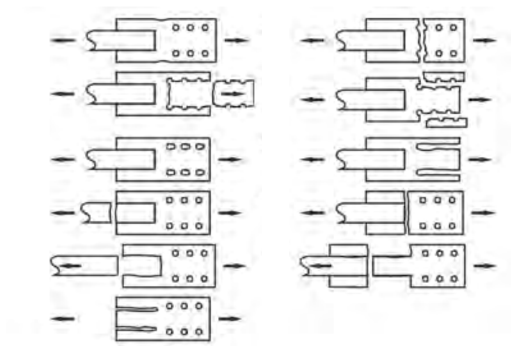
Plastic deformation capacity of connections in tension

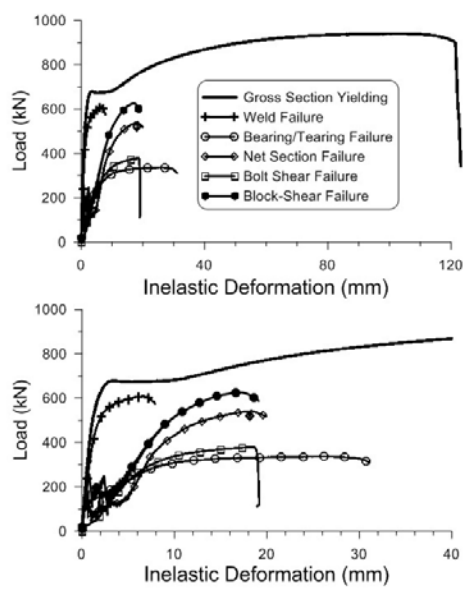
Strength of connections well characterized for most potential failure modes

- **Bolts in shear**
- **Plate yielding**
- **Rupture on net section including shear lag effects**
- **Block-shear failure**
- **Bolt bearing**
- **…**

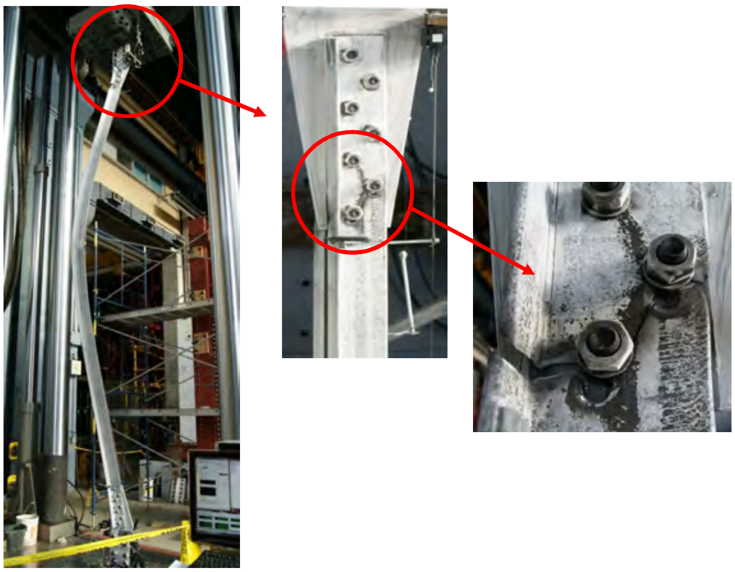


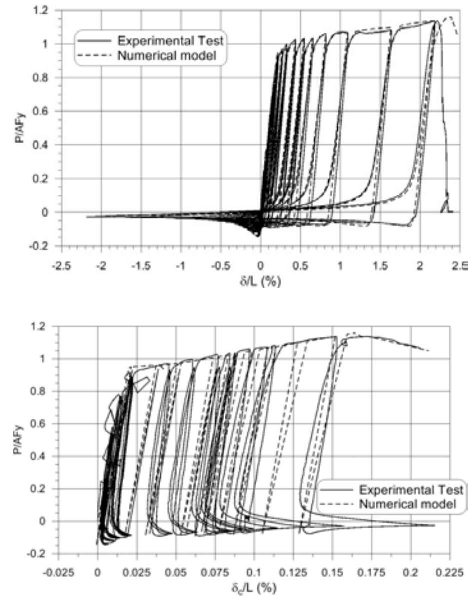
Plastic deformation capacity has not been well documented

Plastic deformation capacity depends on failure mode:

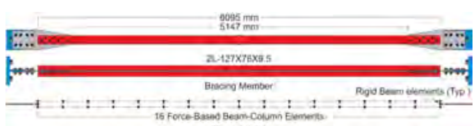


Cyclic test on double-angle braces with connections expected to fail by rupture on net section:

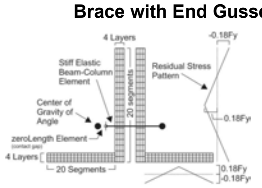




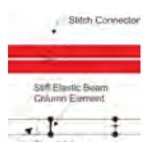
Nonlinear evaluation procedure with explicit consideration of brace connection inelastic response



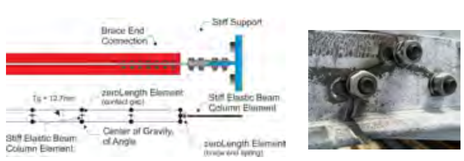
Brace with End Gusset Plate Connections



Fiber Cross-Section

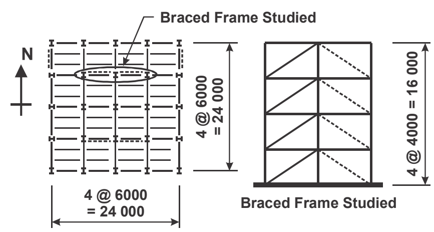


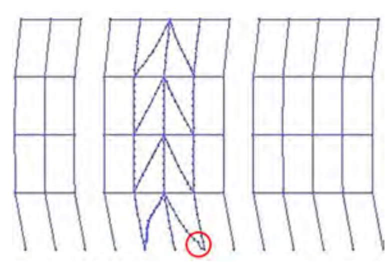
Stitch Connector



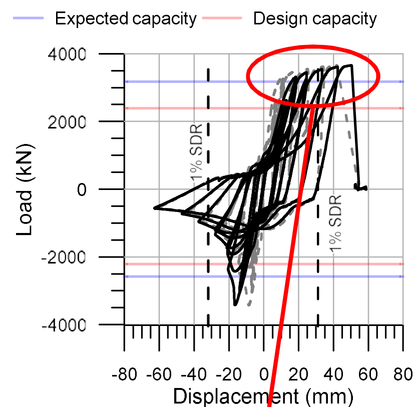
End Connection Model

Analyses indicate that connection failure is likely and may lead to structure collapse



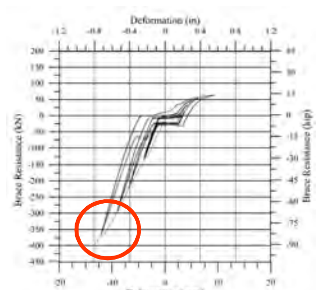


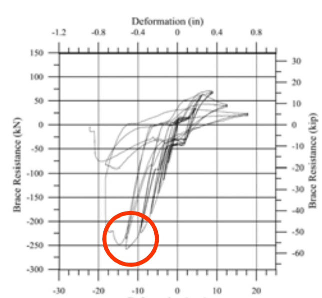
Recent research: Well balanced bolted connections can develop substantial plastic deformation capacity through multiple modes (bearing, tension yielding, bolt shear, ...)



Δ_c = 7.0 mm
δ_{max}/Δ_c = 7.1 !!

Specimens taken from existing (1960's) structures:





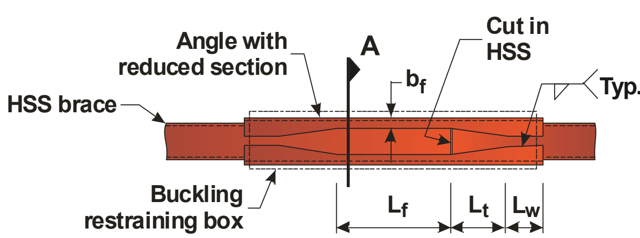
Possible situations:

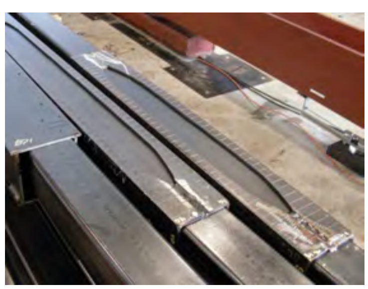
- *Brace connections may not be able to resist tension force demands*
- *Plastic deformation capacity is variable (detailing, material) and is generally limited*
- *Connection failure can have major consequences*

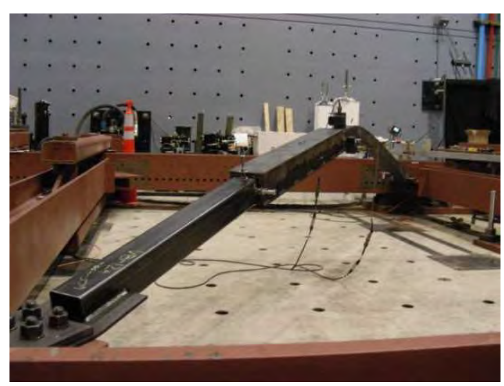
Possible retrofit schemes:

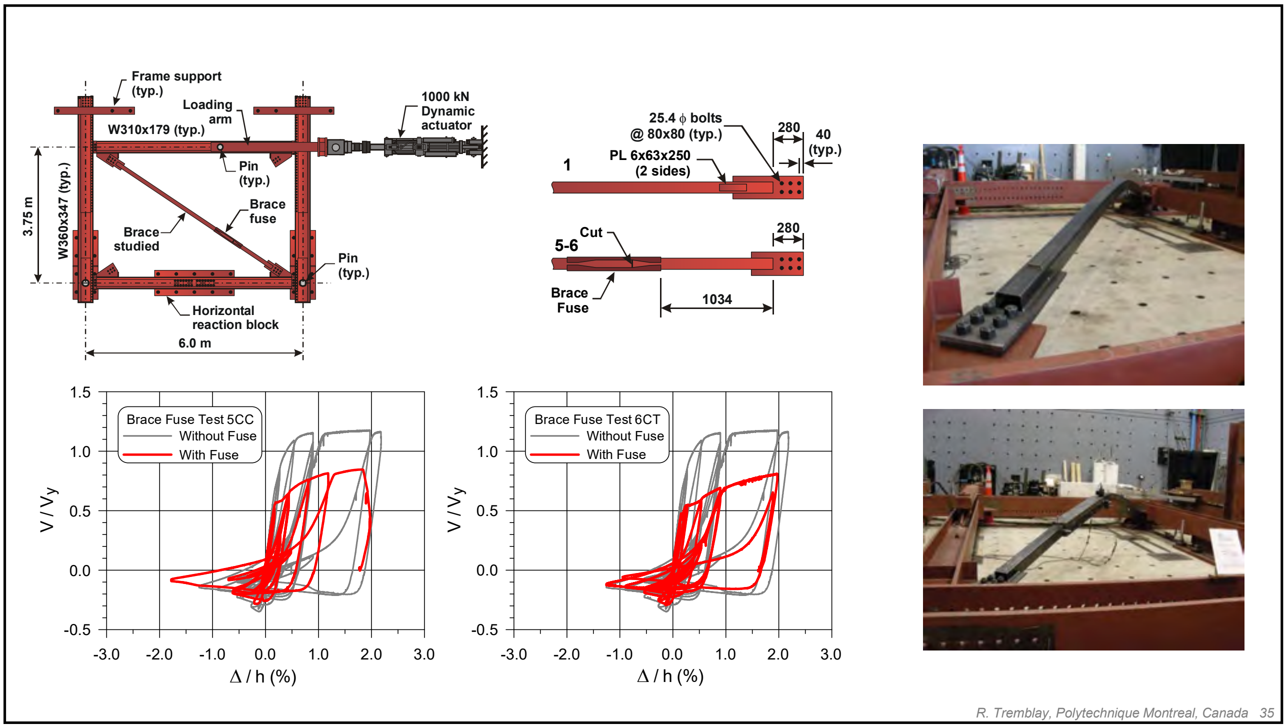
- *Increase connection strength, but this may have detrimental impacts on other SFRS components*
- *Use brace fuses to reduce tension force demands*

Possible Fuse Design for HSS Braces








Frame support (typ.)
Loading arm
W310x179 (typ.)
1000 kN Dynamic actuator
Pin (typ.)
Brace fuse
Brace studied
W360x347 (typ.)
3.75 m
Pin (typ.)
Horizontal reaction block
6.0 m
25.4 ϕ bolts @ 80x80 (typ.)
PL 6x63x250 (2 sides)
280
40 (typ.)
1
5-6
Cut
280
Brace Fuse
1034
Brace Fuse Test 5CC
Without Fuse
With Fuse
V / Vy
Δ / h (%)
Brace Fuse Test 6CT
Without Fuse
With Fuse
V / Vy
Δ / h (%)
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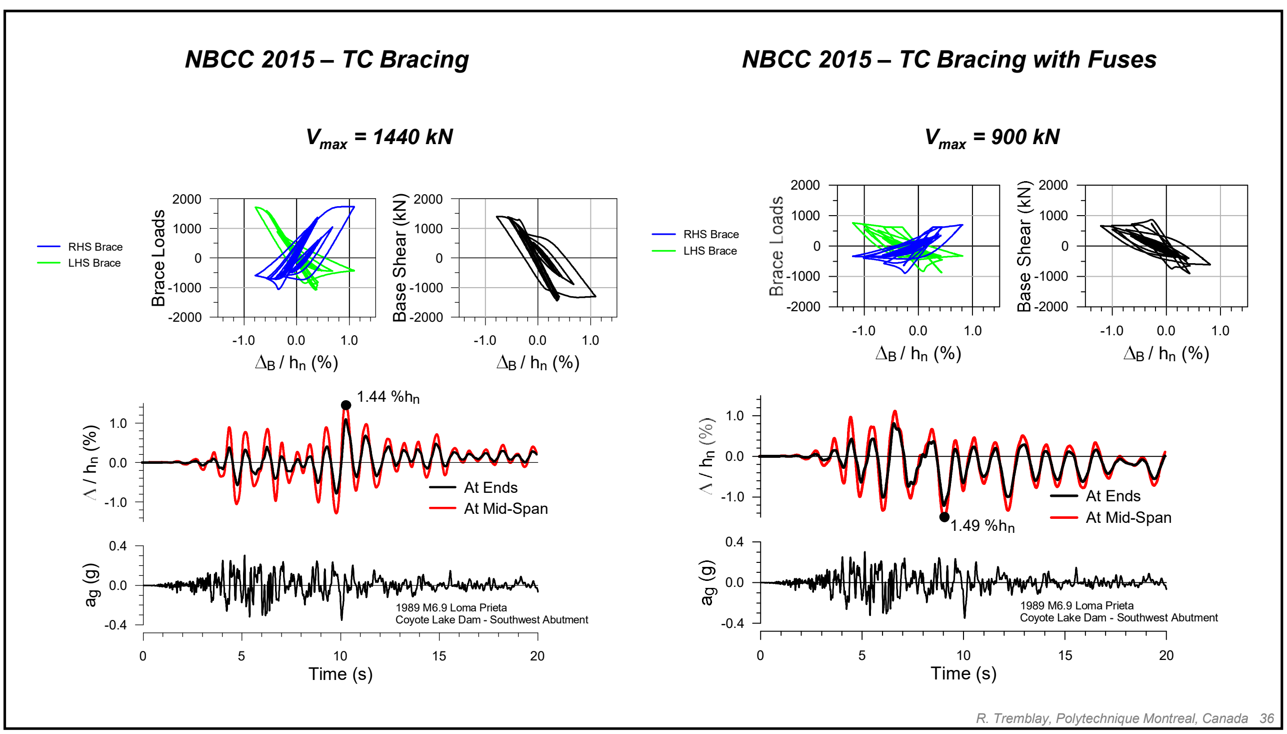
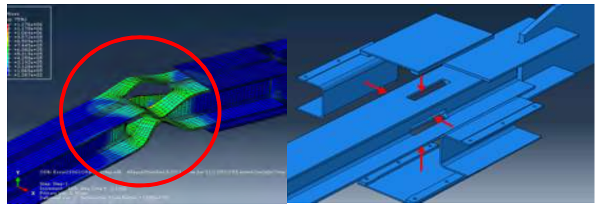
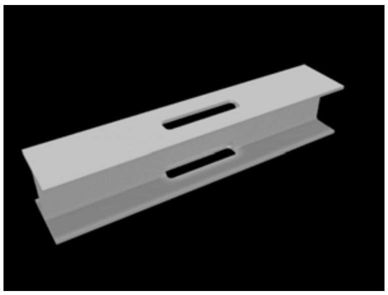
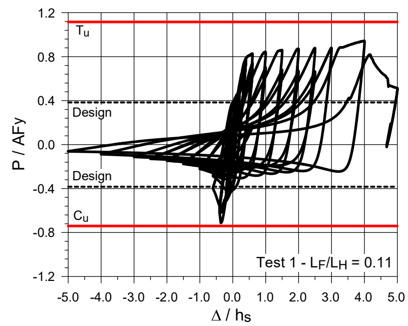

NBCC 2015 – TC Bracing
NBCC 2015 – TC Bracing with Fuses
Vmax = 1440 kN
Vmax = 900 kN
RHS Brace
LHS Brace
Brace Loads
Base Shear (kN)
ΔB / hn (%)
1.44 %hn
Δ / hn (%)
At Ends
At Mid-Span
1.49 %hn
ag (g)
1989 M6.9 Loma Prieta
Coyote Lake Dam - Southwest Abutment
Time (s)
R. Tremblay, Polytechnique Montreal, Canada 36

Possible Fuse Design for W Braces







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Stability of connections in compression?

Practice in Canada:

Braces with lap-splice bolted connections

Double Shear Lap Splice Connections

Single Shear Lap Splice Connections

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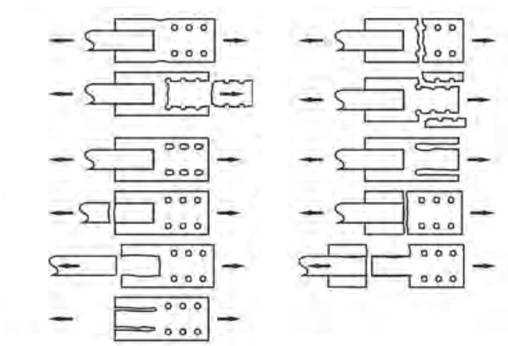
Connections designed to meet ultimate limit states under <u>tension</u> brace forces:

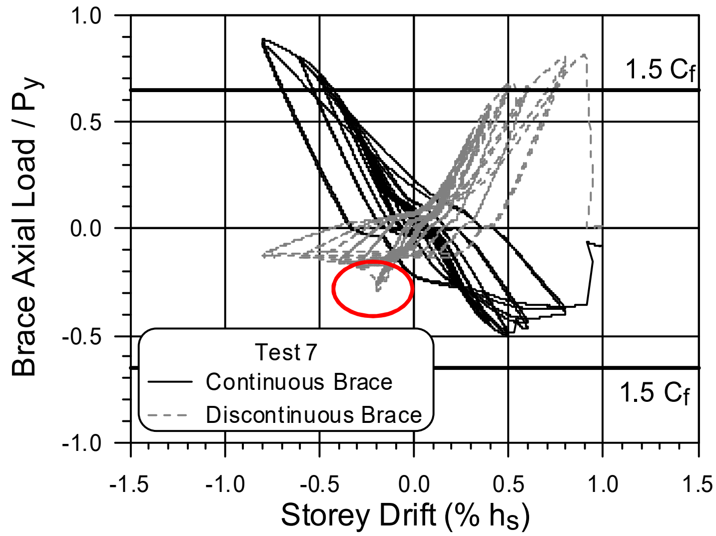
- **Bolts in shear**
- **Plate yielding**
- **Plate net section rupture including shear lag effects**
- **Block-shear failure**
- **Bolt bearing**
- **…**



Limited (no?) provisions for the design of connections for <u>compression</u>

HSS 127x127x8.0 – Single Shear Connections

Fracture of plate due to low-cycle fatigue



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HSS 102x102x6.4 - Double Shear Connections

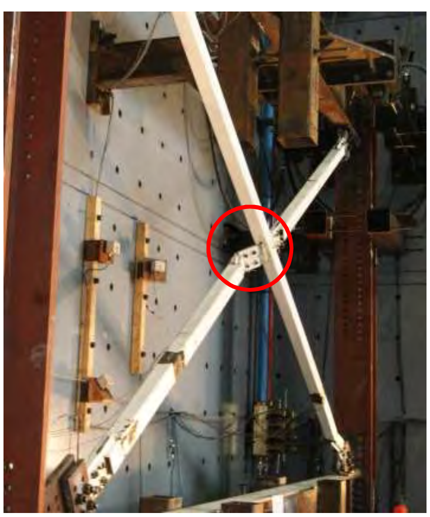

Plate buckling

Rupture of HSS

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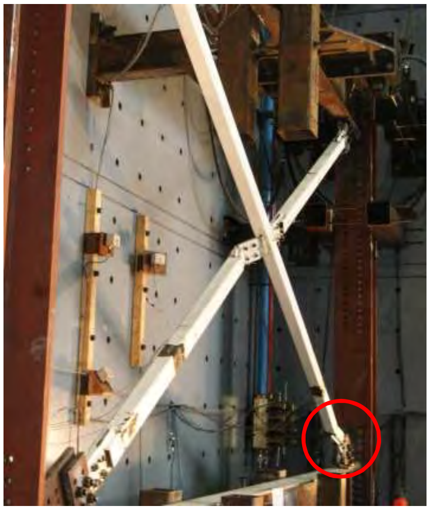


Plate buckling

Rupture of HSS

Double angle braces

2L 127x75x9.5

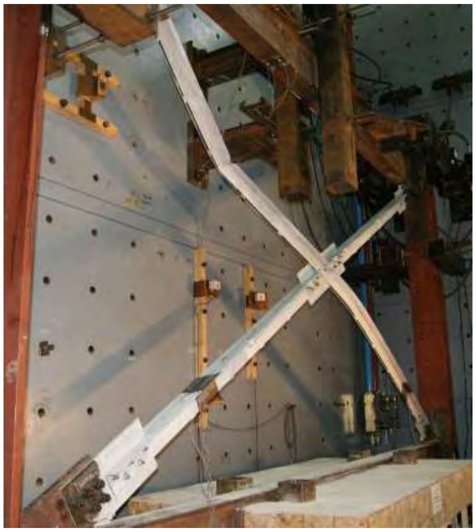


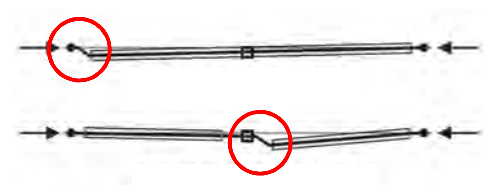
Plate buckling and low-cycle fatigue failure

Instability and low-cycle failures of brace connections observed in past earthquakes

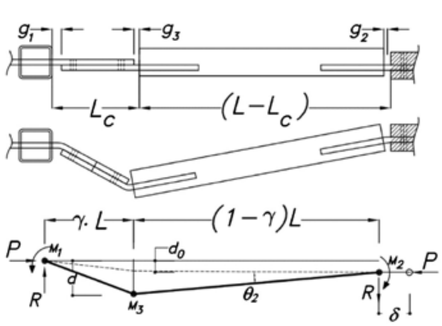
2011 Tohoku Earthquake
http://www.eqclearinghouse.org/2011-03-11-sendai/2011/08/03/eeri-steel-structures-reconnaissance-group/

2011 Tohoku Earthquake
http://www.eqclearinghouse.org/2011-03-11-sendai/2011/08/03/eeri-steel-structures-reconnaissance-group/

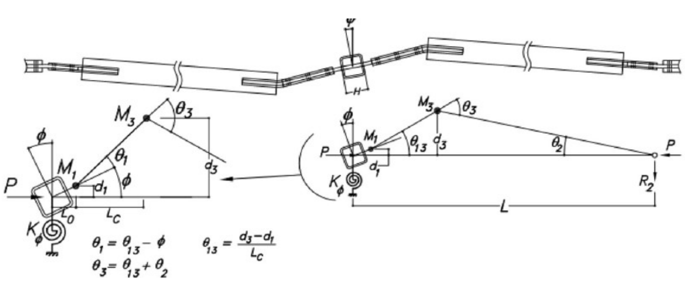
- ***Instability of brace connections should be prevented as it reduces the brace strength and may lead to low-cycle failure***
- ***Methods needed for design and evaluation (in progress)***



Single Shear Connections



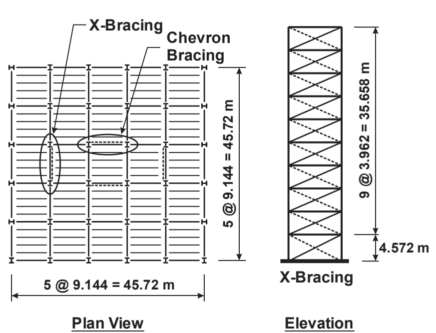
Double Shear Connections



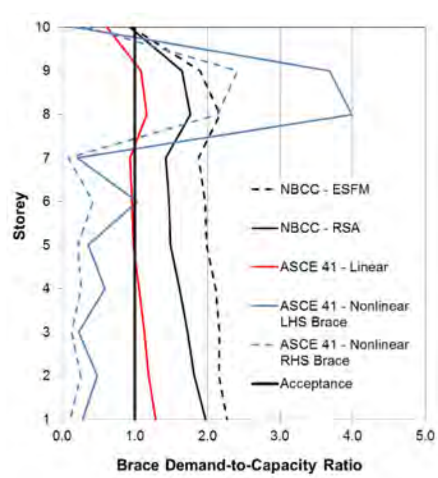
Plan

- Context
- Bracing members
- Brace Connections
- **Multi-Storey Braced Frames**
- Metal Roof Deck Diaphragms
- Conclusions

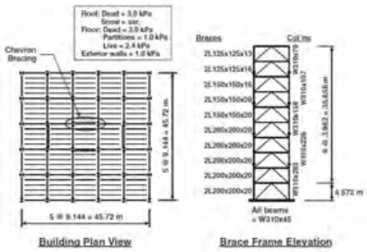
Linear procedure not appropriate for capturing concentration of inelastic deformations along the frame height



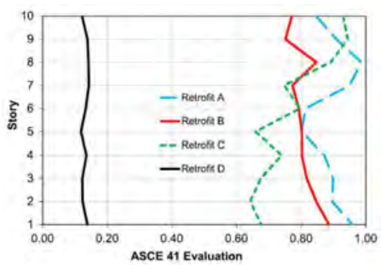
- collapse prevention
- 2% in 50 years earthquakes



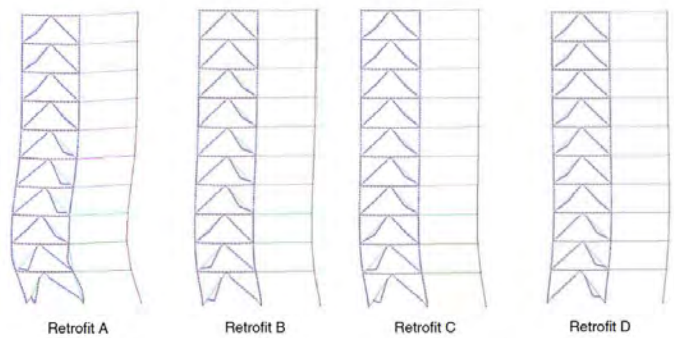
Linear procedure may also result in inadequate seismic retrofit design



Assessment of retrofitted braces using <u>linear procedure</u>



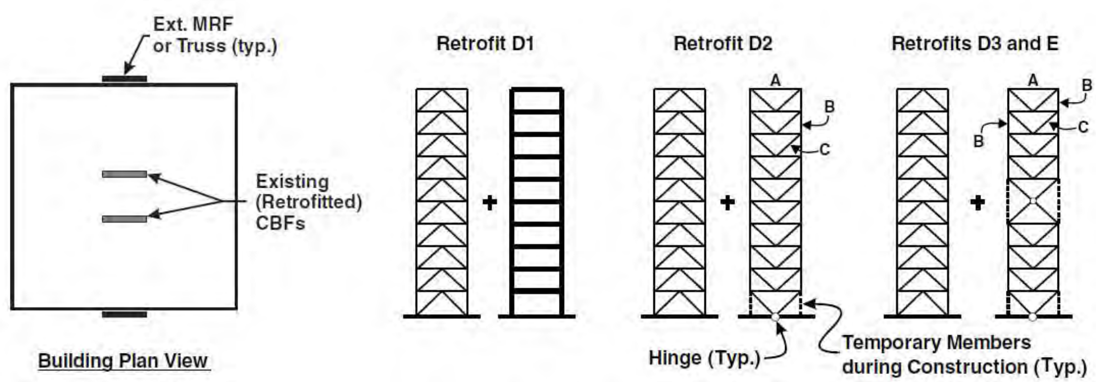
Validation of brace retrofits using <u>nonlinear procedure</u>



Collapse under 50% EQs

Collapse under 30% EQs

Final retrofit strategy included elastic vertical frames along the building sides to mitigate soft-storey response

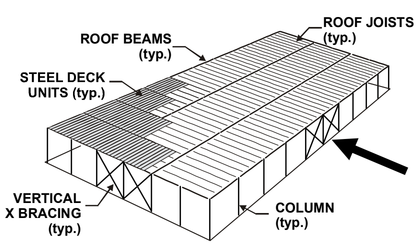


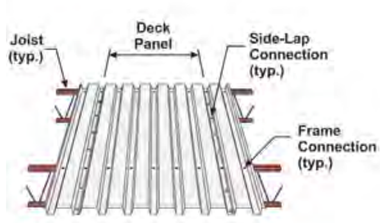
This scheme can provide for temporary lateral bracing during the retrofit of the existing braced frames and allowed keeping the existing braced frame foundations without strengthening

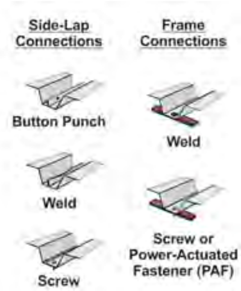
Plan

- Context
- Bracing members
- Brace Connections
- Multi-Storey Braced Frames
- **Metal Roof Deck Diaphragms**
- Conclusions

Roof diaphragms built with steel deck panels

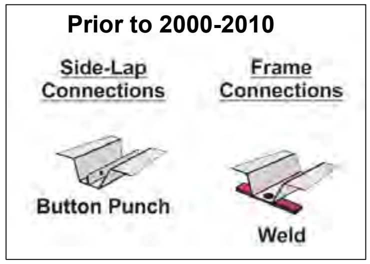






Situation:

- **Design provisions and quality control implemented only in the 1980's**



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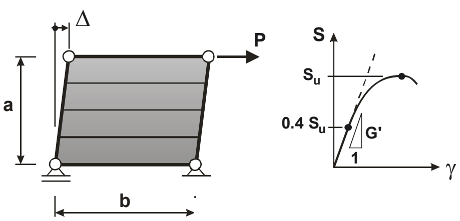
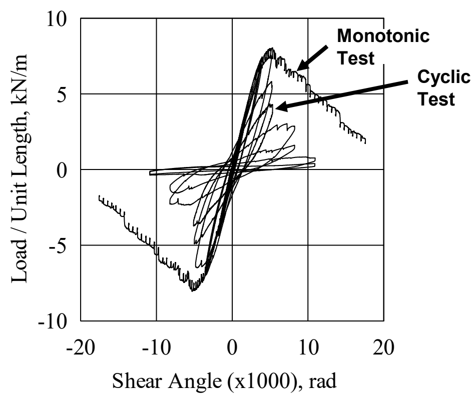
Cantilever Diaphragm Shear Test





Slip & disengagement of the button punches and brittle weld failure

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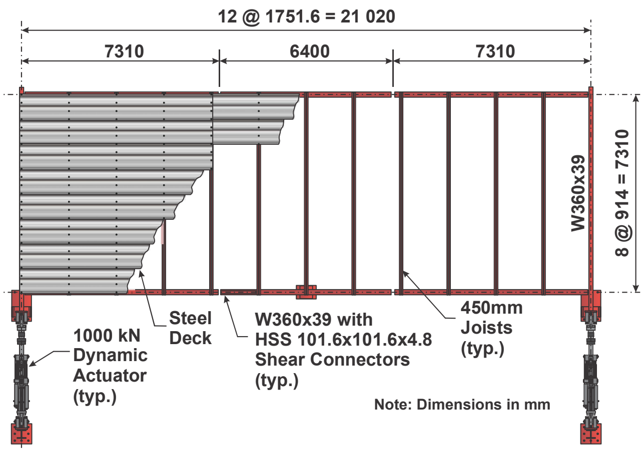
Dynamic Seismic Tests



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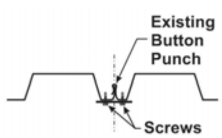
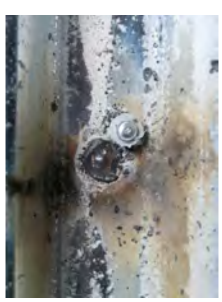
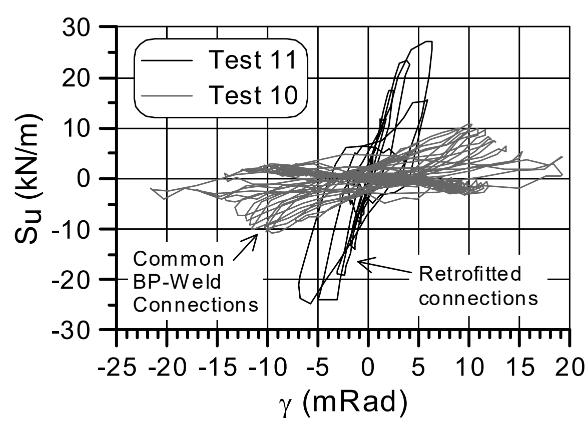
Possible Retrofit Scheme







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Conclusions

- Existing steel BFs in Canada may present several deficiencies related to lateral strength, brace ductility, brace connections, concentration of inelastic deformations in multi-storey buildings, and steel deck diaphragms
- Force-based method may not be appropriate to reliably identify, assess, and address these deficiencies
- ASCE 41 is a useful tool for evaluation and retrofit, but adjustments are needed for Canadian construction practice, including criteria for large HSS braces, bolted brace connections, sensitivity to inelastic deformation concentration, and steel deck diaphragms

Acknowledgements

- Graduate Students
- Technical staff in laboratories
- Funding from CEISCE and NSERC (NSERC Canadian Seismic Research Network

RETROFITTING NON-DUCTILE RC STRUCTURES FOR SEISMIC RESISTANCE USING POST-INSTALLED WING WALL, SHEAR WALL AND RC JACKET

By Dr. W.-I Liao, National Taipei University of Technology

Abstract

Reinforced Concrete (RC) frame structures that were designed and built according to older standards can be damaged during destructive earthquakes as a result of insufficient lateral strength and/or deformation capacity. Such structures must be retrofitted to satisfy the current requirements and to survive future earthquakes. In this study, three cost effectively and general used retrofit methods in Taiwan, i.e., the post-installed RC wing wall, post-installed RC shear wall and RC jacket, are introduced. Procedures for detailed retrofit design, construction method, and encountered problems in engineering practical are presented. In addition, the connected construction method for RC structure with low strength concrete is provided. The test results indicate that the adopted retrofitting methods can effectively improve the seismic performance and lateral strength of the non-ductile RC structures.

Keywords: reinforced concrete, seismic resistance, retrofit, wing wall, RC shear wall, RC jacket

Biography

Dr. Wen-I Liao received his Ph.D. degree (1997) in Civil Engineering at National Taiwan University. Since 2007, he is a Professor at National Taipei University of Technology. Currently, he is the Chair of Department of Civil Engineering. His present research interests include structural health monitoring, application of piezoelectric sensors to stress measurement, and seismic evaluation and retrofit of concrete structures.

RETROFITTING NON-DUCTILE RC STRUCTURES FOR SEISMIC RESISTANCE USING POST-INSTALLED WING WALL, SHEAR WALL AND RC JACKET

Wen-I Liao and S.Y. Chang
National Taipei University of Technology

F.P. Hsiao
National Center for Research on Earthquake Engineering

Joint NRC-Taiwan workshop on Earthquake Engineering
October 7-10, 2019, Ottawa, Canada

Outline

- Retrofit of RC structure using Wing Wall
- Retrofit using RC Jacket
- Post installed RC wall for retrofit of structure with low strength concrete and the connection detail on interface
- Retrofit of short column
- Concluding Remarks

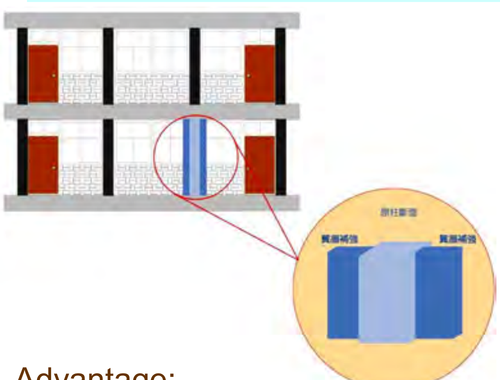
Seismic Retrofit

Wing wall

Reinforced concrete jacketing

Shear wall

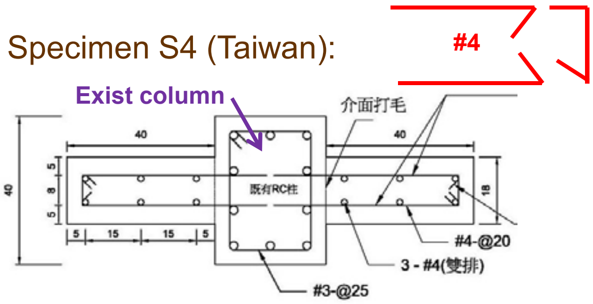
Retrofit using post installed RC wing wall



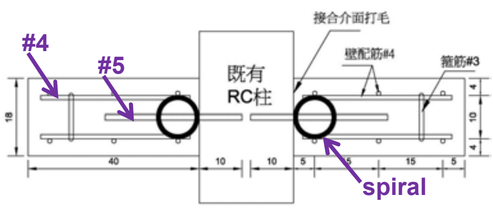
Advantage:
Does not affect corridor space
Disadvantage :
Affect the ventilation and lighting function
Not suitable for low strength concrete structure

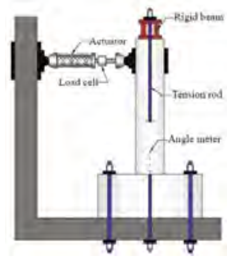
Test of retrofit using RC wing wall

Specimen S4 (Taiwan):



Specimen S5 (Japan):



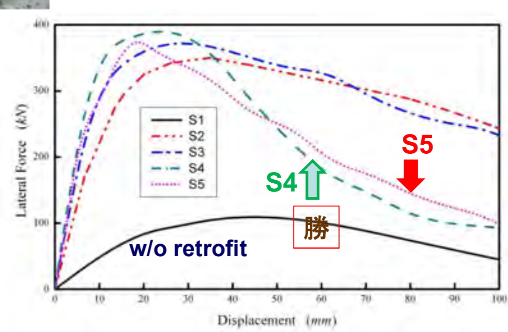


Reference: S.Y.Chang, W.I. Liao，2010，既有RC建築物修復補強工法之性能試驗研究期末報告書，ABRI。

Test results of retrofit using RC wing wall

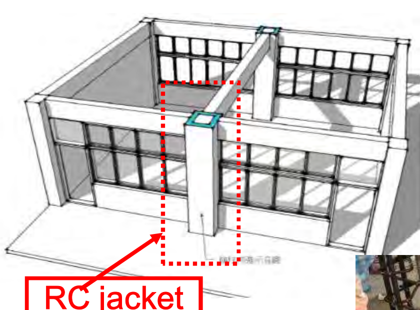
Failure status
S5 (Japan)

Failure status
S4 (Taiwan)



Practical construction procedure of RC wing wall

Retrofit using RC jacket



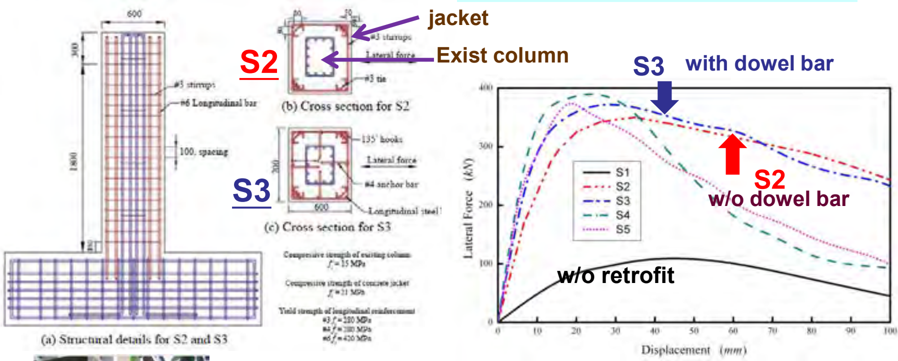
Advantage:

Does not affect the ventilation and lighting function Increase two-direction capacity

Disadvantage :

affect corridor space

Test of retrofit using RC jacket



Reference: S.Y.Chang, W.I. Liao，2010，既有RC建築物修復補強工法之性能試驗研究期末報告書，ABRI。

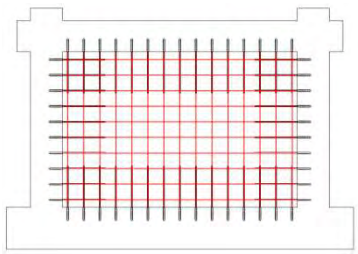
Practical construction procedure of RC jacket

Construction procedure of RC jacket (cont')

Post installed RC wall for retrofit of structure with low strength concrete and the connection method on interface

Retrofit using RC shear wall

- RC wall => high lateral strength and stiffness capacity
- Post-installed RC wall=>widely used technique for non-ductile structure.
- Old RC building => low-strength poor concrete
- **Typically used connected construction method on the interface between existing and new concrete may be not able to provide effective force transfer mechanism.**
- May cause unexpected interface failure in the retrofitted structure.



Research background (1)

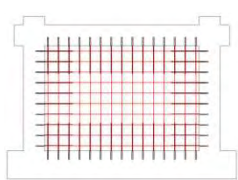
Recent studies have completed a test for post-casted RC wall into frame with traditional interface connected method.

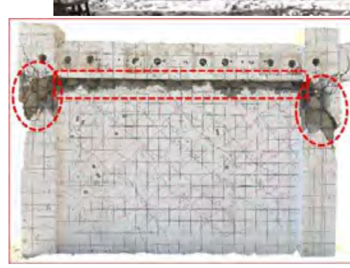
Anchored rebars on interface = rebars of wall panel

⇒ Failure occur on the interface

The sequences of failure:

1. Interface failed in shear friction failure.
2. Load flow to the edge of upper-column.
3. The column top (short column) failed in shear.

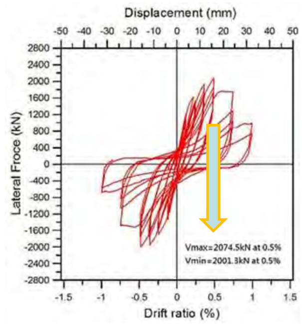




Research background (2)

.shear friction failure on interface

.force concentrate at column top



An Ho(安和) elementary school:

Damaged in the 1999/921 earthquake => retrofit by RC wall
retrofit RC wall damaged again at 2002/331 earthquake

Research purpose

★ To provide effective interface connected methods and construction details for low concrete strength structure.

Three specimens have been tested in this study.

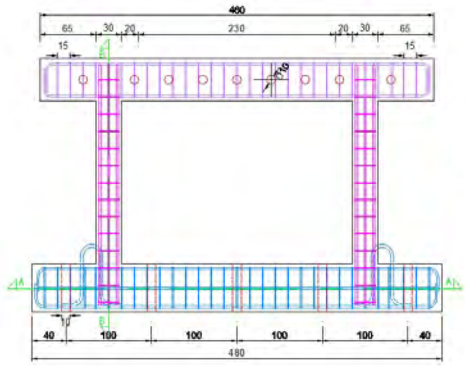
(1) Pure RC frame

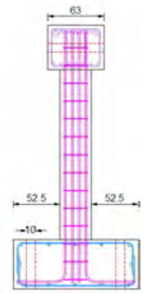
(2) Frame with post-installed RC wall

(3) Frame with post-installed RC wall (with opening)

=> Expect to achieve design goal after improvement; and effectively improve the seismic resistance capacity.

Specimens design (pure frame)





Column : 30x35 cm
Beam : 63x50 cm
fc' = 14 Mpa for exist structure, and 28 Mpa for wall.
Yielding strength of rebar = 280 Mpa.

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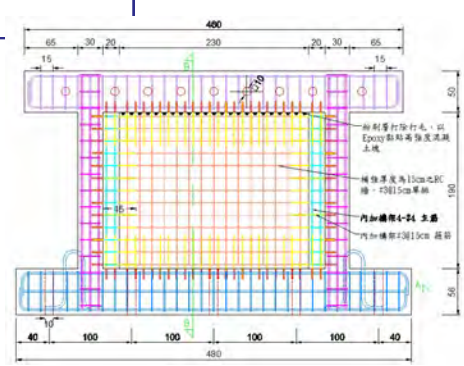
Specimens design (frame + RC wall)

1.The wall anchorage rebars amounts (#4@10cm) are higher than wall panel reinforcements (#3@15cm).

$V_f > V_s + V_c$

2. Adhesive mortar block on interface.

3. Adding inner frame column.



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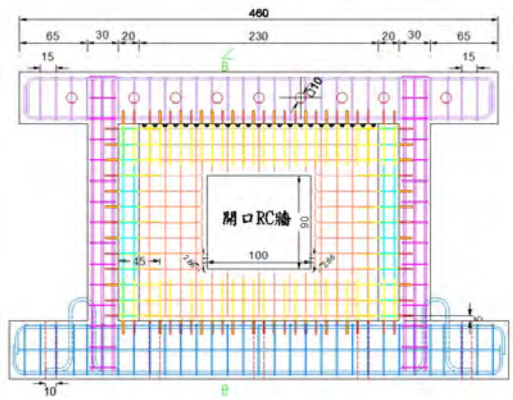
Specimens design (frame + opening RC wall)



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Construction of specimens (1)

(1) Foundation base

(2) Holes for HSB

(3) Foundation reinforcement

(4) Column rebar andstrain gauge marker

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Construction of specimens (2)

(5) Column main rebar anchored to foundation

(6) Foundation formwork

(7) Pouring fresh concrete for foundation

(8) Column stirrup binding

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Construction of specimens (3)

(9) Beam reinforcement

(10) Beam and column formworks

(11) Pouring concrete for beam and column

(12) Remove frameworks, frames completion

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Construction of specimens (4)

(13) RC frame at 28 days and
Roughen the surface

(14) Drill holes with 10 db depth
and rebar anchoring

(15-a) Making cement mortal blocks

(15-b) Attaching cement mortal blocks

Construction of specimens (5)

(16) Internal frame reinforcement and binding

(17-a) S2 wall reinforcement and attaching ribs

(17-b) S3 wall reinforcement and attaching ribs

(18-a) Wall formwork closure

Construction of specimens (6)

(18-b) Fresh concrete channel holes

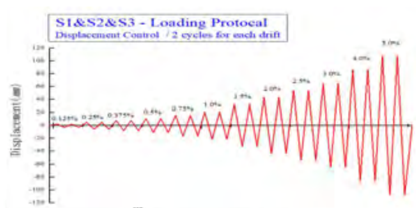
(19) Pouring fresh concrete for wall

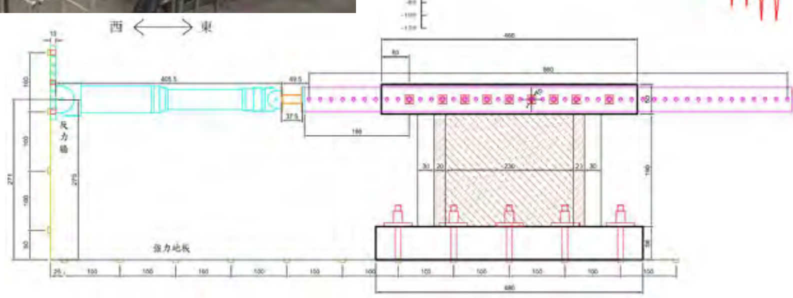
(20-a) Remove frameworks and channel holes, S2 frames completion

(20-b) Remove frameworks and channel holes, S3 frames completion

Test setup

Reversed cyclic loading test was conducted with increment drift at every step until failure





Experimental Results (Pure frame)

S1	Inter-story displacement ratio (drift ratio)	
	0.5%	2.0%
Crack propagation documentations		
Status overview	The flexural cracks at the top and bottom of the column are gradually increase; some of the flexural cracks gradually turn into shear cracks; and the maximum crack width is 0.5 mm.	The shear cracks at the top and bottom of the column appear rapidly. The maximum crack width is about 3 mm in the column. At this drift, the maximum lateral force is reached and the overall lateral stiffness begins to gradually decrease.

Experimental Results (PF + Wall)

S2	Inter-story displacement ratio (drift ratio)	
	0.5%	1.5%
Crack propagation documentations		
Status overview	The shear crack of the wall spreads to the top and bottom of the column. The flexural crack in the end of the column continues to increase. The maximum shear crack width is 4 mm in the diagonal direction of the wall panel.	The shear cracks of the wall continue to enlarged; spalling of concrete; slightly buckling of. At this drift, the lateral force dropped to about 30% of the maximum and the test is stopped.

Experimental Results (PF + Wall with opening)

S3	Inter-story displacement ratio (drift ratio)	
	0.5%	1.0%
Crack propagation documentations		
Status overview	The shear cracks of the section on both sides of the opening gradually increase and spread to the column boundary. The maximum shear crack width is 6 mm at the corner of the wall.	The shear cracks at the corners of the wall continue to enlarge; the concrete is cracked and spalled. At this drift, the lateral force strength dropped to about 60% of the maximum and the test is stopped.

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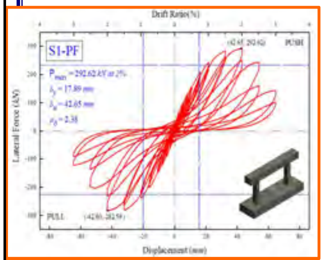
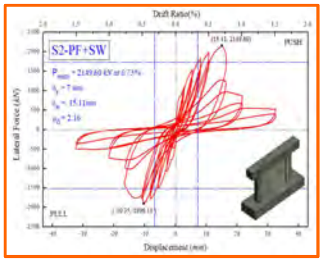
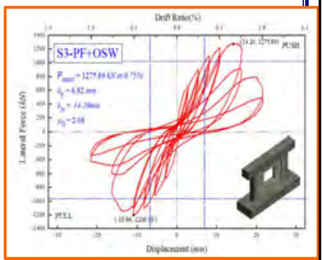
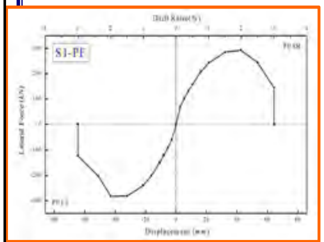
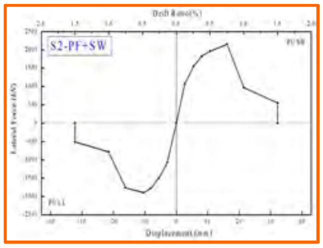
Force-Displacement hysteresis curves

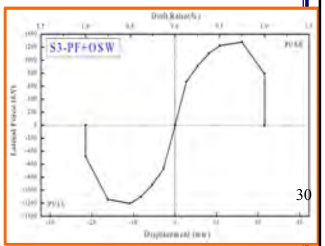












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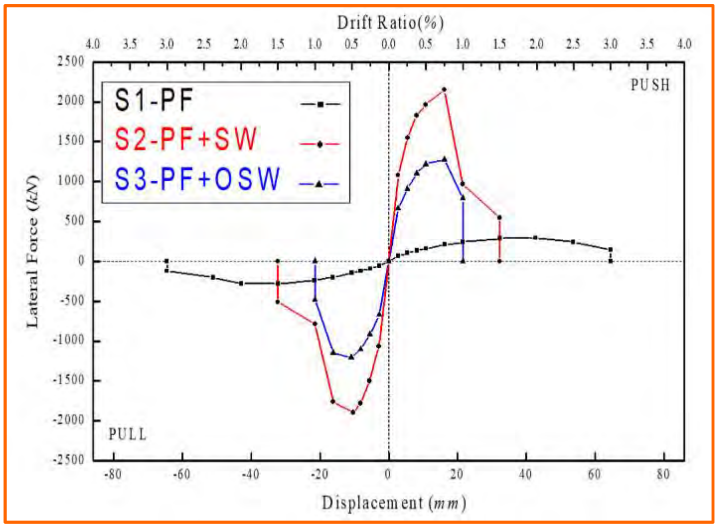
Force-Displacement hysteresis curves



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Short Column Effect (caused by infill wall)

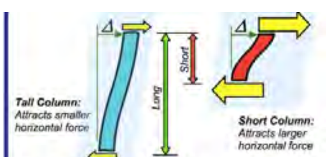
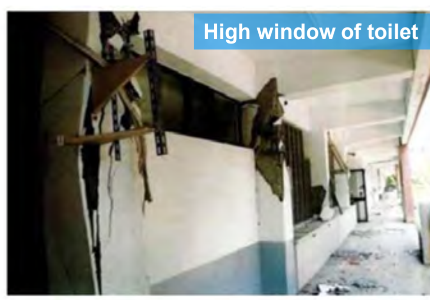


Figure 2: **Short columns are stiffer and attract larger forces during earthquakes** – *this must be accounted for in design.*



High window of toilet

Short column at basement vent

Short column of windowsill

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Tests on short column effect

S1 (H_n/b_w=5)

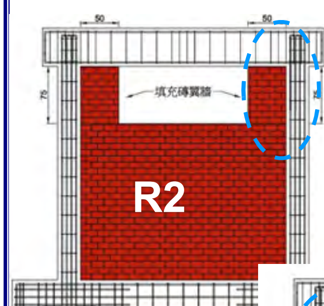
S2 (H_n/b_w=4)

S3 (H_n/b_w=2.5)

S4 (H_n/b_w=1.67)

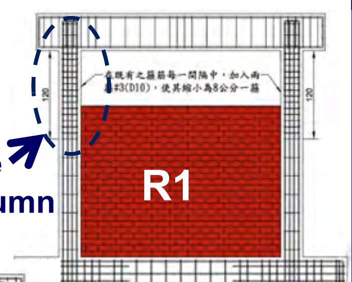
Reference: S.Y. Chang, W.I. Liao，2011，既有RC建築物修復補強工法之性能試驗研究(2)，ABRI。

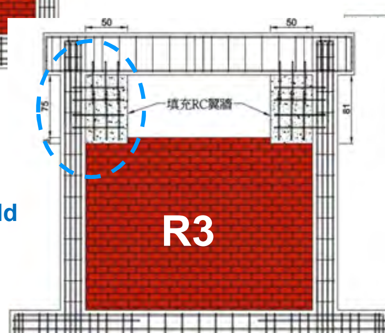
Retrofit method of Short Column



Install brick wing wall

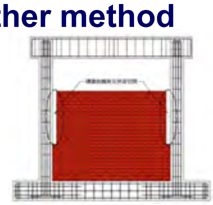
Increase the hoop of column





Install RC wing wall (RC wall should embedded into the exist brick wall)

Other method



Reference: S.Y. Chang, W.I. Liao，2012，既有RC建築物修復補強工法之性能試驗研究(3)，ABRI。

Photos of final failure status

Increase hoop

Brick wing wall

RC wing wall

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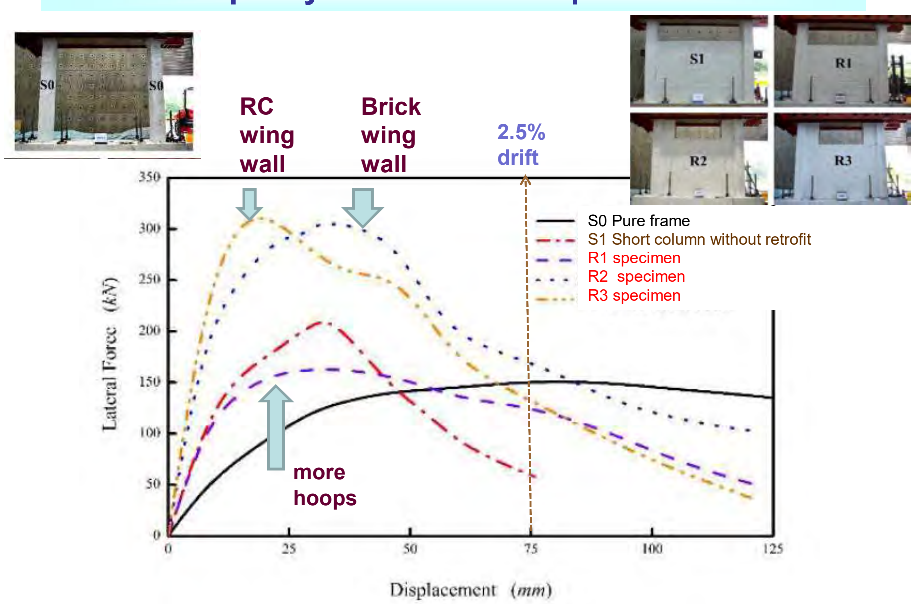
Capacity Curves of test specimens



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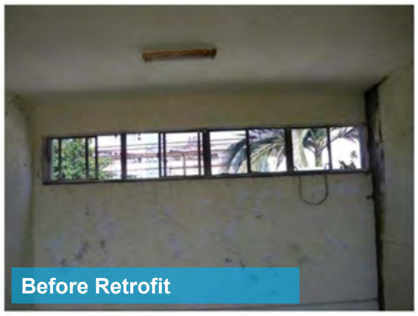
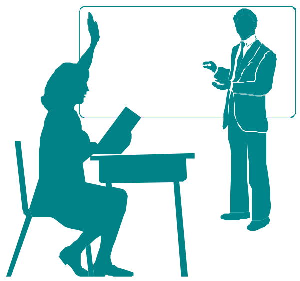
Practical construction case



Conclusions

1. For the post installed RC wall, the proposed connected method to improve the load transfer mechanism on the interface was verified. The strength of the RC wall can be fully developed and the test specimens were damaged in the expected failure mode.
2. The short column effect can be eliminated by just using a small brick wing wall or a RC wing wall .

Many thanks for your attention!



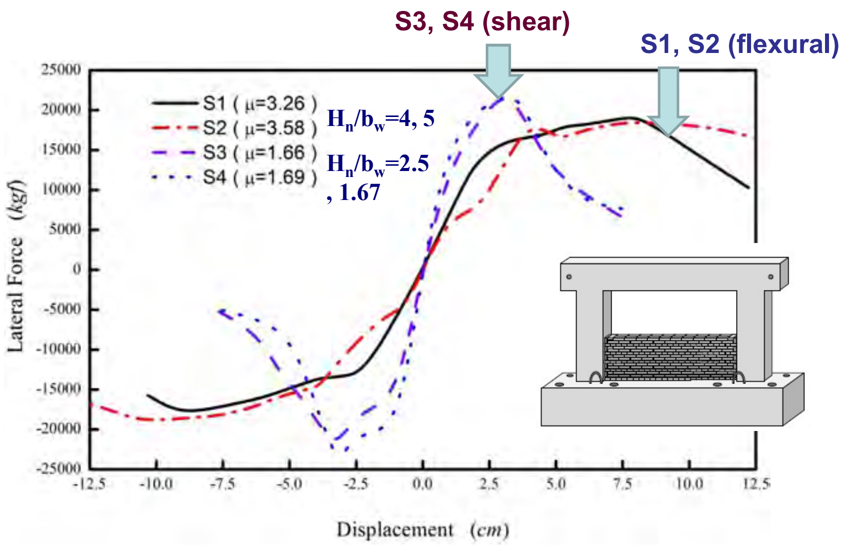
Measurement setup

- External measurement equipments

1. Tempo III magnetic telescopic displacement meter (control and measure specimen displacements, 1 set)
2. Dial gauge (base slip observer, 1 set)
3. NDI optical measurement system (1 set) and Markers photosensitive elements (24 sets)

Retrofitting Short Column

Capacity curves of test specimens



AN OVERVIEW OF SEISMIC RETROFIT TECHNIQUES DEVELOPED AT THE UNIVERSITY OF OTTAWA

By Dr. M. Saatcioglu, University of Ottawa

Abstract

A large proportion of existing building and bridge infrastructure across the world consists of seismically deficient non-ductile structural systems. Performance of structures during recent earthquakes have demonstrated seismic vulnerability of these systems, the majority of which were designed prior to the enactment of modern seismic codes, though some were designed more recently in areas where code enforcement provides challenges. These structures constitute considerable seismic risk, especially in large metropolitan centres. Because it is economically not feasible to replace a large segment of seismically deficient infrastructures with new and improved systems, retrofitting existing structures remains to be a viable seismic risk mitigation strategy. The objective of this presentation is to highlight seismic retrofit strategies for deficient building and bridge infrastructures, with emphasis on experimental and analytical research conducted at the University of Ottawa. The retrofit strategies consist of structural upgrades at the system level, as well as at the element level. Non-ductile reinforced concrete frame retrofits, in the form of different lateral bracing techniques, non-ductile concrete column retrofit strategies, and unreinforced masonry wall retrofit methodologies will be presented. The specific areas of research include: column retrofitting by either external transverse prestressing or FRP wrapping; masonry wall retrofitting with surface bonded FRP sheets, internally added reinforcement and post-tensioning; bracing of non-ductile reinforced concrete frames with diagonal prestressing and buckling restrained braces for strength enhancement and deformation control. An overview of these seismic retrofit research projects will be presented.

Keywords: buckling restrained brace, concrete, fibre reinforced polymer, masonry buildings, seismic retrofit.

Biography

Dr. Murat Saatcioglu is a Distinguished University Professor in the Department of Civil Engineering of the University of Ottawa in Canada. He is also the Director of the Hazard Mitigation and Disaster Management Research Centre of the same university. His research interests include design, analysis and retrofit of structures subjected to extreme loads, including those caused by earthquakes and bomb blasts.

Dr. Saatcioglu is the recipient of numerous national and international research and teaching awards and medals, including the A.B. Sanderson Research Award from the Canadian Society for Civil Engineering (CSCE) in 2015, the Whitman Wright Research

Award of CSCE in 2014, the Wason Medal from the American Concrete Institute (ACI) in 2004, the Raymond C. Reese Research Prize from the American Society of Civil Engineers (ASCE) in 2000, Casimir Gzowski Medal from CSCE in 2001 and 2004, CCEDS-1 Award for Best Paper from McMaster University in 2005 and the Charles Whitney Medal from ACI in 1989. He is a Fellow of the Canadian Academy of Engineers, a Fellow of the Engineering Institute of Canada, a Fellow of the American Concrete Institute, a Fellow of the Canadian Society for Civil Engineering, a Member of the American Society of Civil Engineers, a Member of the Earthquake Engineering Research Institute and the past president of the Canadian Association for Earthquake Engineering. Dr. Saatcioglu is an active member of numerous technical committees of the American Concrete Institute and the Canadian Standards Association. He is a registered Professional Engineer in the Province of Ontario.

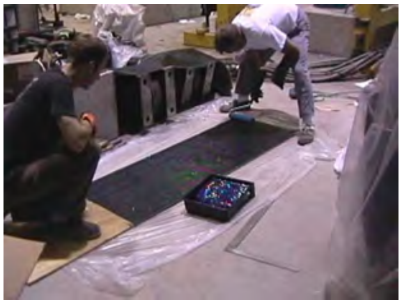
An Overview of Seismic Retrofit Techniques Developed at the University of Ottawa

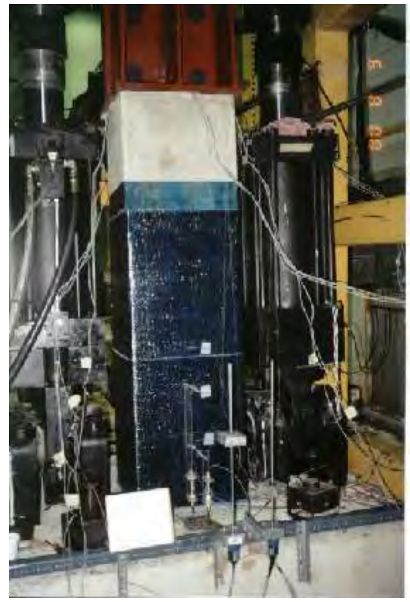
By: Murat Saatcioglu

Seismic Retrofit Research @ uOttawa

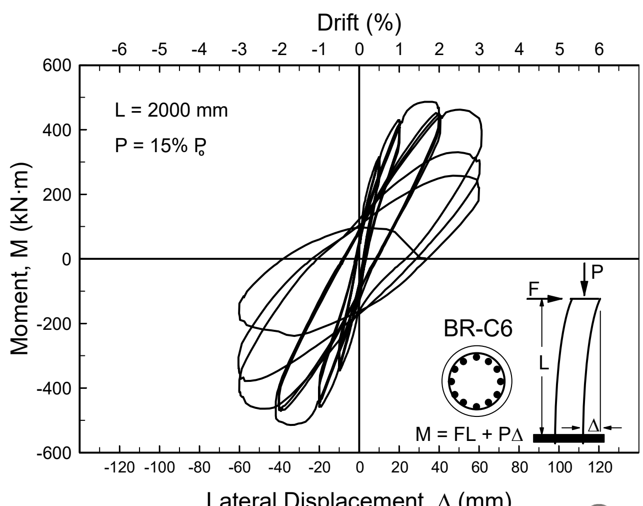
- Column retrofit methodologies.
  - FRP Wrapping
  - Transverse Prestressing
- Lateral bracing of nonductile reinforced concrete frames
  - Frames with masonry infill walls
  - Bare frames braced with diagonal prestressing or BRBs
- Load bearing masonry.
  - Use of externally placed steel strips
  - Use of surface-bonded FRP and ductile steel sheet anchors
  - Addition of internal reinforcement and/or prestressing

FRP Jacketing of Columns

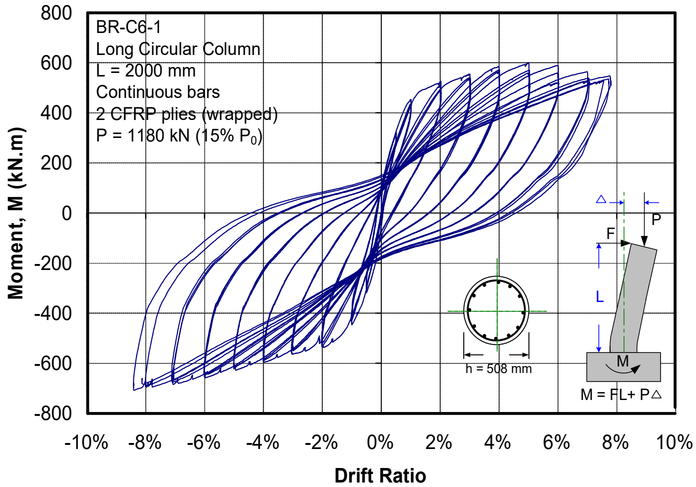


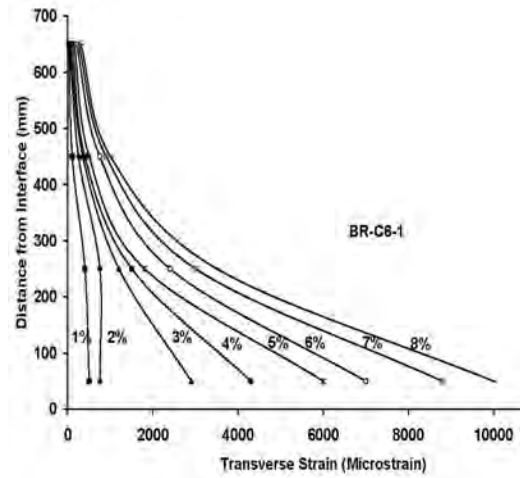


Non-Seismic Column – Flexure-Dominant Response



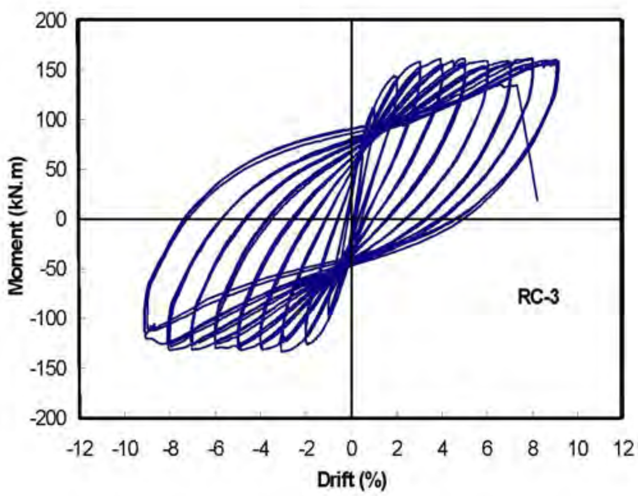
Retrofitted Column – Flexure-Dominant Response

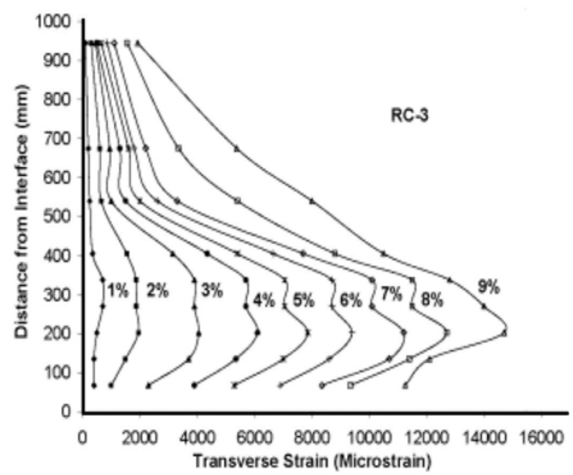




CFRP jacketed circular column under 15% P_o

Retrofitted Column – Flexure-Dominant Response





CFRP jacketed circular column under 47% P_o

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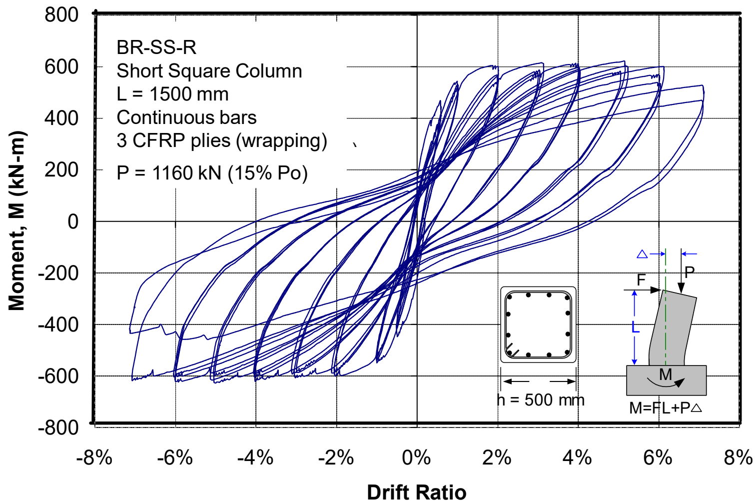
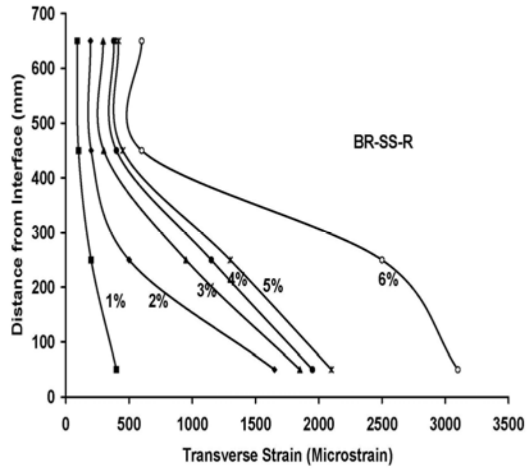
Retrofitted Column – Shear Dominant Response





CFRP jacketed square column under 15% P_o

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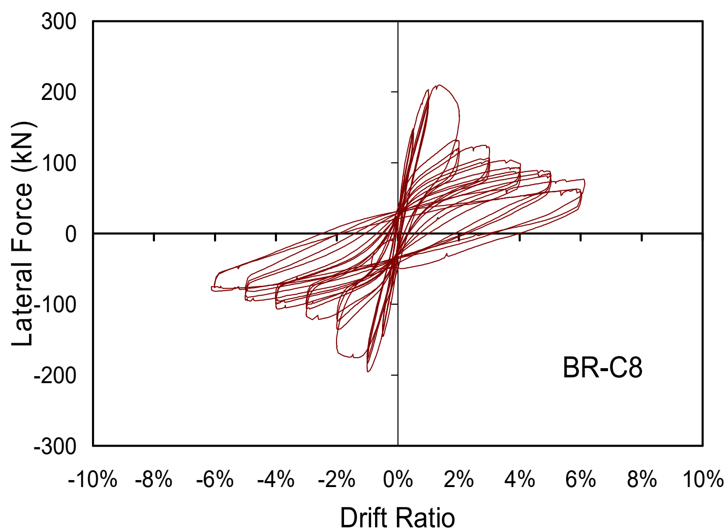
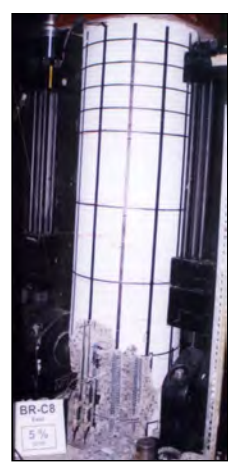
Non-Seismic Splice Deficient Column





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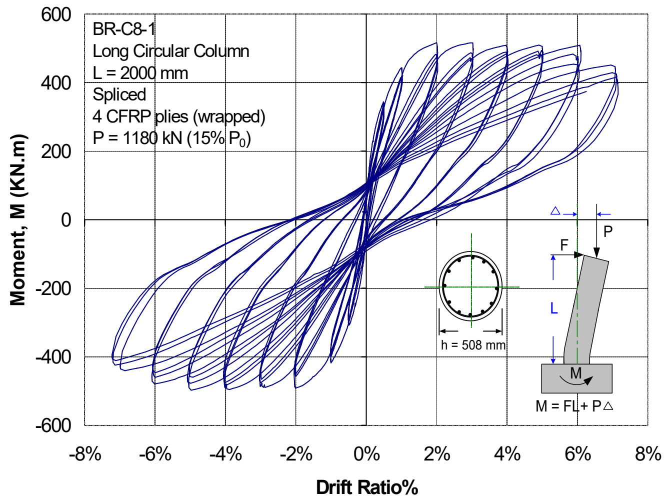
Circular Column Retrofitted for Splice Deficiency



- FRP Jacketing is effective for splice clamping in circular columns provided that the transverse strain in FRP is limited to 0.0015.
- FRP Jacketing has limited effectiveness in square and rectangular columns and hence is NOT allowed by CSA S806 in such columns.

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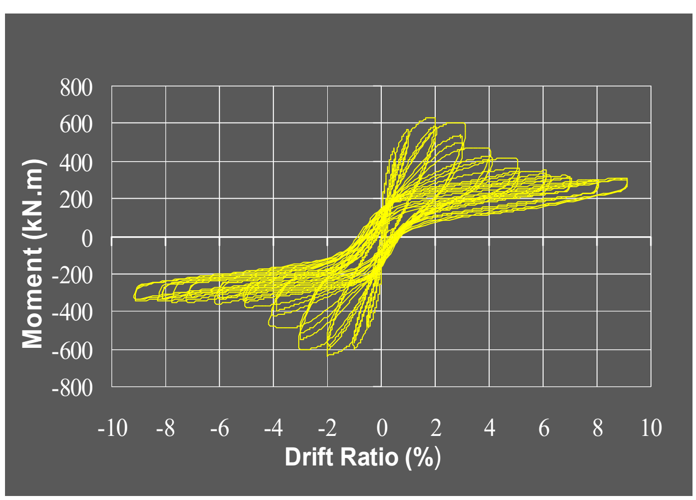
Square Column Retrofitted for Splice Deficiency



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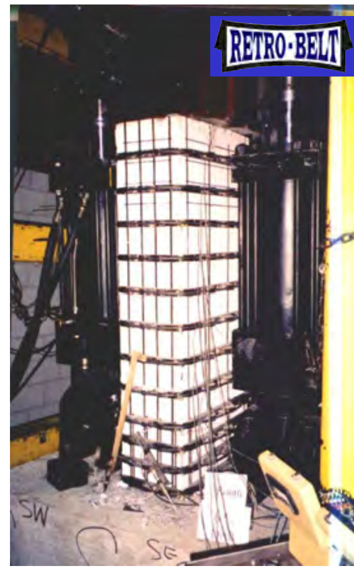
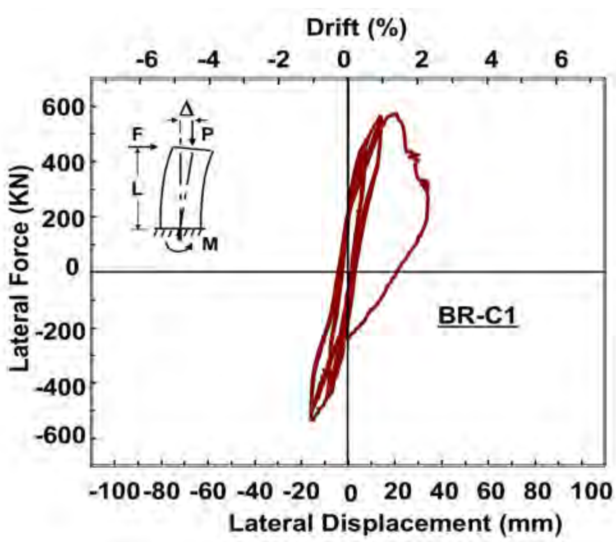
Transverse Prestressing of Concrete Columns

Transverse Prestressing of Columns

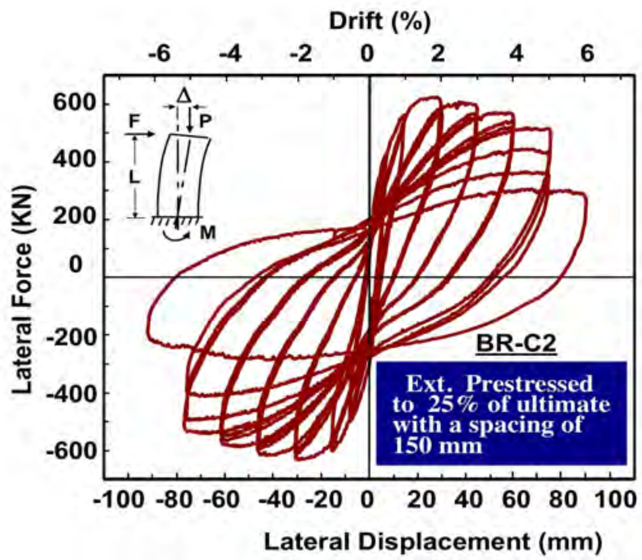
Transverse Prestressing of Columns



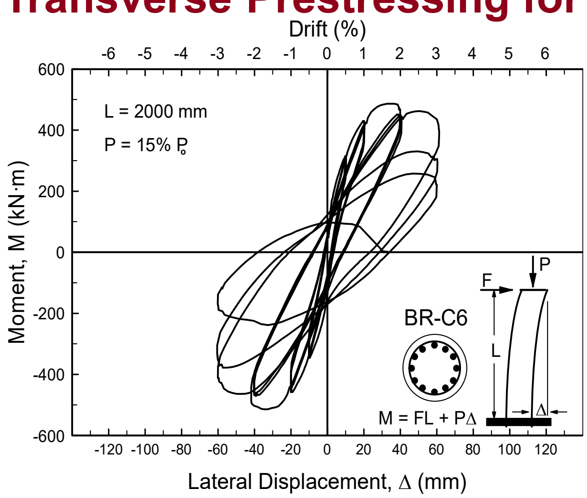
Shear Deficient Column



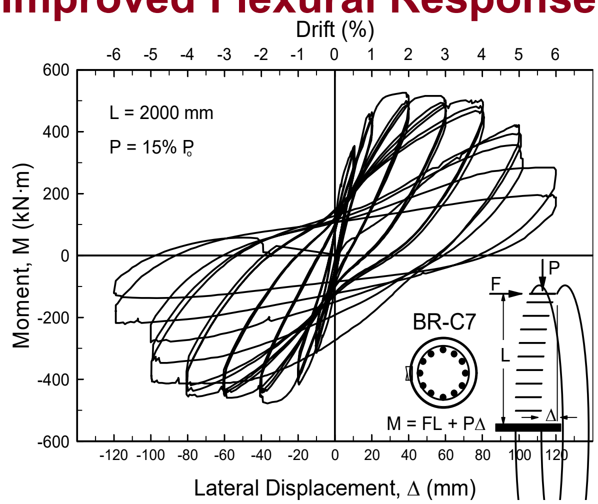
Transverse Prestressing for Improved Shear Response



Transverse Prestressing for Improved Flexural Response



Unretrofitted Column



Retrofitted Column