	6.94×10^{-6}
SSC-Mean	0.0341	0.0315	0.0397	0.0419
SSC-Max	0.112	0.122	0.177	0.150
EFC-Min	N/A	N/A	N/A	1.28×10^{-4}
EFC-Mean	N/A	N/A	N/A	0.0922
EFC-Max	N/A	N/A	N/A	0.280
EPSC-Min	N/A	N/A	N/A	6.02×10^{-5}
EPSC-Mean	N/A	N/A	N/A	0.0339
EPSC-Max	N/A	N/A	N/A	0.161
ESSC-Min	N/A	N/A	N/A	9.82×10^{-6}
ESSC-Mean	N/A	N/A	N/A	0.0322
ESSC-Max	N/A	N/A	N/A	0.0989

Mixed Control

- Control modes on different degrees of freedom of the physical sub-model are different:
  - Each may be constant or switched
- Challenges:
  - All of the above, and...
  - Interaction of independent switching strategies
  - Time-step integration using measured or computed values?

Mixed Control: Implementation

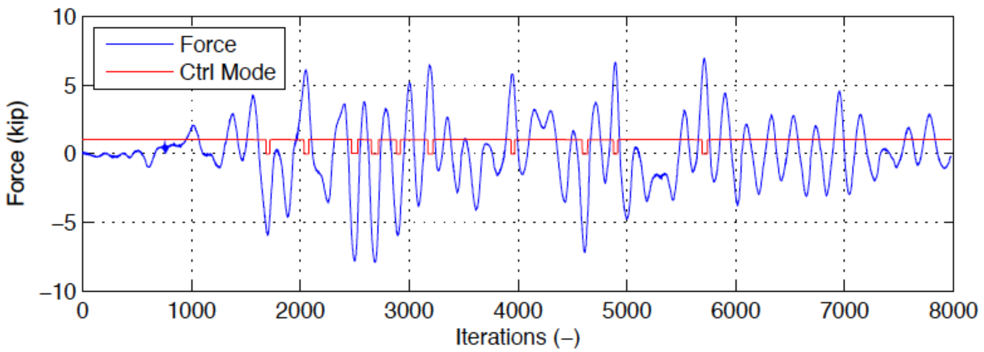


- Compatibility methods:
  - Extended further
- Equilibrium methods:
  - Extended further

Mixed Control: Validation and Verification

- Node 1 displacement errors

Control method	NME	αOS	NMF	NMR
PMC:Broyden-Min (in.)	1.41×10^{-8}	1.25×10^{-9}	8.67×10^{-11}	N/A
PMC:Broyden-Mean (in.)	7.38×10^{-4}	9.33×10^{-4}	6.20×10^{-4}	N/A
PMC:Broyden-Max (in.)	0.00587	0.0475	0.00570	N/A
PMC:BFGS-Min (in.)	1.68×10^{-9}	4.84×10^{-9}	1.06×10^{-8}	1.98×10^{-11}
PMC:BFGS-Mean (in.)	5.53×10^{-4}	5.67×10^{-4}	5.40×10^{-4}	5.57×10^{-4}
PMC:BFGS-Max (in.)	0.00642	0.00497	0.00528	0.00684
PMC:Intrinsic-Min (in.)	9.74×10^{-9}	5.14×10^{-9}	2.72×10^{-9}	3.32×10^{-9}
PMC:Intrinsic-Mean (in.)	7.47×10^{-4}	6.12×10^{-4}	0.00144	8.13×10^{-4}
PMC:Intrinsic-Max (in.)	0.00579	0.00469	0.00565	0.00564



Conclusions

- Force control implemented in OpenFresco:
  - Comparable to displacement control
  - Compatibility methods easier to implement
- Switch control implemented, too:
  - Stability and accuracy sensitive to integration method choice
- Mixed control implemented, but:
  - Difficulties with actuator interaction
- More work is needed...

Conclusions

- This extension:
  - Covers the duality between forces and displacements in structural mechanics
  - Enables hybrid simulation of complex models under combined long- and short-term load effects
- Hybrid simulation advantage:
  - Enables proof-testing of structural systems by physically testing only their crucial components, not entire systems

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