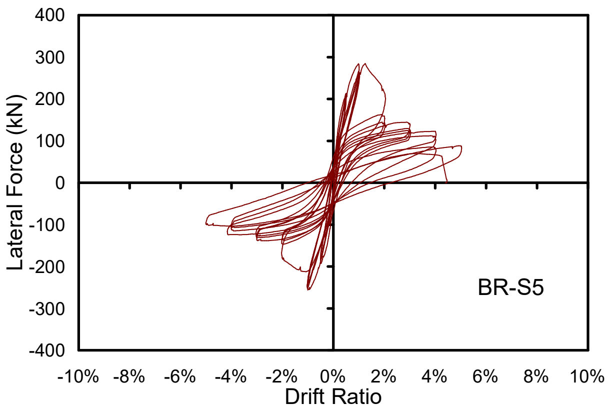
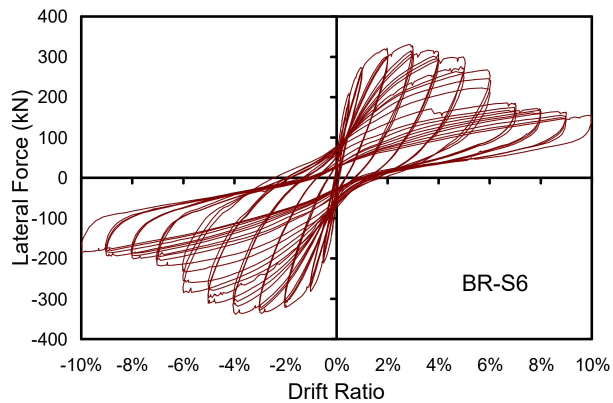
Transverse Prestressing for Improved Splice Deficiency





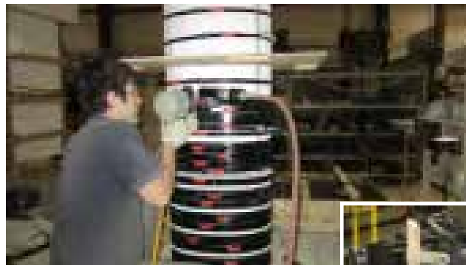
Unretrofitted Column | **Retrofitted Column**

Squarer Columns

Transverse Prestressing of Columns

Field Application

Transverse Prestressing with Steel Straps



Column retrofit with high-strength steel straps

Transverse Prestressing with Steel Straps

Precast concrete raiser units were manufactured to complete square and rectangular sections to circular and elliptical shapes.

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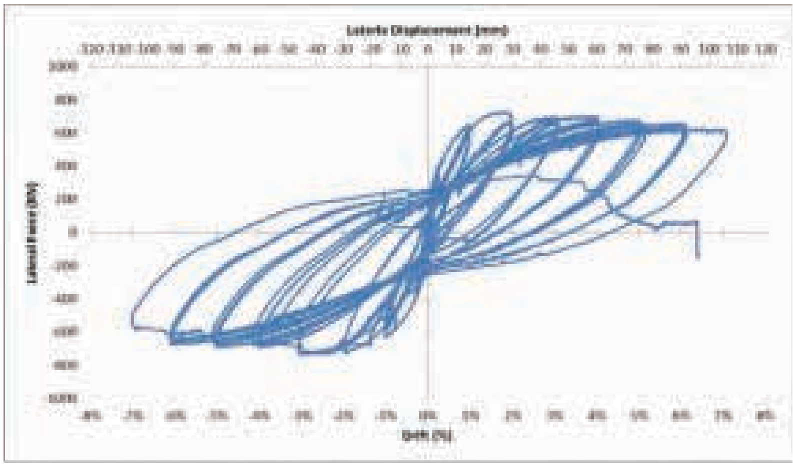
Transverse Prestressing with Steel Straps



Retrofit of a circular column with single straps

@ 7% Drift

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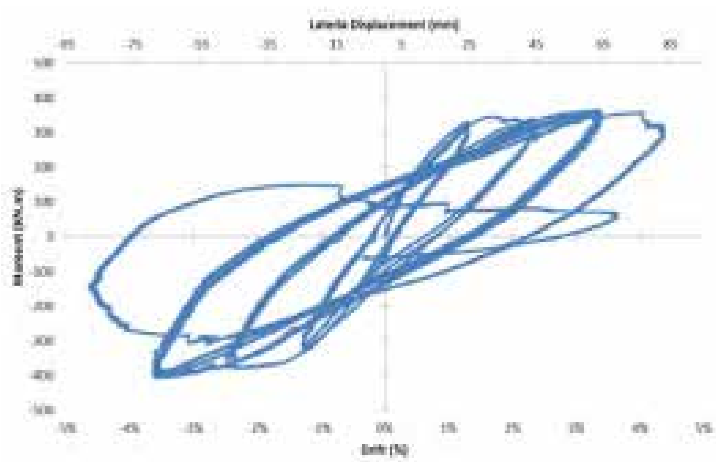
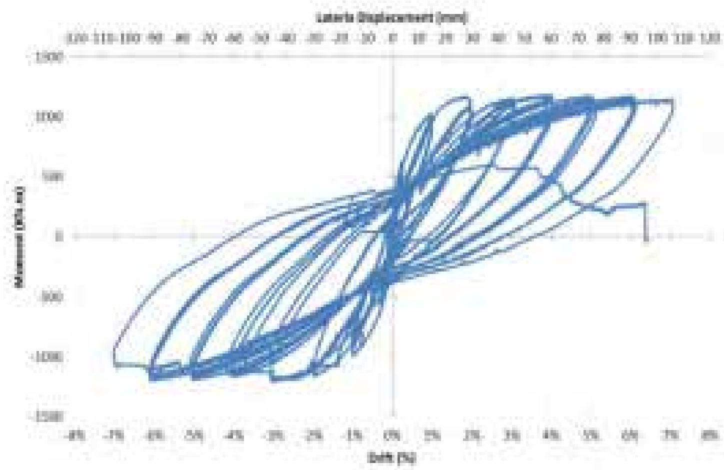
Transverse Prestressing with Steel Straps



Retrofit of a rectangular column with single straps

@ 4% Drift

Transverse Prestressing with Steel Straps



Retrofit of a square column with double straps

@ 7% Drift

The Effect of Infill Panels

Masonry, Providing Sufficient Bracing

The Effect of Infill Panels

External Masonry, Sufficient to Protect Frames

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The Effect of Infill Panels

Insufficient Bracing and Failure of Frames

Seismic Retrofit Strategy?

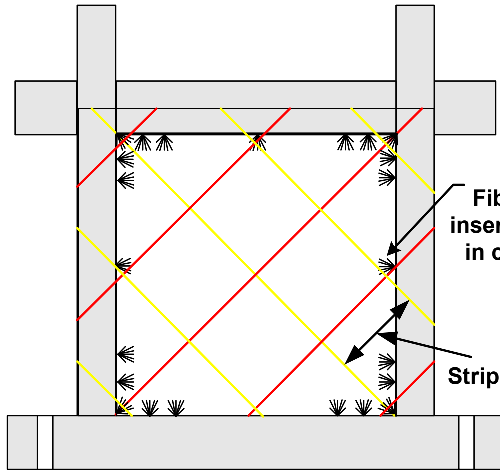
- Retrofitting individual non-ductile URM walls to increase their force and deformation capacity.
- Bracing the structure so that lateral drift is minimized and non-ductile members are not forced beyond their elastic limits

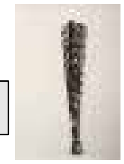
Masonry Infill Walls

Crushing of Blocks at 2% Drift

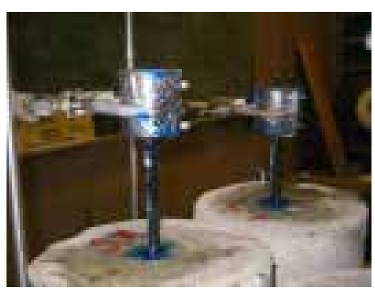
End of Test

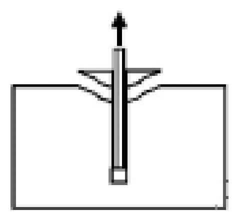
Surface-Bonded FRP



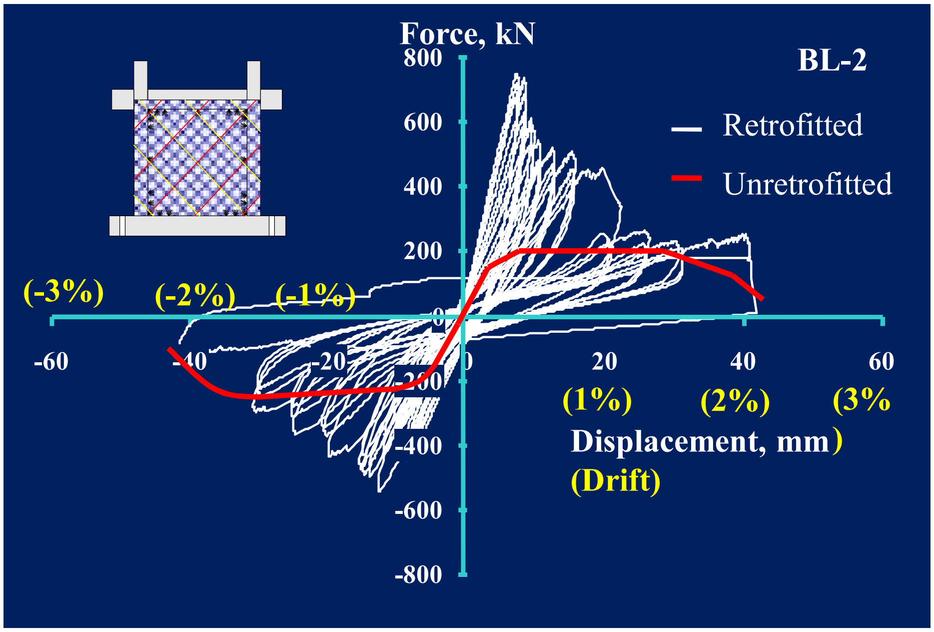


FRP Anchors

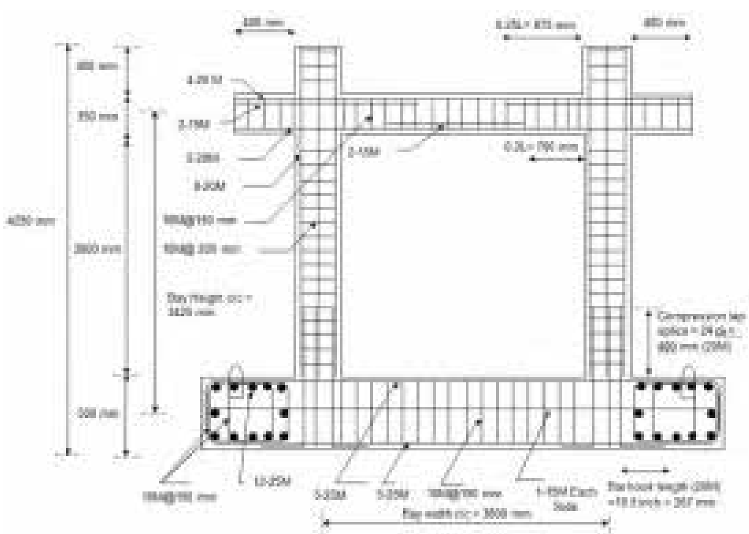




Surface-Bonded FRP



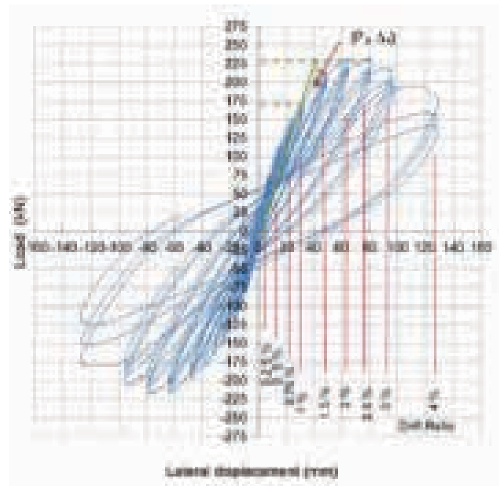
Bare RC Frames



Reinforced concrete frames were designed and built based on ACI318-1965 to be retrofitted with diagonal braces.

Bare RC Frames

Unretrofitted frame

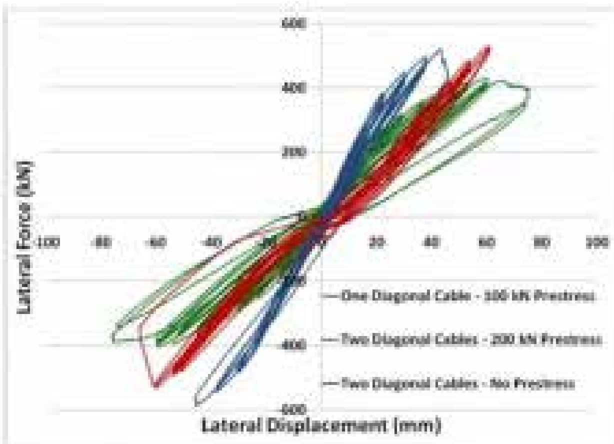


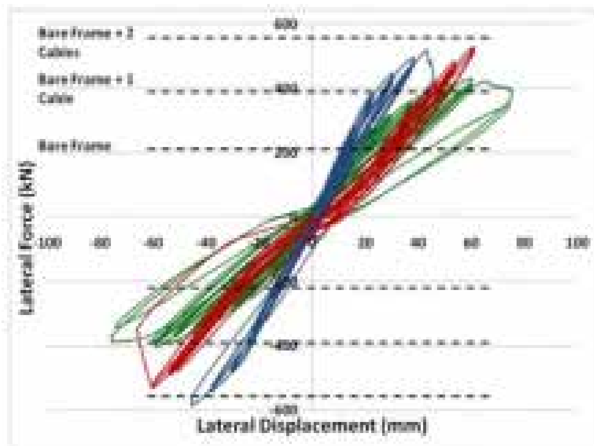
Bare RC Frames

Diagonal bracing with prestressing strands:

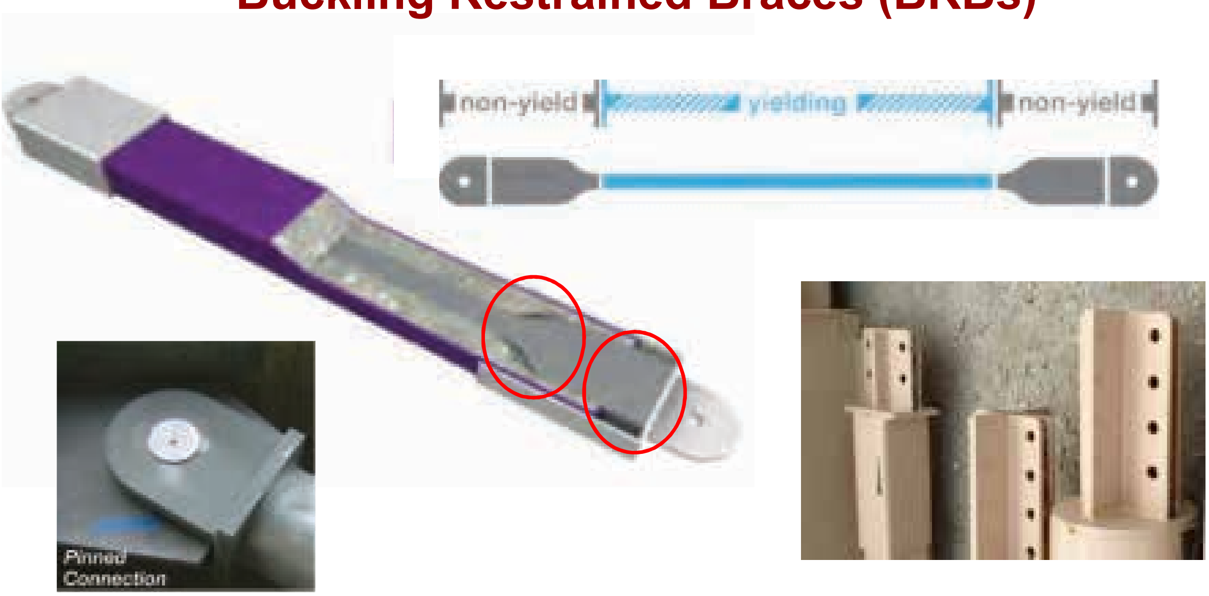
- One strand with 100kN of initial prestressing
- Two strands with 100kN of initial prestressing
- Two strands without initial prestressing

Retrofitting through Diagonal Prestressing

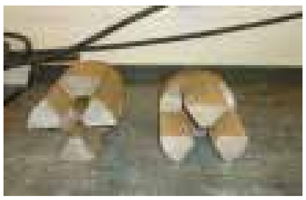




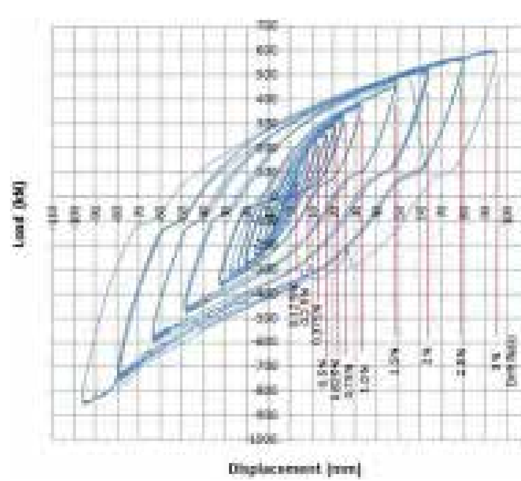
Buckling Restrained Braces (BRBs)



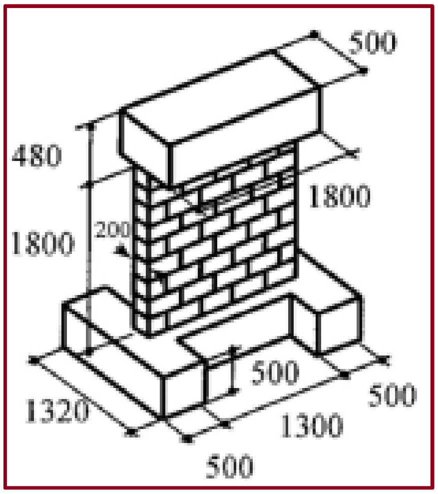
Development of a New Buckling Restrained Brace (BRB)

Development of a New Buckling Restrained Brace (BRB)

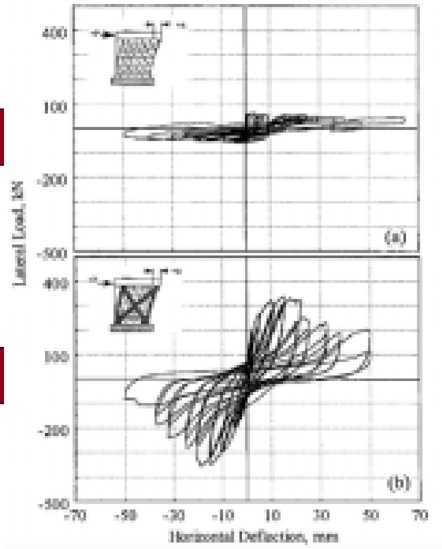
URM Load Bearing Walls Retrofitted with Steel Strips



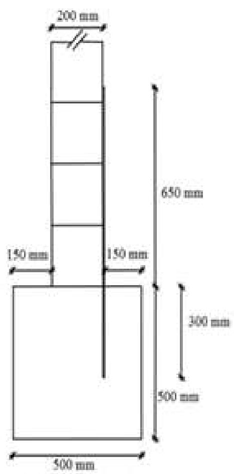
Unreinforced Masonry Wall Retrofit

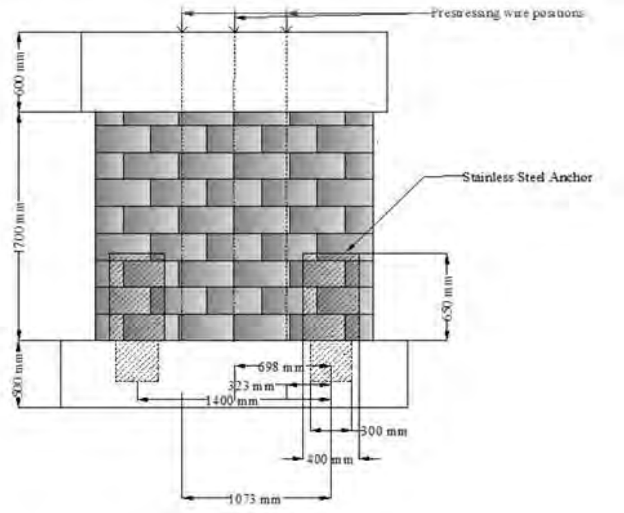
Without Retrofit →

With Retrofit →



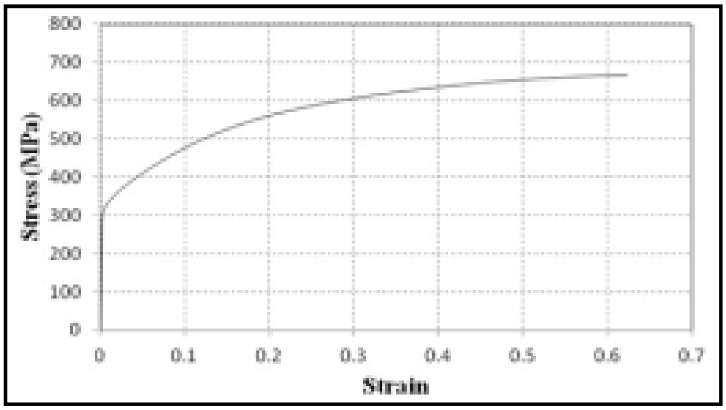
URM Walls – FRP Retrofit with Ductile Steel Sheet Anchors





URM Walls – FRP Retrofit with Ductile Steel Sheet Anchors

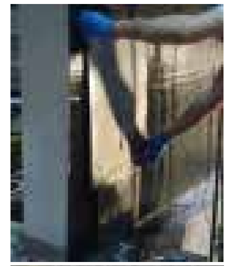
Stainless steel developed 60% elongation prior to tensile rupture



URM Walls – FRP Retrofit with Ductile Steel Sheet Anchors

Foundation concrete is cut

Anchors are epoxy glued into the foundation concrete. They are bolted to delay buckling.



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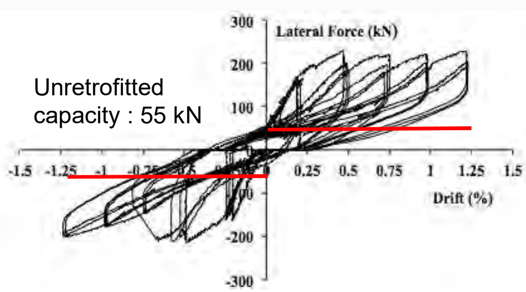
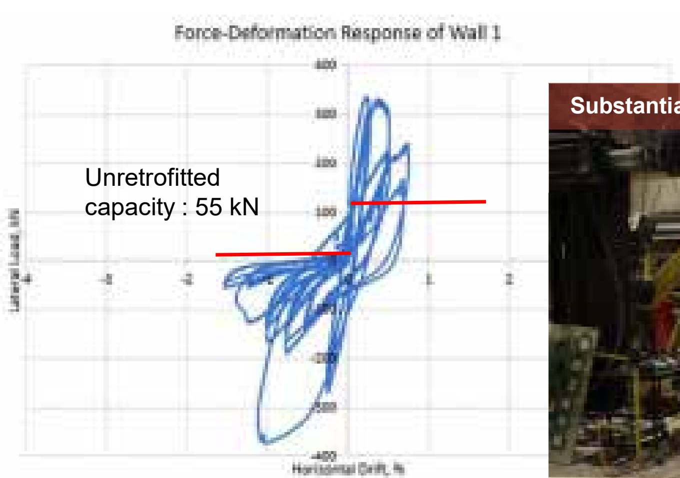
URM Wall – FRP Retrofit with Ductile Steel Sheet Anchors



URM Load Bearing Wall Retrofits with Internal Reinforcement

Placement of 2-15M bars at each wall end for flexural strengthening.

URM Load Bearing Wall Retrofits with Internal Reinforcement



Substantial strength gain followed by shear compression failure

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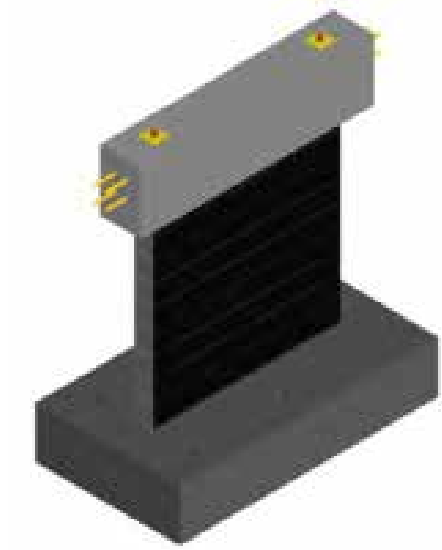
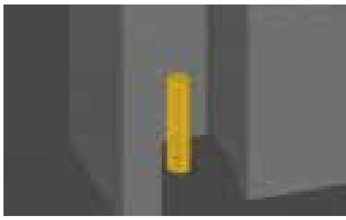
URM Load Bearing Wall Retrofits with Internal Reinforcement

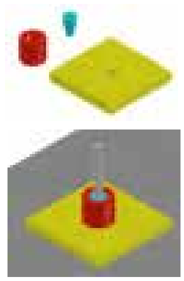


Two 7-wire strands were used, one at each end. Each strand was stressed to 500 MPa.



Threaded rod secured in foundation

Prestressing cylinders at the bottom



Anchor system
at the top

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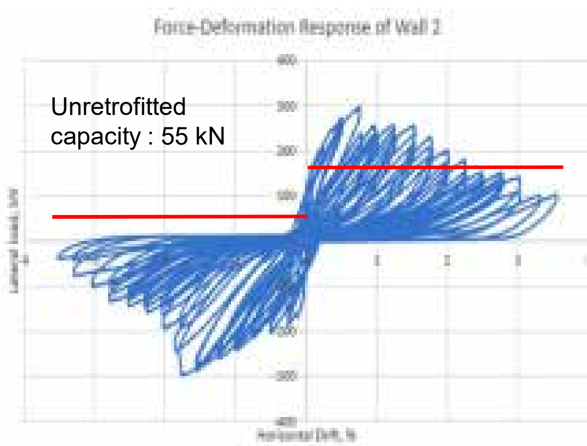
URM Load Bearing Wall Retrofits with Internal Reinforcement



Substantial strength and ductility enhancement with self centering capability until toe crushing.

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Thank You for Your Attention

Questions or Comments?

EMERGING NOVEL MATERIALS FOR SEISMIC RETROFIT

By Dr. D. Palermo, York University

Abstract

Recent experimental and complementary numerical modelling research on emerging novel materials for reinforced concrete structural elements, including squat and slender shear walls and limited ductility frames, is presented. The objective is to improve seismic performance and structural resiliency by controlling residual deformations and damage. Residual deformations are controlled by substituting traditional steel reinforcement with novel metals, such as Shape Memory Alloys, which possess superelastic, strain recovery properties. Damage to the concrete is suppressed by the application of Engineered Cementitious Concrete, which is tailored to provide enhanced mechanical properties in tension, such as tension strain hardening. Research with these novel materials has been implemented in both retrofit/repair applications as well as in new construction of concrete structural elements. In addition, nonlinear dynamic analysis has been used to illustrate the applicability and the potential benefits of the materials under earthquake scenarios representative of Canadian seismicity.

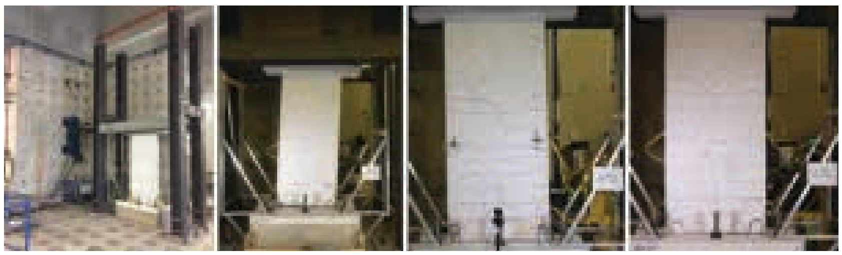
Keywords: retrofit, repair, emerging materials, nonlinear finite element analysis, shape memory alloys, engineering cementitious concrete.

Biography

Dr. Dan Palermo is a Professor of Structural Engineering and the Chair of the Department of Civil Engineering at York University. His research interests include behaviour of concrete structures, large-scale testing of concrete and masonry structures, seismic repair and retrofit with emerging materials, nonlinear finite element modelling, ultra-high-performance fiber reinforced concrete, and the effects of tsunami loading. In 2018, he received the York University President’s University-Wide Teaching Award and was elected Fellow of the CSCE.

EMERGING NOVEL MATERIALS FOR SEISMIC RETROFIT

DAN PALERMO
PROFESSOR, DEPARTMENT OF CIVIL ENGINEERING
VICE DEAN, LASSONDE SCHOOL OF ENGINEERING
YORK UNIVERSITY



OUTLINE

- Research Focus
- Emerging Materials
- Experimental and Modelling Research
  - New Construction
  - Retrofit
  - Repair

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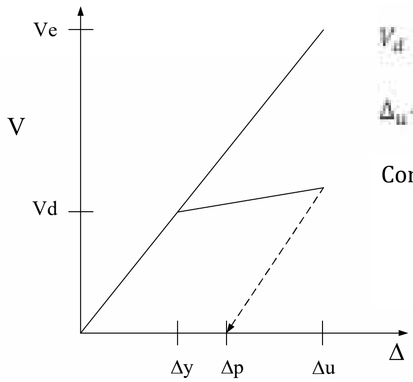
RESEARCH DIRECTION

Force-Based Seismic Design Philosophy

Primary Objective: minimize loss of life during DGM

Performance: prevent collapse
expect permanent structural damage



$$V_d = \frac{S(T_a) M_v I_E W}{R_d R_o}$$ Design Base Shear Force

$$\Delta_u \rightarrow drift\ \left({}^{\Delta}/_{h_s} \right) \leq code\ limit$$

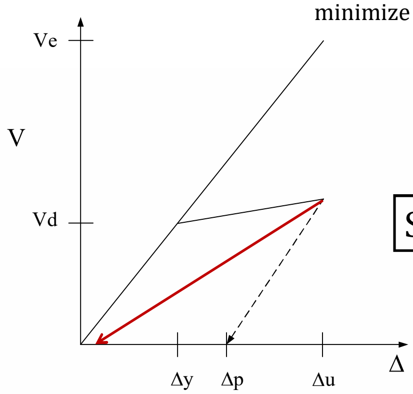
Consequences: damage
permanent deformations
extensive repairs
operational?
demolition?

RESEARCH DIRECTION

Performance-Based Seismic Design Philosophy

Primary Objective: operational structure

Performance: reduce damage to critical areas
reduce residual deformations
minimize repairs



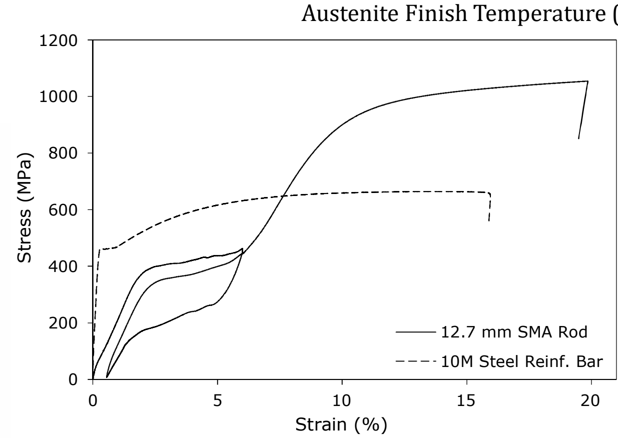
$$\Delta_p \leq limit$$

Permanent Displacement

Self-Centering Structures

SHAPE MEMORY MATERIALS: SE-SMA

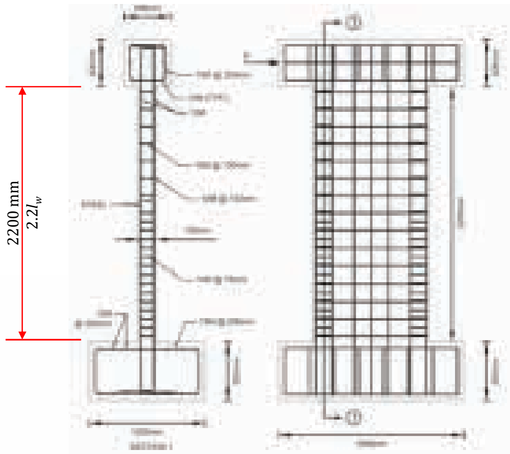
Typical Specifications: Superelastic SMA (ϕ = 12.7 mm)
Nickel-Titanium (NiTi)
Nickel (Ni) – 55% & Titanium (Ti) – 45%
Austenite Start Temperature (A_s) – 30°C
Austenite Finish Temperature (A_f) – 10°C

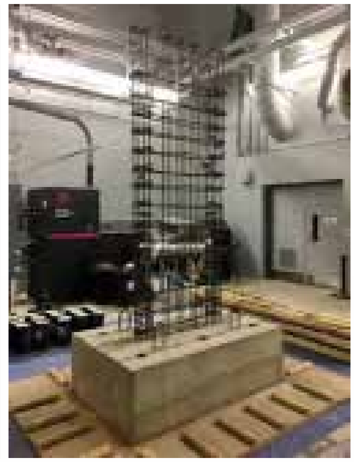


Cortes and Palermo (2017)

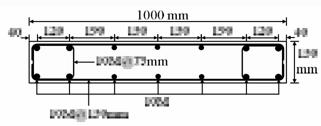
NEW CONSTRUCTION

STEEL REINFORCED WALL



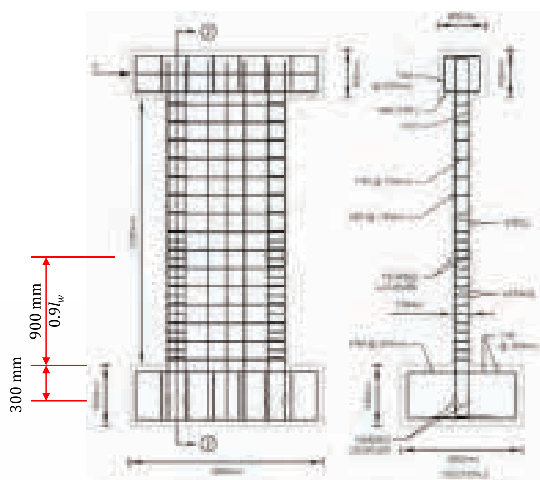


Morcos and Palermo (2019)

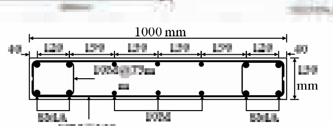


CSA A23.3 Section 21: Ductile Shear Walls

HYBRID-SMA WALL

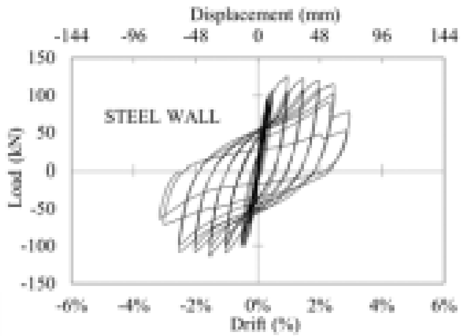


Morcos and Palermo (2019)

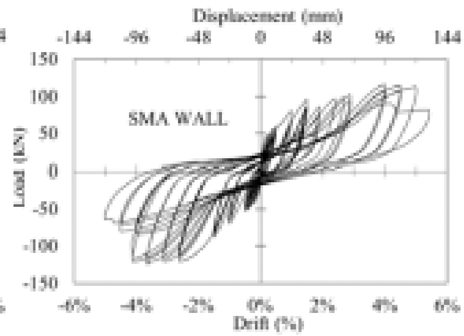


CSA A23.3 Section 21: Ductile Shear Walls

LOAD-DISPLACEMENT



Deformed Steel-Reinforced Wall (SWS-R)



Hybrid-SMA Reinforced Wall (SWN)

Wall	Yield			Peak			Ultimate		
	Load (kN)	Drift (%)	Displ. (mm)	Load (kN)	Drift (%)	Displ. (mm)	Load (kN)	Drift (%)	Displ. (mm)
SWS-R	97	0.36	8.7	118	1.25	30	101	2.5	60
SWN	93	1.88	45	118	3.80	91	113	4.29	103

Morcos and Palermo (2019)

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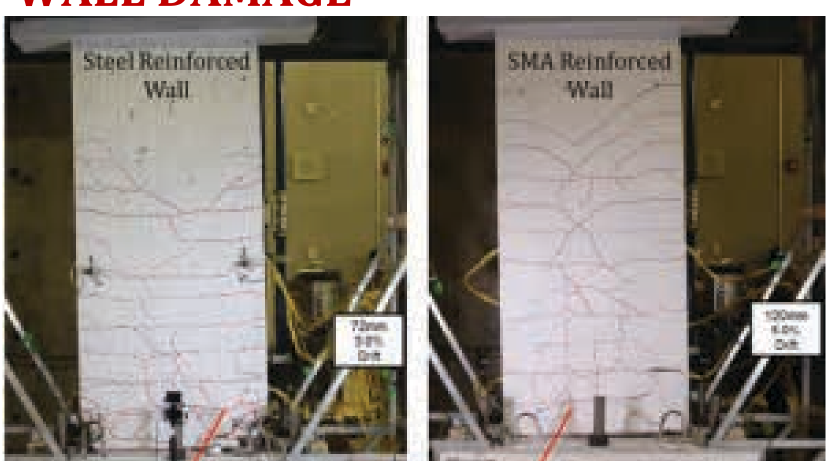
WALL DAMAGE



Ultimate Unloaded

Morcos and Palermo (2019)

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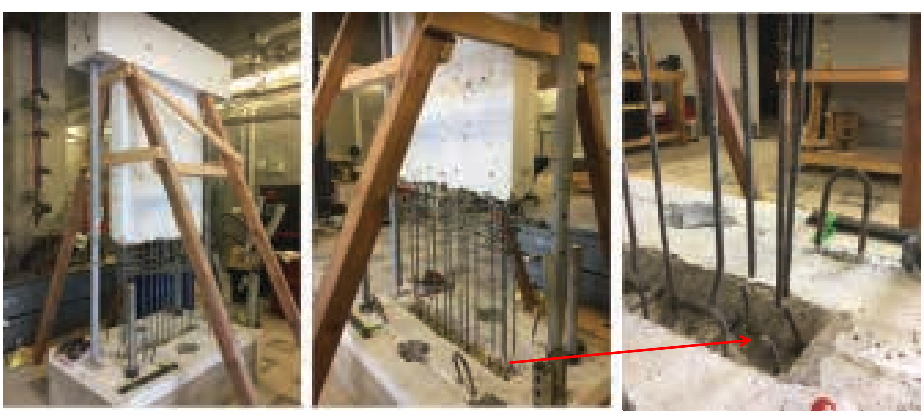
SMA WALL DAMAGE

Soto Rojas and Palermo (2020)

Fractured Web Bars

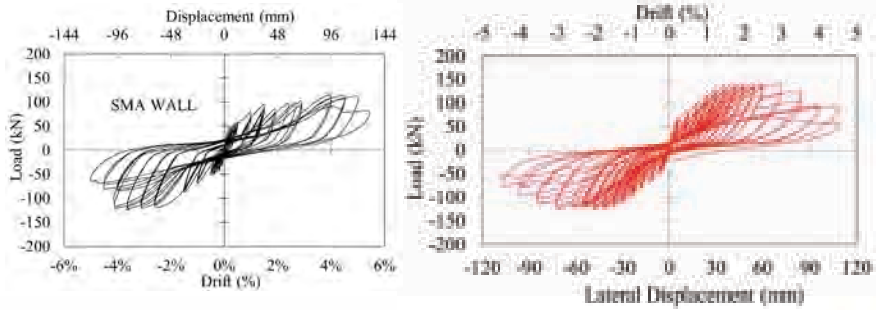
STEEL WALL DAMAGE

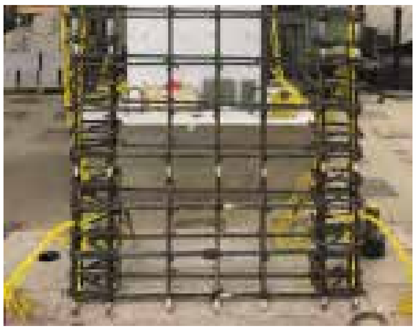


Soto Rojas and Palermo (2020)

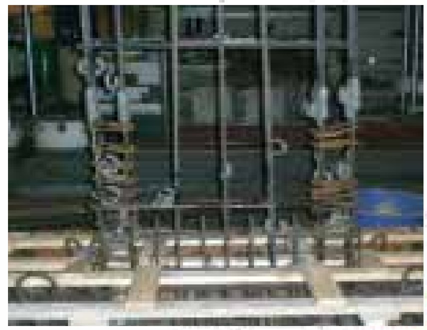
Fractured Boundary Bars

LOAD-DISPLACEMENT





Morcos and Palermo (2019)

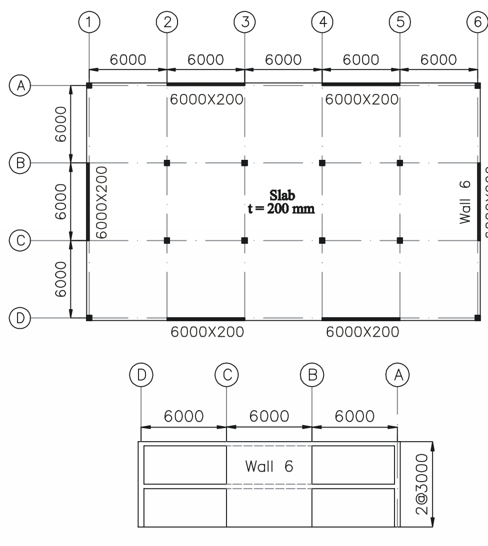


Abdulridha and Palermo (2017)

RETROFITTING

SQUAT WALLS

Prototype Structure



Cortes and Palermo (2017)

Vancouver, BC

NBCC 1965 (Original)

$$V_{D,1965} = V_{1965} = 0.083W$$

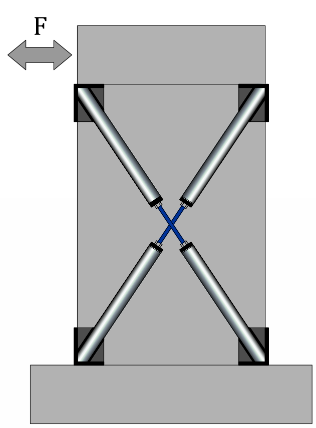
NBCC 2010 (Retrofit)

$$V_{D,2005} = 0.309W$$

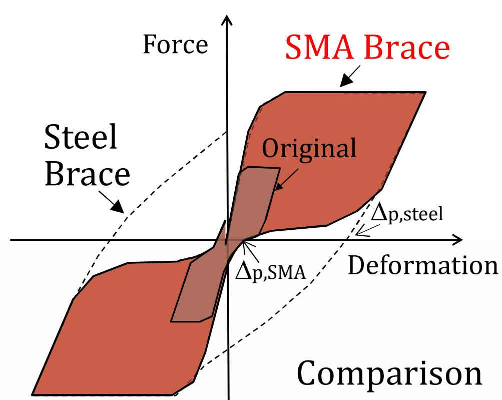
$$\frac{V_{D,2010}}{V_{D,1965}} = 3.72 \approx 4.00$$

SMA RETROFITTING BRACE

Retrofit Strategy: Tension-only bracing system



Cortes and Palermo (2017)



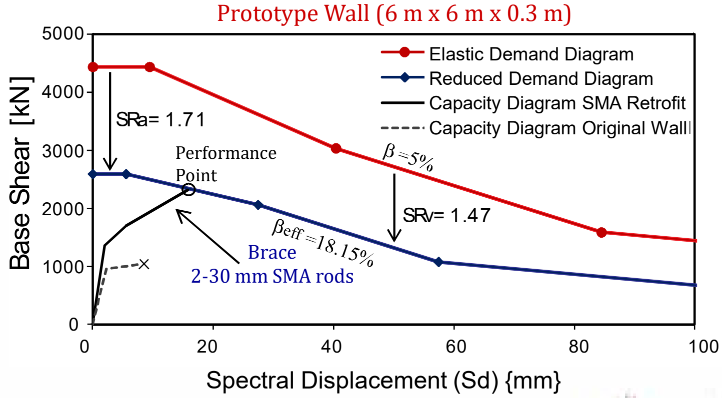
Comparison with Steel Retrofit

SMA RETROFITTING BRACE

Assessment of prototype shear wall:

Capacity Spectrum Method

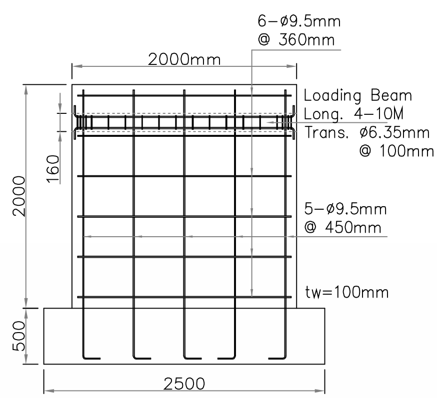
Prototype Wall (6 m x 6 m x 0.3 m)



Cortes and Palermo (2017)

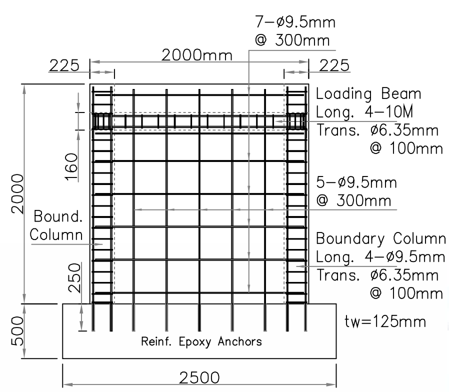
SMA BRACE RETROFITTING

Scaled Squat Shear Walls



Reinf. SQ1/SQ1a/SQ1S

Web: 0.18% long., 0.20% trans.

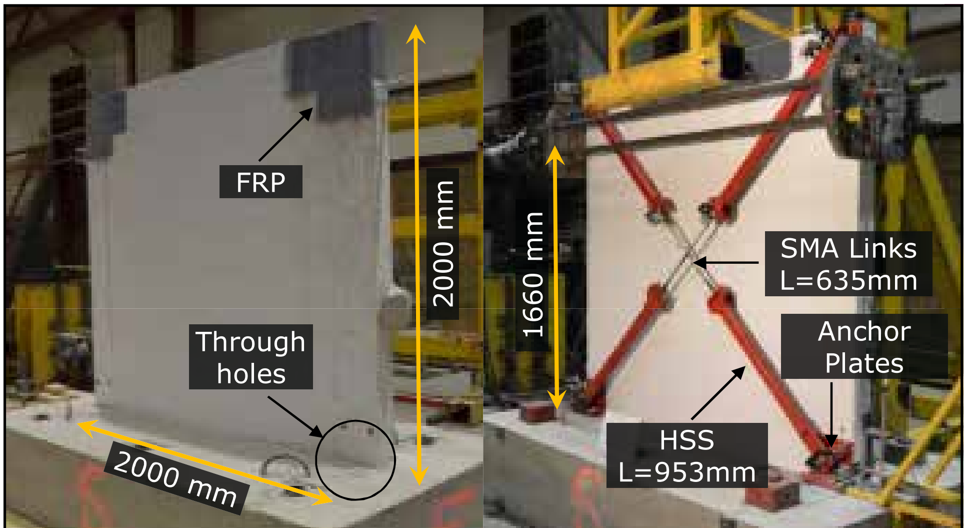


Reinf. SQ2/SQ2S

Web: 0.18% long., 0.20% trans.

Boundary zones: long. 1%

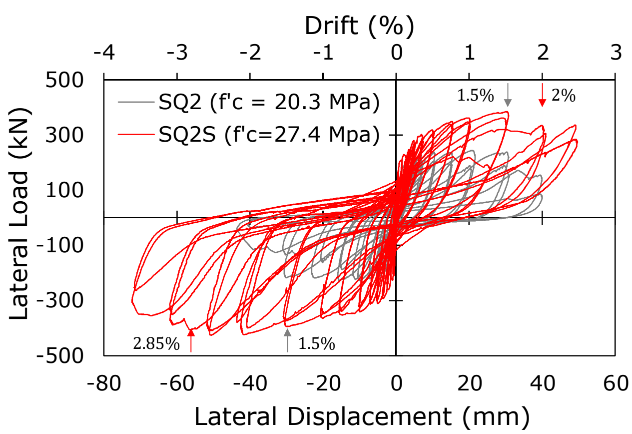
Cortes and Palermo (2018)



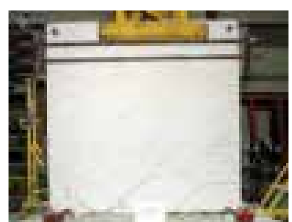
Retrofitting of Walls SQ1S/SQ2S

Cortes and Palermo (2018)

LOAD-DISPLACEMENT



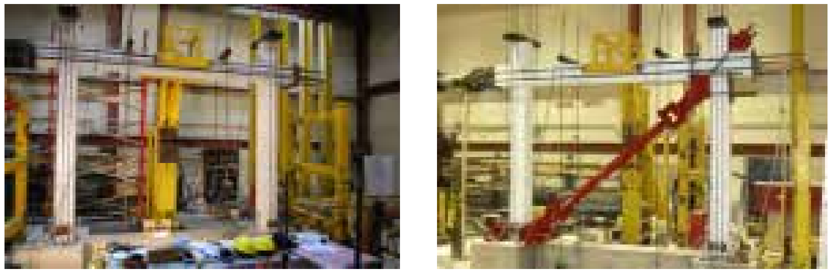
Cortes and Palermo (2017)



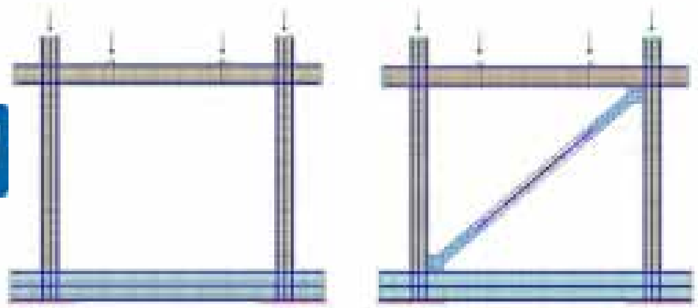
Wall SQ2

Wall SQ2S

LIMITED DUCTILITY CONCRETE FRAMES

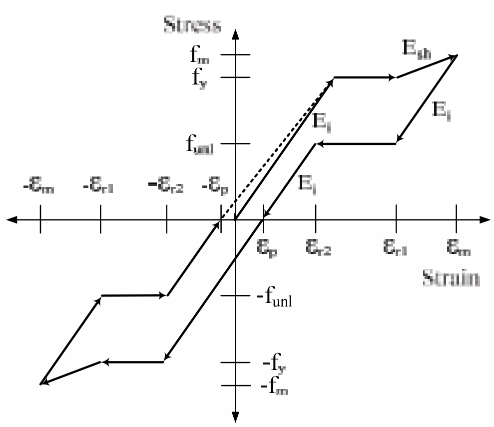


Al-Sadoon, Saatcioglu, and Palermo (2019)



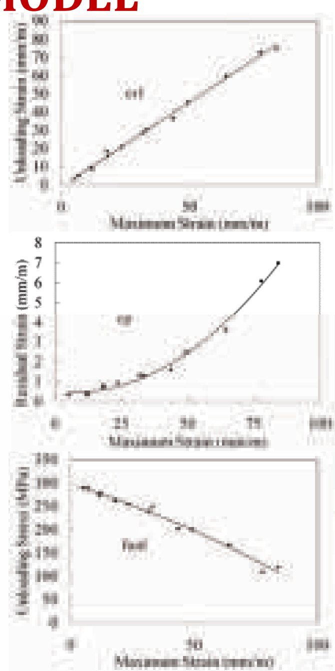
Rocha and Palermo (2020)

SE-SMA CONSTITUTIVE MODEL

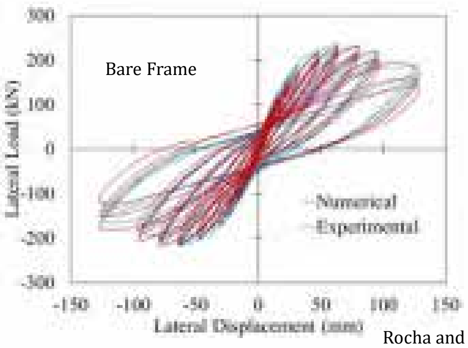


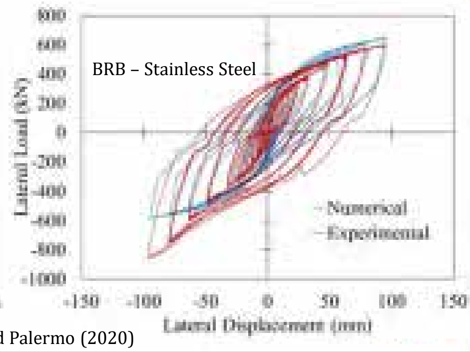
Hysteretic Constitutive Model
SE-SMA

Abdulridha, Palermo, Foo, and Vecchio (2013)



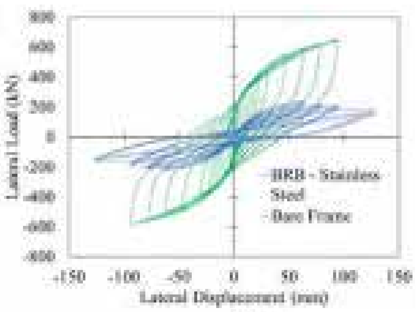
BRB RETROFIT OF FRAMES

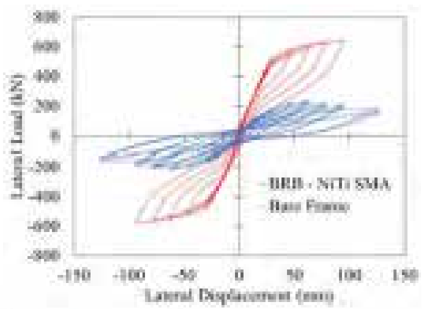


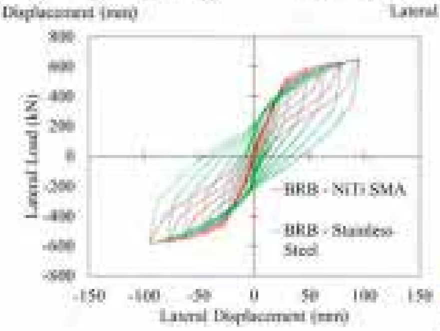


Rocha and Palermo (2020)

BRB RETROFIT OF FRAMES - MODELLING







Rocha and Palermo (2020)

LASSONDE

YORK

REPAIR

SLENDER WALLS – REPAIR/ RETROFIT

Original SMA (NiTi) bars
Control of permanent deformations with Shape Memory Alloy metals (Superelastic NiTi) – strain recovery

New longitudinal web bars

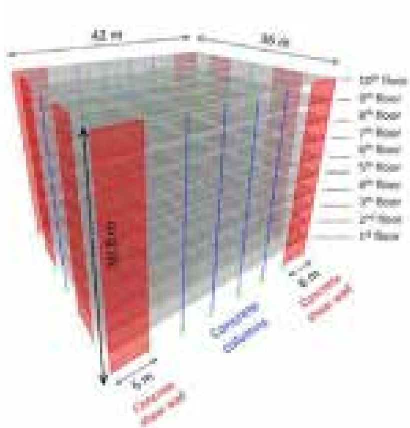
New repair concrete – UHP-FRC
Control of damage with Ultra-High-Performance Fibre Reinforced Concrete – high strength concrete and enhanced mechanical properties in tension – strain hardening in tension

Soto Rojas and Palermo (2020)

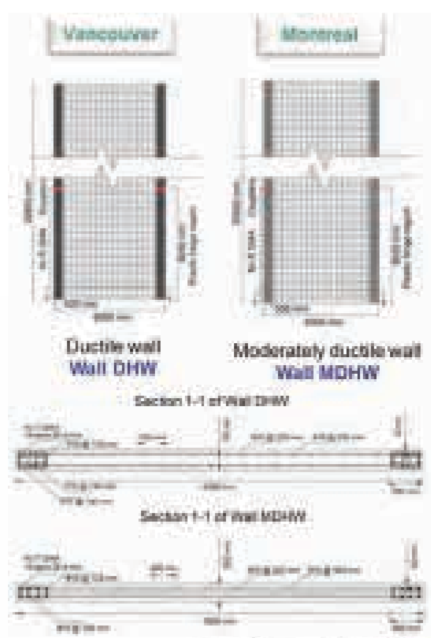
DYNAMIC ANALYSIS

NUMERICAL MODELLING

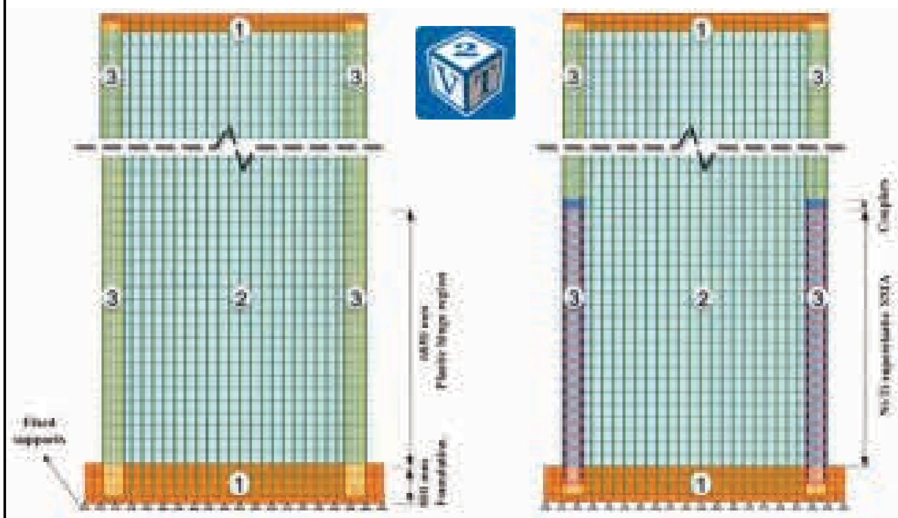
Dynamic Analysis:
- Reduced Energy Dissipation with SMA
- Reduced Stiffness with SMA
- Recovery Capacity with SMA
- Ratcheting Effect
- Earthquake Scenario



Maciel, Cortes, and Palermo (2020)

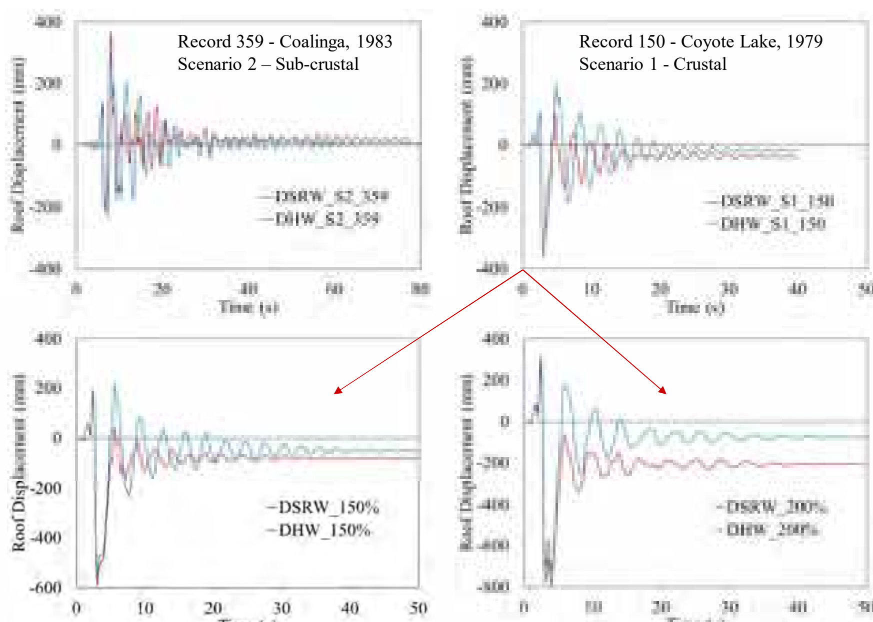


WALL FINITE ELEMENT MODELS



Maciel, Cortes, and Palermo (2020)

DISPLACEMENT TIME-HISTORIES



Maciel, Cortes, and Palermo (2020)

THANK YOU

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Morcos, M., and Palermo, D., "SMA-Reinforced Concrete Shear Walls Subjected to Reverse Cyclic Loading," Fifth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2019), Postdam, Germany, August 2019.

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Abdulridha, A., Palermo, D., Foo, S., and Vecchio, F.J., "Behavior and Modeling of Superelastic Shape Memory Alloy Reinforced Concrete Beams," Engineering Structures, Elsevier, V. 49, No. 4, pp. 893-904, 2013.

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SEISMIC PERFORMANCE ASSESSMENT OF INTACT, REPAIRED AND RETROFITTED RC MOMENT RESISTING FRAMES THROUGH HYBRID SIMULATIONS

By Dr. O.-S. Kwon, University of Toronto

Abstract

Hybrid simulation allows integration of physical specimens with numerical models for seismic performance assessment of a structural system. To facilitate the application of the hybrid simulation method, the research group has developed the UT-SIM framework (www.ut-sim.ca). This presentation will give a brief overview of the UT-SIM framework and a few application examples. Then, the newly developed weakly-coupled hybrid simulation method (WCHS) will be presented which allows integration of an experimental setup which cannot fully satisfy the boundary conditions at the interface between numerical substructure and physical specimen. The WCHS is applied to evaluate the seismic performance of intact, repaired, and retrofitted three-storey reinforced concrete moment frames where one of the first storey columns was physically modelled while the rest of the system was modelled numerically in OpenSees. The test results show that FRP-repaired column was able to restore the structures performance to the pre-damage response when excited by the same seismic sequence scenario.

Keywords: pseudo-dynamic hybrid simulation, retrofitted structure, repaired structure, reinforced concrete moment resisting frame.

Biography

Dr. Oh-Sung Kwon received his Ph.D. degree at the University of Illinois at Urbana-Champaign in 2007 and worked as a Post-doctoral Researcher. He was appointed as an Associate Professor at the Missouri University of Science and Technology from 2008 to 2010. He moved to the University of Toronto in 2010 and promoted to an Associate Professor in 2015. He is currently serving as an Associate Editor of the ASCE Journal of Structural Engineering.

SEISMIC PERFORMANCE ASSESSMENT OF INTACT, REPAIRED AND RETROFITTED RC MOMENT RESISTING FRAMES THROUGH HYBRID SIMULATIONS

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UNIVERSITY OF TORONTO

October 7, 2019. NRC-MOST/NCREE Taiwan Workshop

PRESENTATION OUTLINE

1. INTRODUCTION
2. UT-SIM FRAMEWORK
3. WEAKLY COUPLED HYBRID SIMULATION METHOD
4. APPLICATIONS TO RC MOMENT RESISTING FRAME
5. SUMMARY

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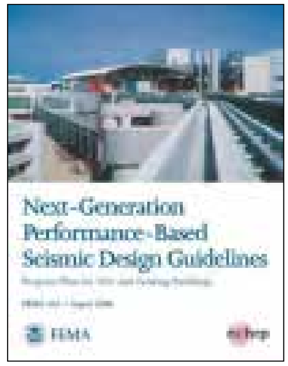
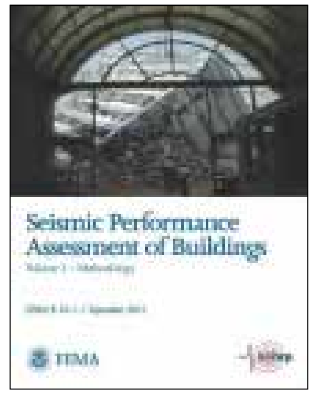
1. INTRODUCTION

SEISMIC PERFORMANCE ASSESSMENT

- Realistic assessment of seismic performance: One of the important elements in "Next Generation of Performance Based Seismic Design Guidelines"

- Challenges with the modelling and prediction of inelastic dynamic response of structures

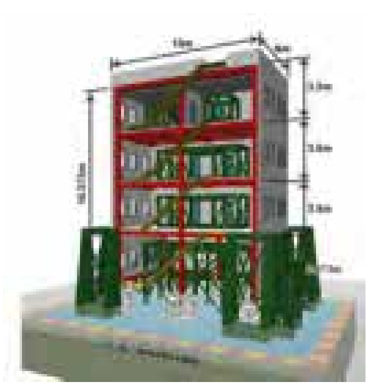




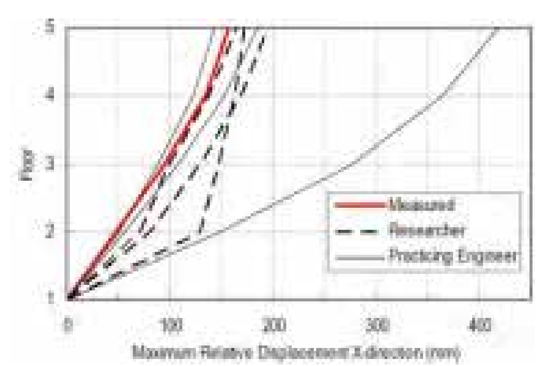
1. INTRODUCTION

SEISMIC PERFORMANCE ASSESSMENT

How accurately can we predict structural response subjected to earthquake load?



3D Analysis Blind Prediction Results
(measured and best 3 teams of each category. Total 30 participants)

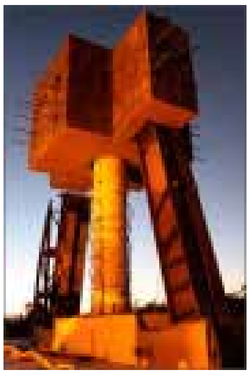


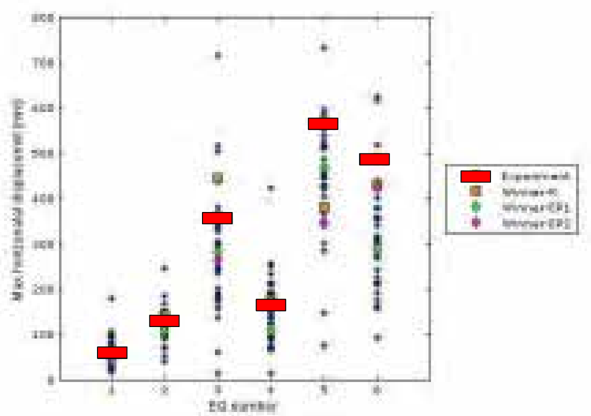
Collapse test of a full-scale four-story steel building , 2007.
http://www.bosai.go.jp/hyogo/blind-analysis/2008/2007/kekka/BA_e.pdf

1. INTRODUCTION

SEISMIC PERFORMANCE ASSESSMENT

How accurately can we predict structural response subjected to earthquake load?





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Vesna Terzic, Matthew J. Schoettler, Jose I. Restrepo, and Stephen A. Mahin (2015), *Concrete Column Blind Prediction Contest 2010: Outcomes and Observations*, PEER 2015/01,

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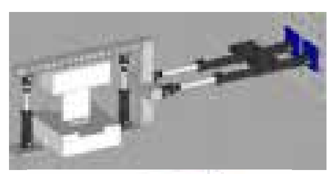
1. INTRODUCTION

Experimental Methods

SEISMIC PERFORMANCE ASSESSMENT

- **Static cyclic test of components**
  - Predefined loading history
  - Performance of structural elements under cyclic load reversals
- **Shaking table test**
  - Most complete and accurate method
  - Limitation in the scale of specimen
  - Expensive
- **Pseudo-dynamic or real time hybrid simulation**
  - Equation of motion is solved numerically
  - Whole or part of a structure is tested physically
  - Allows geographically distributed testing
  - Allows testing of large-scale structural elements



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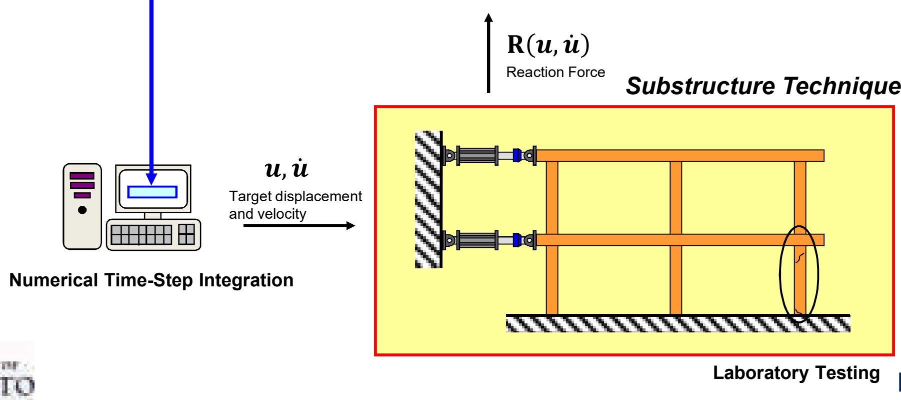
1. INTRODUCTION

HYBRID (EXPERIMENTAL-NUMERICAL) SIMULATION

Equations of Motion

$$\mathbf{M}\ddot{\boldsymbol{u}}(t) + \mathbf{C}\dot{\boldsymbol{u}}(t) + \mathbf{R}(\boldsymbol{u}, \dot{\boldsymbol{u}}) = \mathbf{F}(t)$$



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1. INTRODUCTION

HYBRID (EXPERIMENTAL-NUMERICAL) SIMULATION

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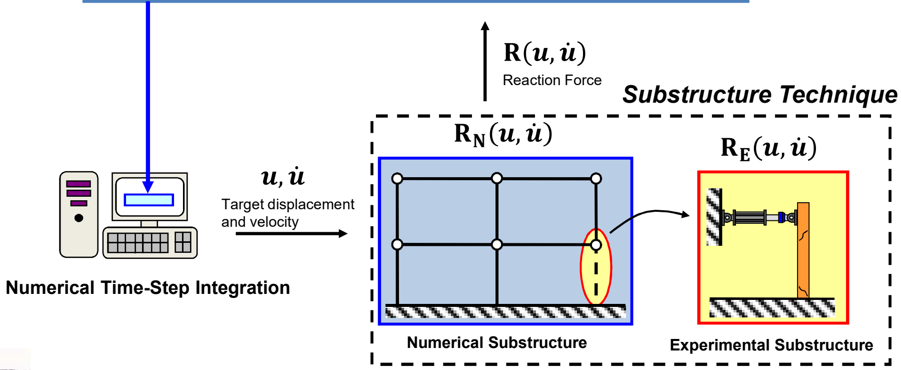

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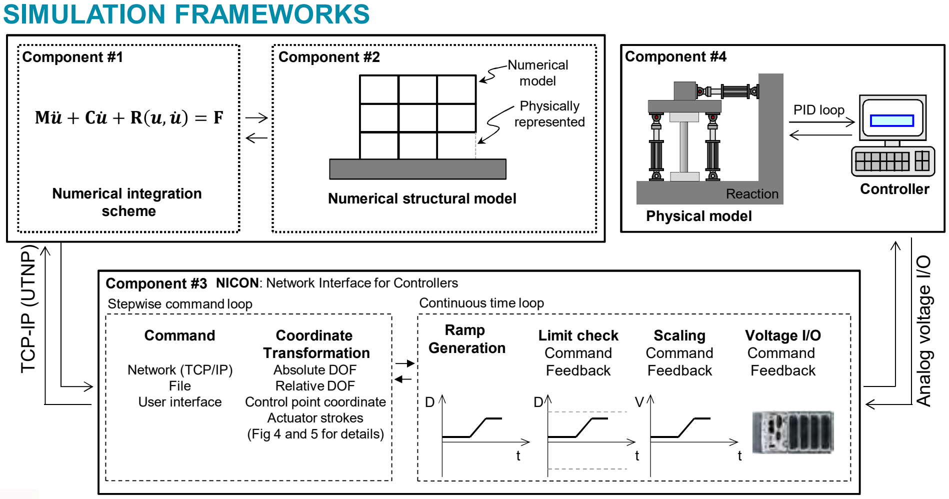
2. UT-SIM FRAMEWORK

HYBRID SIMULATION FRAMEWORKS



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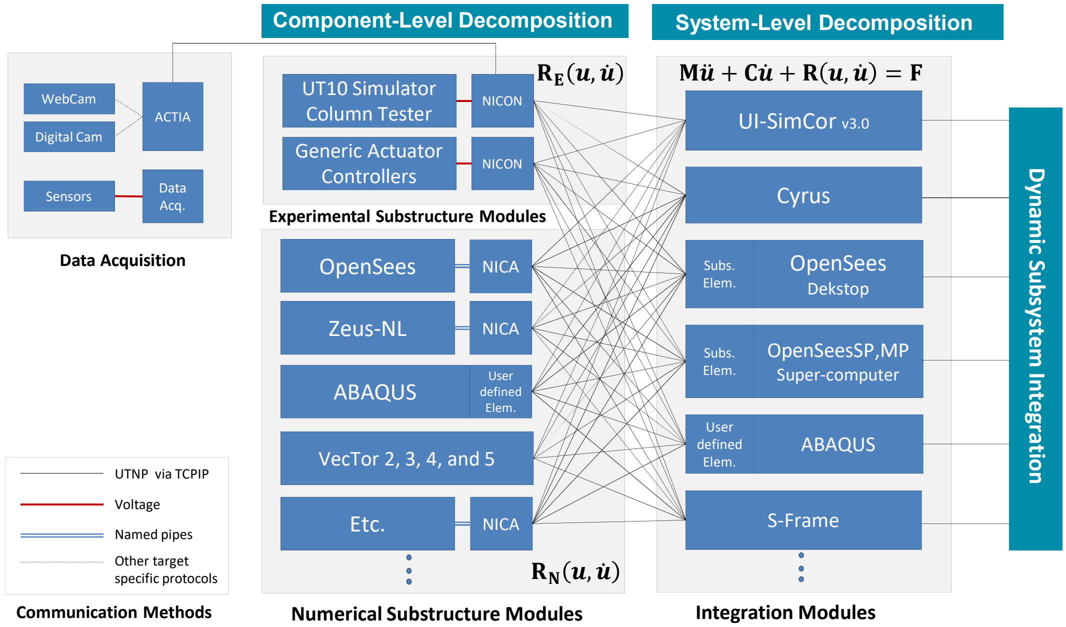
2. UT-SIM FRAMEWORK

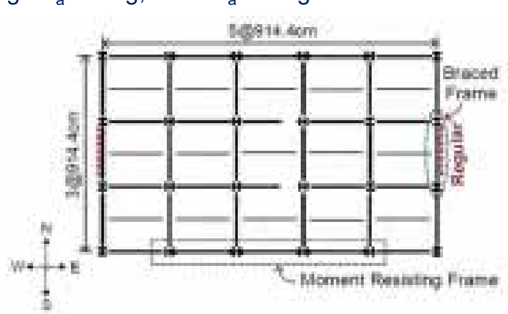
www.ut-sim.ca

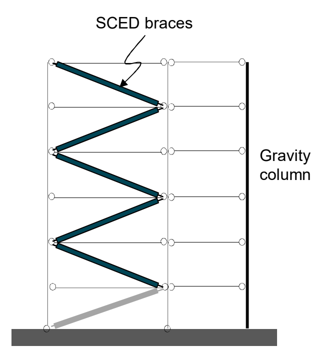


2. UT-SIM FRAMEWORK

2.1 EXAMPLE: SIX-STOREY STEEL FRAME WITH SCED BRACE

- Designed with ASCE 7-05
- Los Angeles, CA
- Design S_a = 1.4g, MCE S_a = 2.1g





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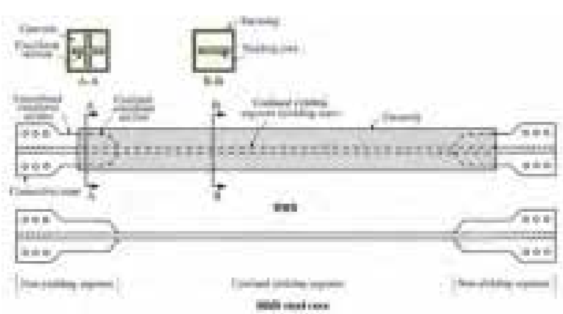
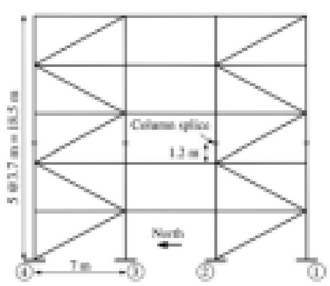
HST_TM1_14

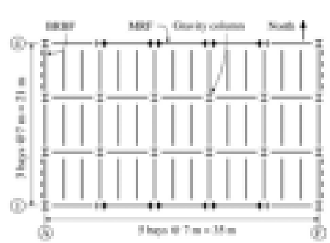
Input GM: CHY080N.txt

2. UT-SIM FRAMEWORK

2.2 FIVE-STOREY BUCKLING RESTRAINED BRACED FRAME







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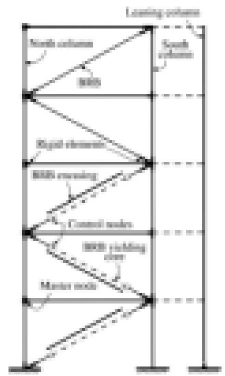
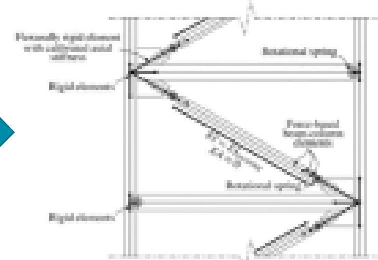
2. UT-SIM FRAMEWORK

2.2 FIVE-STOREY BUCKLING RESTRAINED BRACED FRAME



BRBF model (numerical substructure)



SubStructure element

TCP/IP network connection

AYB specimens (physical substructure)

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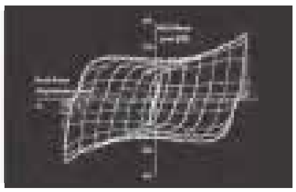
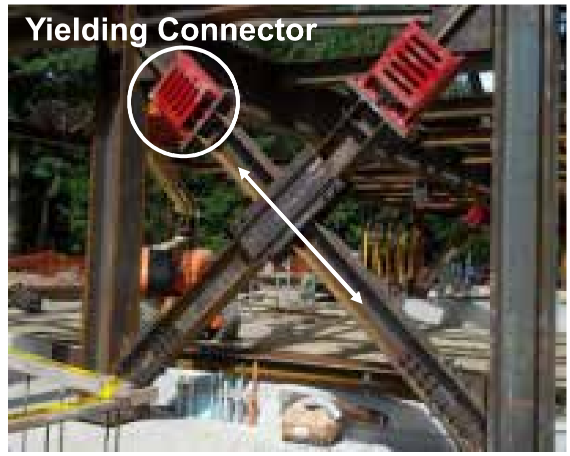
2. APPLICATION EXAMPLES

2.3 A STEEL FRAME WITH STEEL YIELDING CONNECTION ELEMENTS





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2. APPLICATION EXAMPLES

2.3 A STEEL FRAME WITH STEEL YIELDING CONNECTION ELEMENTS

Integrated Model

=

Integration Model

+

Substructure

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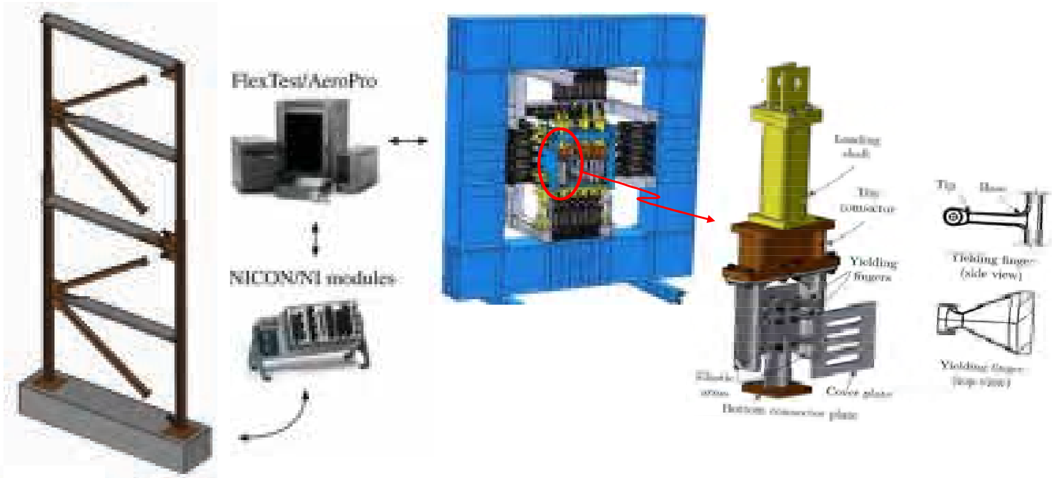
2. APPLICATION EXAMPLES

2.3 A STEEL FRAME WITH STEEL YIELDING CONNECTION ELEMENTS



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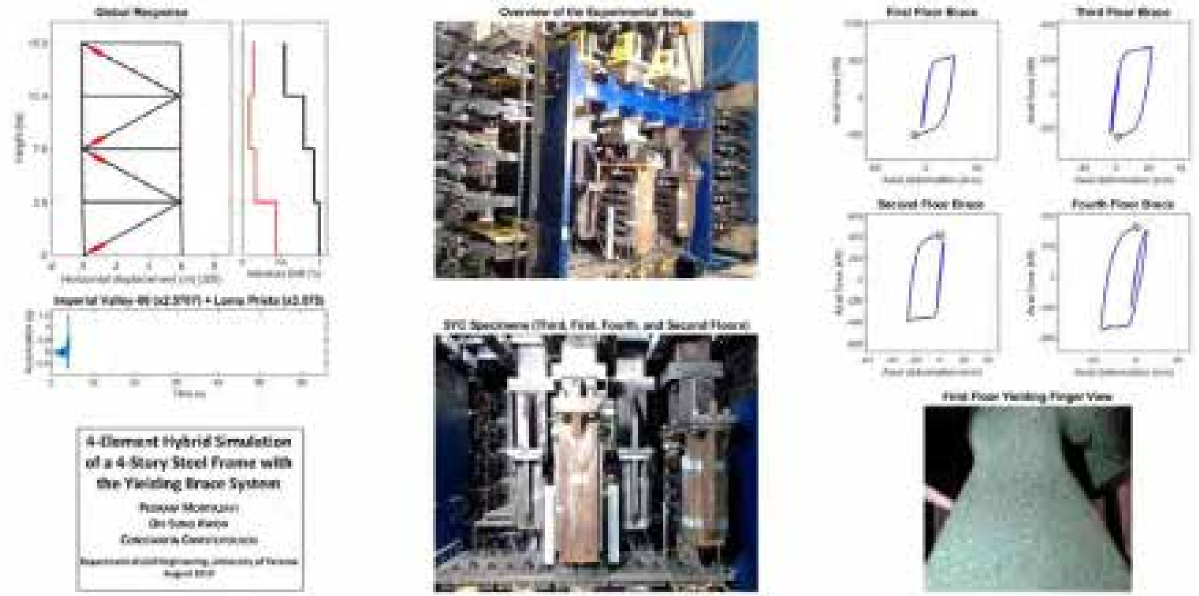

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PRESENTATION OUTLINE

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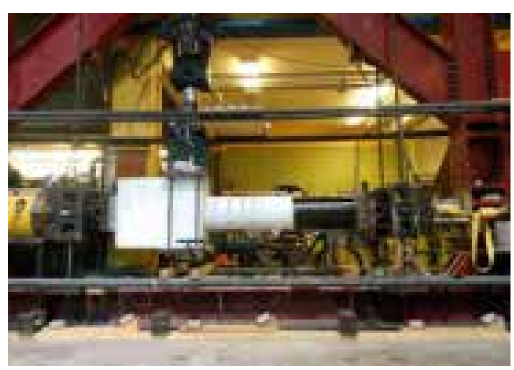

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3. WEAKLEY-COUPLED HYBRID SIMULATION METHOD

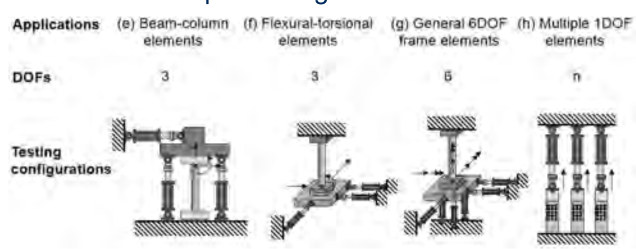
CONVENTIONAL HYBRID SIMULATION APPROACH

- Combines numerical model with experimental testing
- The equation of motion is solved numerically

Physically evaluated restoring forces

$$\underbrace{M\ddot{x}_{i+1} + C\dot{x}_{i+1} + R_{N,i+1}}_{\text{Numerically evaluated components}} + \boxed{R_{E,i+1}} = F_{i+1}$$

- The number of actuators should be equal to or greater than the number of DOFs at the interface.



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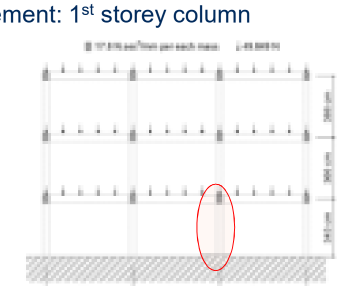
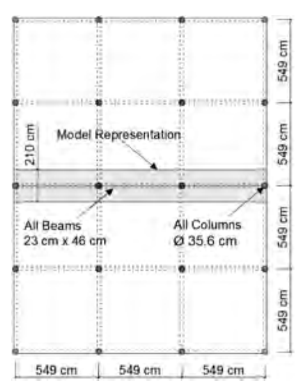
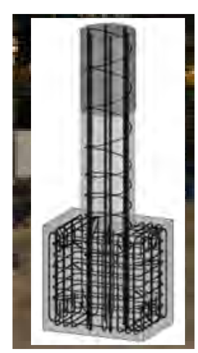
3. WEAKLEY-COUPLED HYBRID SIMULATION METHOD

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- **Building Configuration**
  - Three storey, three bay RC structure
  - Designed for gravity loads only
  - Modeling technique: fiber-section elements
  - Critical element: 1st storey column







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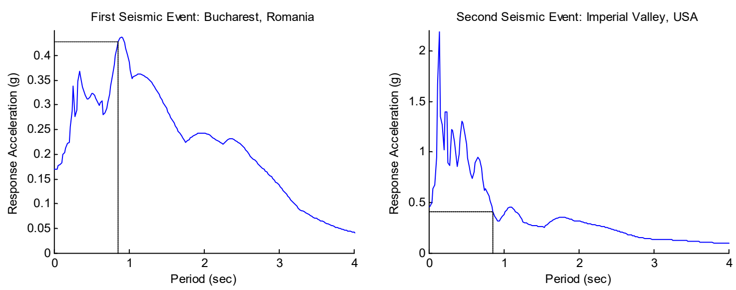
3. WEAKLEY-COUPLED HYBRID SIMULATION METHOD

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- Seismic Sequence
  - Bucharest, Romania (Mar. 4th, 1977)
    - PGA: 0.17 g, Sa: 0.43g
  - Imperial Valley, USA (Oct. 15th, 1979)
    - Scaling Factor: 1.45
    - PGA: 0.46 g, Sa: 0.41g



Elastic acceleration response spectra (T_1=0.859sec, T_2=0.295sec & T_3=0.200sec)

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3. WEAKLEY-COUPLED HYBRID SIMULATION METHOD

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- **Experimental Setup**
  - Inadequately equipped for the proper control of the boundary conditions for a hybrid simulation
    - Structure subjected to planar motion: the control of 3 DOF is required
    - Each DOF requires at least one actuator
    - Limitation: Only two actuators available (2 Coupled DOF) accounting for the contraflexure point

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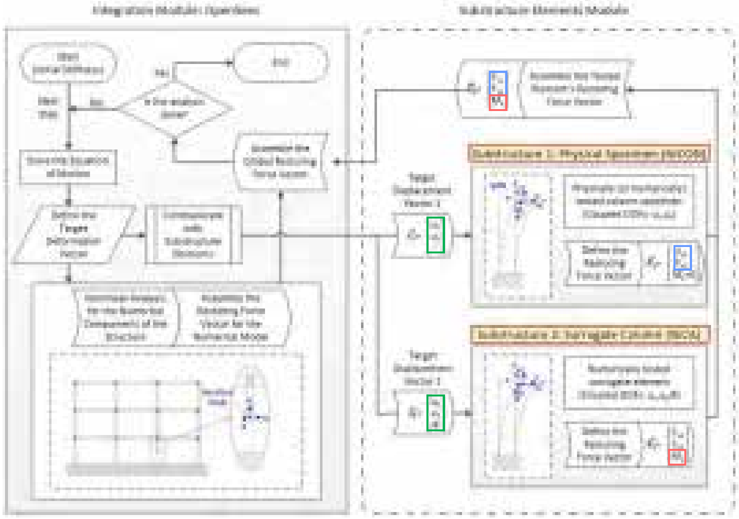
3. WEAKLEY-COUPLED HYBRID SIMULATION METHOD

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

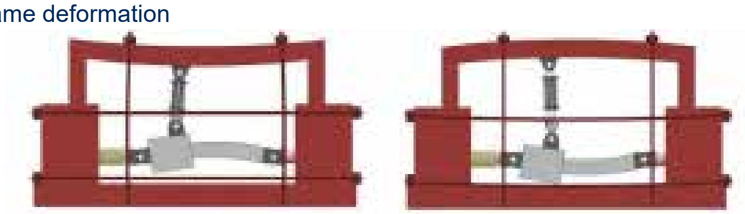


Giotis, G., Kwon, O., and Sheikh, S. (2019) "A Weakly-Coupled Hybrid Simulation Method for Structural Testing. Theoretical Framework and Numerical Verification," ASCE Journal of Structural Engineering (accepted on June 5)

3. WEAKLEY-COUPLED HYBRID SIMULATION METHOD

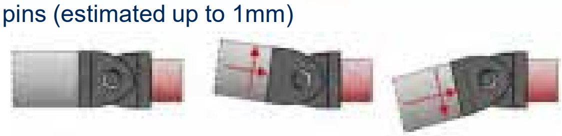
SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- **Error Sources in the Deformation Control**
  - Loading frame deformation



Positive Lateral Deformation *Negative Lateral Deformation*

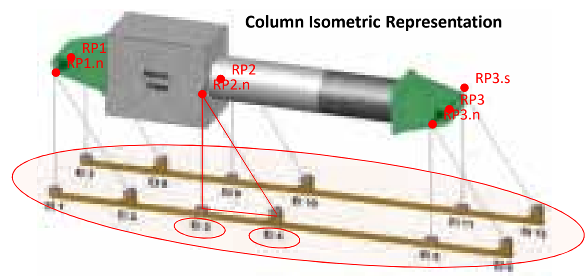
  - Slack in connecting pins (estimated up to 1mm)



3. WEAKLEY-COUPLED HYBRID SIMULATION METHOD

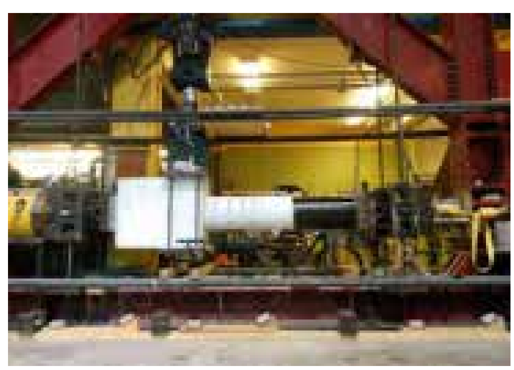
SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- **Deformation Measurement through External Instrumentation**
  - The instrumentation coordinates are measured before testing
  - The law of cosines is implemented for calculating the coordinates of the reference points
  - The reference point coordinates are averaged between the south and north face and are used for the coordinate transformation and for error compensation
  - The error compensation scheme is developed to eliminate the deformation error sources



PRESENTATION OUTLINE

1. INTRODUCTION
2. UT-SIM FRAMEWORK
3. WEAKLY COUPLED HYBRID SIMULATION METHOD
4. **APPLICATIONS TO RC MOMENT RESISTING FRAME**
5. **SUMMARY**



4. APPLICATIONS TO RC MOMENT RESISTING FRAME

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

Test Matrix

Test Sequence	Specimen		
	A	B	C
1	Low Intensity Hybrid Simulation	Hybrid Simulation Intact Structure	Hybrid Simulation Retrofitted Structure
2	Hybrid Simulation Intact Structure: 1st GM	Hybrid Simulation Repaired Structure	Hybrid Simulation Retrofitted Structure & Higher Axial Loads
3	Axial Response Investigation	Quasi-static Axial Load: 2430 kN	Quasi-static Axial Load: 1173 kN
4	Hybrid Simulation Intact Structure: 2nd GM		
5	Quasi-static Axial Load: 740 kN		

	Intact Specimen		Repaired Specimen		Retrofitted Specimen

4. APPLICATIONS TO RC MOMENT RESISTING FRAME

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- **Case B-1: Intact Structure**
  - Max. drift: 2.41%
  - Observed damage
    - Concrete spalling at the compression face
    - Flexural cracks at the tension face and diagonal shear cracks at the side faces
    - All the longitudinal bars and the transverse reinforcement have yielded into the critical area

4. APPLICATIONS TO RC MOMENT RESISTING FRAME

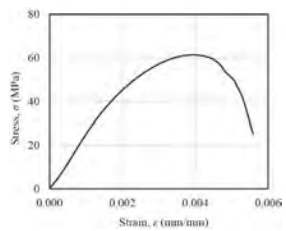
SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- **Case B-2: Repaired structure**
  - Repairing Procedure According to CSA S448.1
    - Applied both in Specimen 1 and Specimen 2
    - Hammer tap survey and loose concrete removal
    - Crack treatment for cracks greater than 0.2 mm injecting low viscosity epoxy resin (Sika Crack Fix)
    - Application of the repair mortar (EMACO S88CI) with a water/cement ratio equal to 0.14

Crack Injection

Repair Mortar Application

Repair Mortar Stress-Strain curve (Cylinder Tests)



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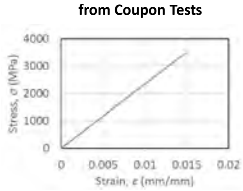
4. APPLICATIONS TO RC MOMENT RESISTING FRAME

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- **Case B-2: Repaired structure, Case C-1: Retrofitted structure**
  - Carbon Fiber-Reinforced Polymer Application
    - Coupon tests for evaluating the CFRP wrap properties (ST-200 by Nippon Oil)
    - Application of the one layer of unidirectional wrap using saturant epoxy (Tyfo-S by Fyfo)
    - Use of thermal shrink tape for the better application of the CFRP wrap of the concrete surface

Coupon Test

FRP Properties from Coupon Tests



Repaired and Wrapped Specimen prior to Testing

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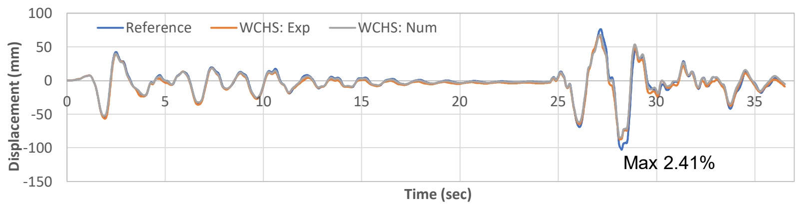
4. APPLICATIONS TO RC MOMENT RESISTING FRAME

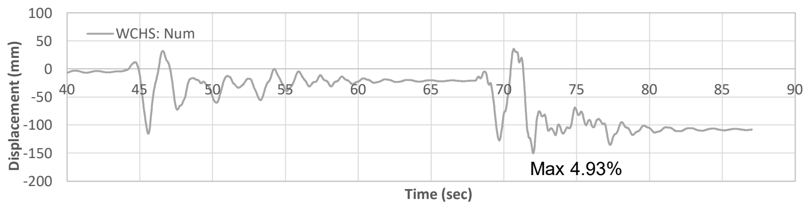
SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- 1st storey displacement

B-1 Intact structure



Response of damaged structure (numerical simulation only. Subjected to identical seismic sequence of B-1)



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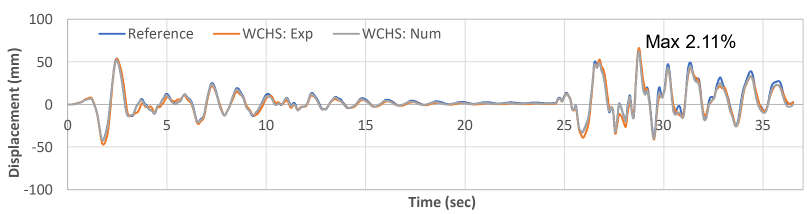
4. APPLICATIONS TO RC MOMENT RESISTING FRAME

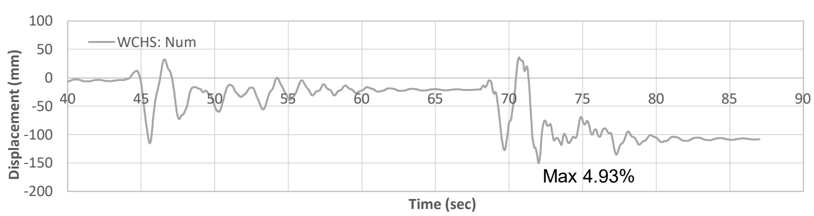
SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- 1st storey displacement

B-2 Repaired structure



Response of damaged structure (Numerical simulation only)



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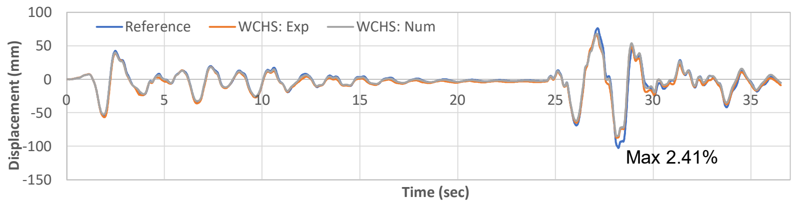
4. APPLICATIONS TO RC MOMENT RESISTING FRAME

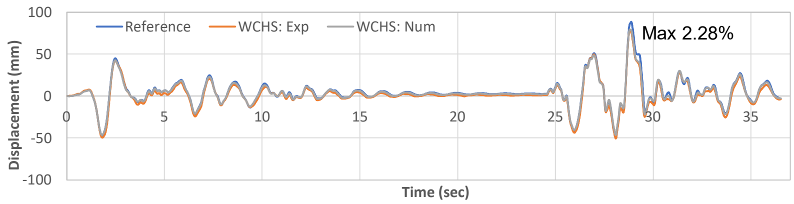
SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- 1st storey displacement

B-1 Intact structure



B-3 Retrofitted structure



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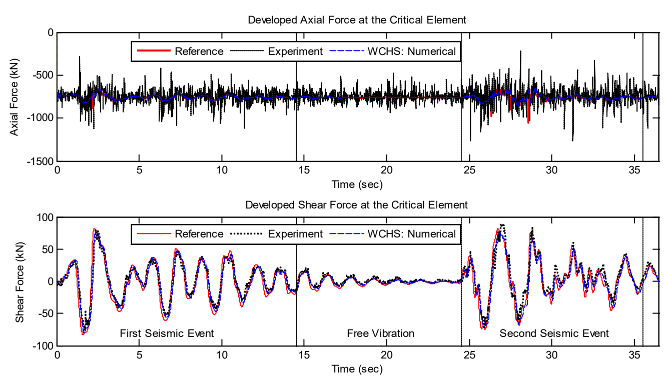
4. APPLICATIONS TO RC MOMENT RESISTING FRAME

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- Case B-1: Intact Structure – Force history of the specimen



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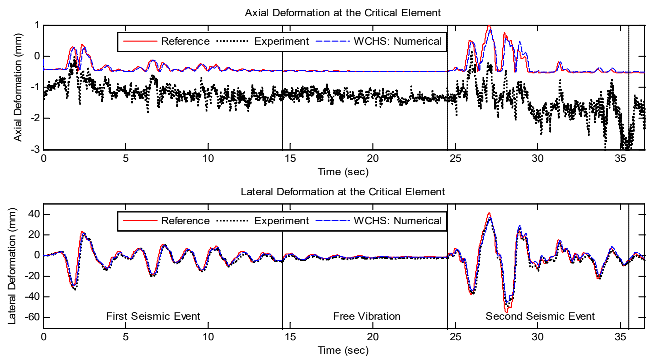
4. APPLICATIONS TO RC MOMENT RESISTING FRAME

SEISMIC PERFORMANCE ASSESSMENT OF A THREE-STOREY OMRCF

- Case B-1: Intact Structure – Deformation history of the specimen



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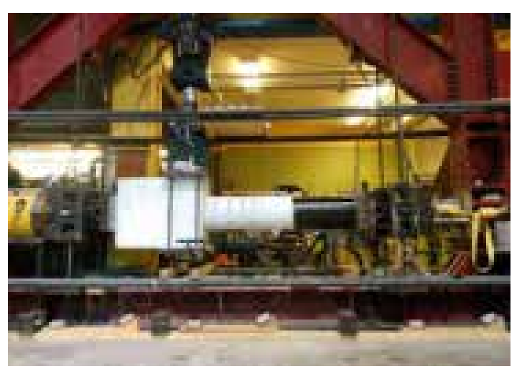

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6. SUMMARY

- In the UT-SIM framework, the implementation of hybrid simulation is generalized such that multi-platform substructure simulation can be readily carried out with commercial or open-source software.
- WCHS has been developed to allow hybrid simulation with an equipment which do not have sufficient number of DOFs.
- Hybrid simulation method is applied to an intact, repaired, and retrofitted RC ordinary moment resisting frames.
- FRP-repaired column was able to restore the structures' performance to the pre-damage response when excited by the same seismic sequence scenario. The structure's performance was not significantly improved with the use of the retrofitted column because the demand on the column did not reach its upgraded performance.
- By employing hybrid simulation, inconsistencies related to the numerical model can be identified and a more realistic performance assessment of the structure can be achieved.

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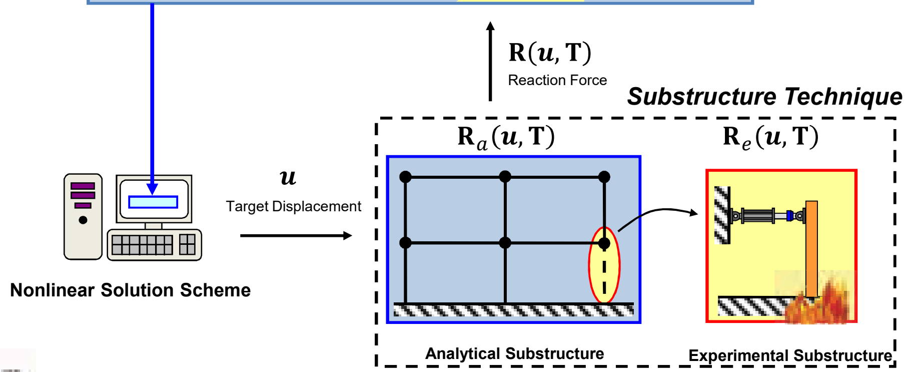
APPLICATIONS TO FIRE AND WIND LOAD

STRUCTURAL PERFORMANCE ASSESSMENT

Hybrid (experimental-numerical) Simulation

Equilibrium Equations

$$\cancel{M\ddot{u}(t)} + \cancel{C\dot{u}(t)} + \mathbf{R}(\boldsymbol{u}, \mathbf{T}) = \mathbf{F}$$



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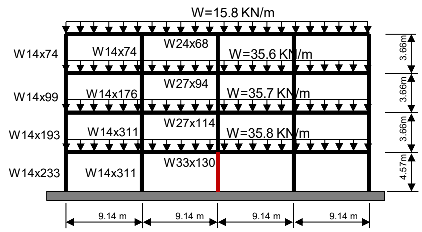
APPLICATIONS TO FIRE AND WIND LOAD

HYBRID FIRE SIMULATION METHOD

- Development of hybrid fire simulation method for columns
- Development of hybrid fire simulation method for beams considering catenary action
- Application of the method for fire performance assessment of steel MRFs and RC MRFs



Wang, X., Kim, R., Kwon, O., and Yeo, I. (2018) "Hybrid Simulation Method for a Structure Subjected to Fire and its Application to a Steel Frame." ASCE Journal of Structural Engineering, 144(8):04018118, DOI:10.1061/(ASCE)ST.1943-541X.0002113
Wang, X., Kim, R., Kwon, O., Yeo, I., Ahn, J. (2019) "Continuous Real-Time Hybrid Simulation Method for Structures Subject to Fire." ASCE Journal of Structural Engineering (accepted on March 29)

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APPLICATIONS TO FIRE AND WIND LOAD

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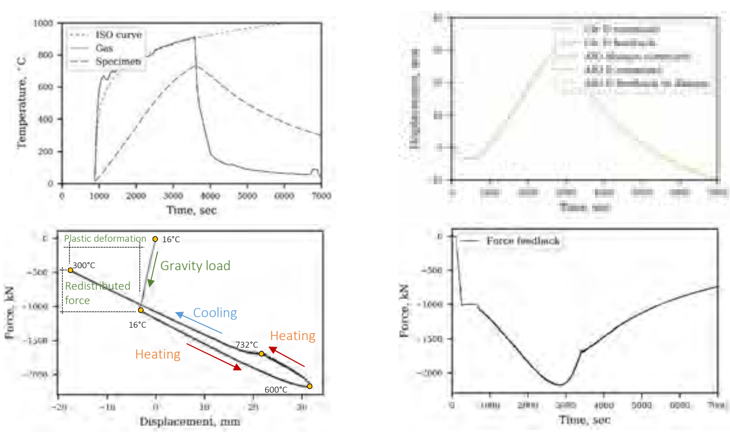

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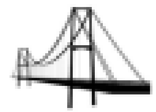
APPLICATIONS TO FIRE AND WIND LOAD

STRUCTURAL PERFORMANCE ASSESSMENT

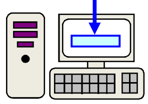
Hybrid (experimental-numerical) Simulation

Equations of Motion

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{F}(t, \mathbf{u}, \dot{\mathbf{u}})$$



External Force



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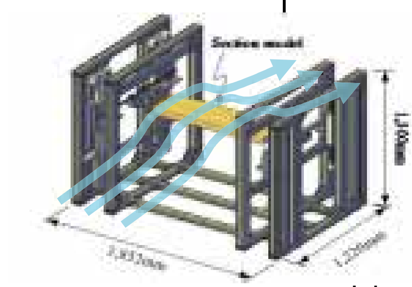
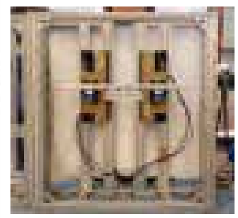
Target Displacement

Numerical Integration Scheme

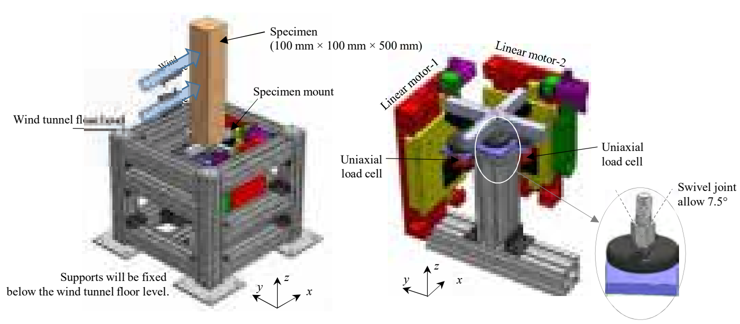




Laboratory Testing

APPLICATIONS TO FIRE AND WIND LOAD

HYBRID WIND SIMULATION METHOD



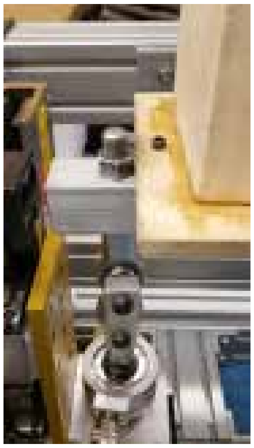
(a) Overview of hybrid simulation apparatus for high-rise building model.

(b) Details

Kwon, O., Kim, H., Jeong, U., Hwang, Y., and Moni, M. (2019) "Design of experimental setup for real-time wind-tunnel hybrid simulation of bridge decks and buildings" ASCE Structures Congress, Orlando, FL, April 24-27.

APPLICATIONS TO FIRE AND WIND LOAD

HYBRID WIND SIMULATION METHOD



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THANK YOU.

Keynote Speaker

Dr. D. Mitchell

A Framework for Performance-Based Seismic Design-

The Canadian Highway Bridge Design Code

A FRAMEWORK FOR PERFORMANCE-BASED SEISMIC DESIGN-THE CANADIAN HIGHWAY BRIDGE DESIGN CODE

By Dr. D. Mitchell, McGill University

Abstract

The Performance-Based Design provisions, first developed in 2014 for the Canadian Standards Association (CSA) Canadian Highway Bridge Design Code and revised in 2019, are discussed. The need to address the importance of the bridge (Importance Category), the use of seismic Performance Categories and the role played by assessing the regularity of bridges are explained. Performance-Based Design is required for the majority of bridges in moderate to high seismic regions. The role of the Seismic Performance Category, the Importance Category and bridge regularity in determining the required analysis methods are described. The Code has target Performance Criteria, together with Damage Indicators to determine if the performance would be satisfied. The challenges in applying Performance-Based Design for the evaluation and retrofit of existing bridges are discussed. Aspects from these bridge seismic design provisions that provide a framework for developing a similar approach for building structures are explored.

Keywords: performance-based design, bridges, seismic design, concrete, capacity design.

Biography

Dr. Denis Mitchell is a James McGill Professor in Civil Engineering at McGill University. He has played a major role in the development of codes of practice. He has chaired technical committees of the Canadian Standard for the Design of Concrete Structures, the Seismic Design Provisions of the Canadian Highway Bridge Design Code and the Design Standards for Nuclear Structures. He has also contributed to the seismic design provisions of the National Building Code of Canada.

A Framework for Performance-Based Seismic Design:
The Canadian Highway Bridge Design Code

Denis Mitchell
McGill University

Joint NRC-MOST Taiwan Workshop

October 7 & 8, 2019 - Ottawa

National Research Council Canada | Conseil national de recherches Canada

MOST 科技部 Ministry of Science and Technology

Performance-Based Design (PBD) Introduced in 2014 CHBDC

- PBD is main design approach
- Multi-hazard levels used for PBD
- Performance Levels provided for important bridges
- Performance criteria based on damage indicators for different hazard levels
- Force-Based Design approach retained for certain cases
- Also applies to evaluation and retrofit of existing bridges
- 2019 CHBDC will provide some updates

Importance Categories

- Lifeline
  - Vital to integrity of transportation network, economy, security
- Major-route
  - bridge on or over a route required to facilitate post-earthquake emergency response, security and defense purposes during recovery
- Other
  - does not fall into the importance categories of Lifeline or Major-route bridges

Three Hazard Levels

S6-14 and S6-19 Hazard provided for:

- 2% probability of exceedance in 50 years (return period of 2475 years)
- 5% probability in 50 years (975 years)
- 10% probability in 50 years (475 years)

Site Classes (NBCC 2015)

Site class	Ground profile name	Average properties in top 30 m: Shear wave average velocity, $\bar{V}_s$ (m/s)	Standard penetration resistance, $\bar{N}_{60}$	Soil undrained shear strength, s_u
A	Hard rock[1,2]	$\bar{V}_s > 1500$	Not applicable	Not applicable
B	Rock[1]	$760 < \bar{V}_s \leq 1500$	Not applicable	Not applicable
C	Very dense soil and soft rock	$360 < \bar{V}_s < 760$	$\bar{N}_{60} > 50$	$s_u > 100$ kPa
D	Stiff soil	$180 < \bar{V}_s < 360$	$15 \leq \bar{N}_{60} \leq 50$	$50 < s_u \leq 100$ kPa
E	Soft soil	$\bar{V}_s < 180$	$\bar{N}_{60} < 15$	$s_u < 50$ kPa
		Any profile with more than 3 m of soil with the following characteristics: • Plastic index PI > 20; • Moisture content w ≥ 40%; and • Undrained shear strength s_u < 25 kPa		
F	Other soil[3]	Site specific evaluation required		

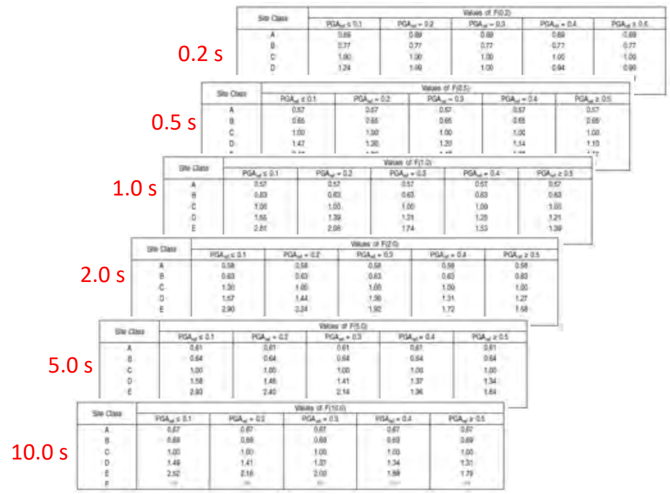
Foundation Factors, F(T)

- Foundation factors F(T) given as a function of period (T), Site Class and peak ground acceleration (PGA)
- $S_a(T)$ = 5% damped spectral response acceleration, expressed as a ratio to gravitational acceleration, for a period of T
- $S(T)$ = design spectral response acceleration, expressed as a ratio to gravitational acceleration, for the fundamental period of T

Foundation Factors,
F(T) for T = 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0s

Function of:

- Reference peak ground acceleration
- Site Class



Design Spectral Acceleration

For T $\leq$ 0.2 sec: S(T) = F(0.2)S_a(0.2) or F(0.5) S_a(0.5)
Whichever larger

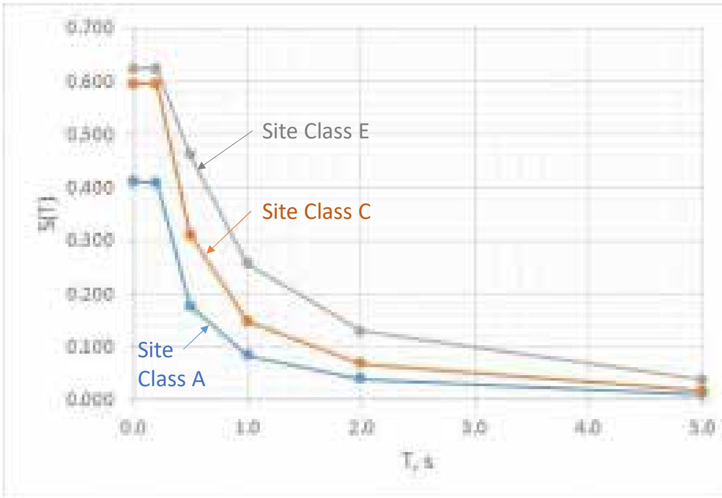
For T = 0.5 sec: S(T) = F(0.5) S_a(0.5)

For T = 1.0 sec: S(T) = F(1.0) S_a(1.0)

For T = 2.0 sec: S(T) = F(2.0) S_a(2.0)

For T = 5.0 sec: S(T) = F(5.0) S_a(5.0)

For T $\geq$ 10.0 sec: S(T) = F(10.0) S_a(10.0)



Montreal Design Spectrum

5% damping
2475 – year
Return period

Note: Based on the 2015 NBCC
Changes will be made to 2020 NBCC

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Seismic Performance Category (SPC)

Table 4.10
Seismic performance category based on 2% in 50 year exceedance spectral values
(See Clause 4.10.3.)

		Seismic performance category	
For $T < 0.5$ s	**For $T \geq 0.5$ s**	**Lifeline bridges**	**Major-route and other bridges**
$S(0.2) < 0.20$	$S(1.0) < 0.10$	1	1
$0.2 \leq S(0.2) < 0.35$	$0.10 \leq S(1.0) < 0.30$	3	2
$S(0.2) \geq 0.35$	$S(1.0) \geq 0.30$	3	3

Note 1: For lifeline bridges in SPC 1, detailing of structural elements shall adopt requirements for SPC 2 as a minimum.

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Minimum Design Requirements: PBD or FBD?

Seismic performance category	Lifeline bridges		Major-route bridges		Other bridges	
	Irregular	**Regular**	**Irregular**	**Regular**	**Irregular**	**Regular**
1	No seismic analysis required					
2	PBD	PBD	PBD	FBD	FBD	FBD
3	PBD	PBD	PBD	PBD	PBD	FBD

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Types of Analysis

- ESA = Elastic Static Analysis including Uniform-Load method (UL) or single-mode Spectral Method (SM).
- EDA = Elastic Dynamic Analysis
- ISPA = Inelastic Static Push-over Analysis.
- NTHA = Nonlinear Time-History Analysis.

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Minimum Seismic Analysis Requirements

Seismic performance category	Lifeline bridges		Major route bridges		Other bridges	
	Irregular	Regular	Irregular	Regular	Irregular	Regular
1	No seismic analysis required					
2	EDA, ISPA, and NTHA	EDA and ISPA	EDA and ISPA	ESA	EDA	ESA
3	EDA, ISPA, and NTHA	EDA and ISPA	EDA and ISPA	EDA and ISPA	EDA and ISPA	ESA

Regular Bridge Requirements

	Number of spans				
	≤2	3	4	5	6
Maximum skew angle	20°	20°	20°	20°	20°
Maximum subtended angle (curved bridge)	30°	30°	30°	30°	30°
Maximum span length ratio for adjacent spans	3	2	2	1.5	1.5
Maximum bent or pier stiffness ratio from span to span (excluding abutments)					
Continuous superstructure or multiple simple spans with longitudinal restrainers and transverse restraint at each support or a continuous deck slab	—	4	4	3	2
Multiple simple spans without restrainers or a continuous deck slab	—	1.25	1.25	1.25	1.25

Minimum Performance Levels

Seismic ground motion probability of exceedance in 50 years (return period)	Lifeline bridges		Major-route bridges		Other bridges	
	Service	Damage	Service	Damage	Service	Damage
10% (475 years)	—	—	Immediate	Minimal	Service limited	Repairable
5% (975 years)	Immediate	Minimal	—	—	—	—
2% (2475 years)	Service limited	Repairable	Service disruption	Extensive	Life safety	Probable replacement

Performance Criteria - Damage Indicators

Immediate Service: Bridge will be fully serviceable; repair work shall not cause service disruption.

- **Minimal Damage**: Essentially elastic (minor damage)
- Concrete Structures: Concrete compressive strains shall not exceed 0.006 and reinforcing steel strains shall not exceed 0.010

Minimal Damage – Cover Spalling

Initial localized spalling can start at a strain of 0.004 in columns with little confinement

Strain limited to 0.006 in well-confined columns

Lehman and Moehle, 2000 “Seismic Performance of Well-Confined Concrete Bridge Columns”, PEER Repost 1998/01.

Performance Criteria - Damage Indicators

Limited Service: Usable for emergency traffic; repairable without closure; at least half lanes operational; normal service within a month.

- **Repairable Damage**: Some inelastic behaviour and moderate damage may occur. However, primary members need not be replaced, may be repaired in place; capable of carrying dead + live load.
- Concrete Structures: Tensile steel strains ≤ 0.025

Performance Criteria - Damage Indicators

Service Disruption: Usable for restricted emergency traffic; repairable; repairs to restore full service my require closure.

- **Extensive Damage:** Inelastic behaviour is expected. Members may have extensive damage but strength decay shall not occur. Members shall be capable of supporting dead + 50% live load, excluding impact, but including P-delta effects.
- Concrete Structures: concrete spalling is permitted but the confined core concrete shall not exceed 80% of its ultimate confined strain limit. Reinforcing steel tensile strains shall not exceed 0.05.

Extensive Damage – Bar Buckling

The tensile strain limit of 0.05 in the longitudinal reinforcing bars represents the tensile strain prior to the onset of bar buckling.

Priestley, Calvi and Kowalsky, 2007
"Direct Displacement-Based Seismic Design of Structures", Pavia, IUSS Press.

Goodnight, Feng, Kowalsky and Nau, 2012, The effects of load history and design variables on performance limit states of circular bridge columns", Alaska DOT.