school buildings in British Columbia, by making use of existing materials and location specific seismic demands based on non-linear dynamic analysis. With minimal training Engineers experience with seismic retrofitting are able to understand and design using this methodology.

Keywords: performance-based design, seismic retrofit, probabilistic seismic hazard assessment, incremental dynamic analysis, school buildings.

Biography

Dr. Carlos Ventura is a Civil Engineer with specializations in structural dynamics and earthquake engineering. He has been a faculty member of the Department of Civil Engineering at the University of British Columbia (UBC) in Canada since 1992. He is currently the Director of the Earthquake Engineering Research Facility (EERF) at UBC, and is the author of more than 480 papers and reports on earthquake engineering, structural dynamics and modal testing. Dr. Ventura has conducted research about earthquakes and structural dynamics for more than thirty years. Three of his most significant contributions in recent years are the development and implementation of performance-based design methods for seismic retrofit of low-rise school buildings, a unique seismic structural health monitoring program for bridges in BC, known as the BCSIMS project, and the first network-based earthquake early warning system for schools and public institutions in BC. These projects have contributed in a very significant manner to the seismic risk reduction efforts in BC. In addition to his academic activities, Dr. Ventura is a recognized international consultant on structural vibrations and safety of large civil engineering structures. The quality of his research work has been recognized by several national and international awards, as well as being appointed as member of the Canadian Academy of Engineering and of the Engineering Institute of Canada, and Fellow of Engineers Canada. He is also a member of several national and international professional societies, advisory committees and several building and bridge code committees.

SEISMIC ASSESSMENT AND RETROFIT OF SCHOOL BUILDINGS IN BRITISH COLUMBIA, CANADA

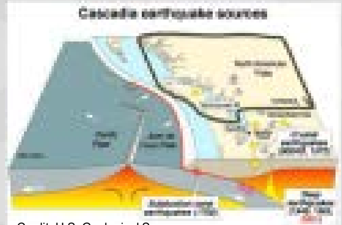
Carlos E. Ventura Ph.D., P.Eng., P.E.

What are the Seismic Retrofit Guidelines, SGR3?

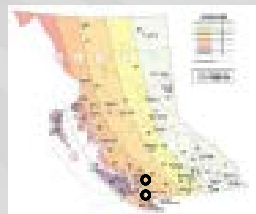
- Guidelines for assessment and retrofit of **existing** low-rise school buildings in British Columbia
- Performance-based tool that is both **simple** and **rational**.
- Cost-effective
  - Existing materials
  - Local seismicity (including soil type)

Seismic Retrofit Guidelines

- BC population: 4.4 millions
- More than 800 schools in moderate to high seismic hazard
- 80% of schools in high seismic hazard (Victoria and Vancouver)



Credit: U.S. Geological Survey


Credit: U.S. Geological Survey

Seismic Retrofit Guidelines

- BC population: 4.4 millions
- More than 800 schools in moderate to high seismic hazard
- 80% of schools in high seismic hazard (Victoria and Vancouver)

BC Ministry of Education launched seismic mitigation program

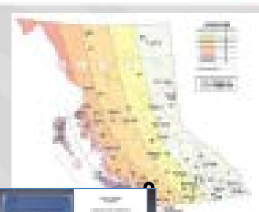
- Address the highest priority needs
- Cost and time efficient guidelines

University of British Columbia
- Laboratory tests
- Analytical development

Professionals
- Local engineers
- External peer review

Guidelines

Credit: U.S. Geological Survey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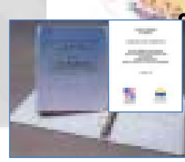


Guideline Development

• "Bridging Guidelines, 1st Edition"	July 2005
• "Bridging Guidelines, 2nd Edition"	Nov 2006
• "Seismic Retrofit Guidelines, 1st Edition"	Sept 2011
• "Seismic Retrofit Guidelines, 2nd Edition"	Nov 2013
• "Seismic Retrofit Guidelines, 3rd Edition"	Sept 2016
• "Seismic Retrofit Guidelines, 4th Edition"	Fall 2020

- Every release complete with training of structural engineers
- APEGBC retains list of engineers, companies attending such sessions
- Intent that School Districts only retain trained engineers/firms

Assessment and Retrofit Steps

- **Seismic Project Identification Report (SPIR)**
  - Funded by Ministry of Education of BC (not individual School Districts)
  - Structural engineer led
  - Drawing review, site visits
  - Assessment of risk using SRG
  - Upgrade concept, demand per SRG, with sketches
  - Geotechnical, material testing as needed to support concept
  - Cost estimate, cost consultant to visit site, include all ancillary costs

Assessment and Retrofit Steps

- **Seismic Project Identification Report (SPIR)**

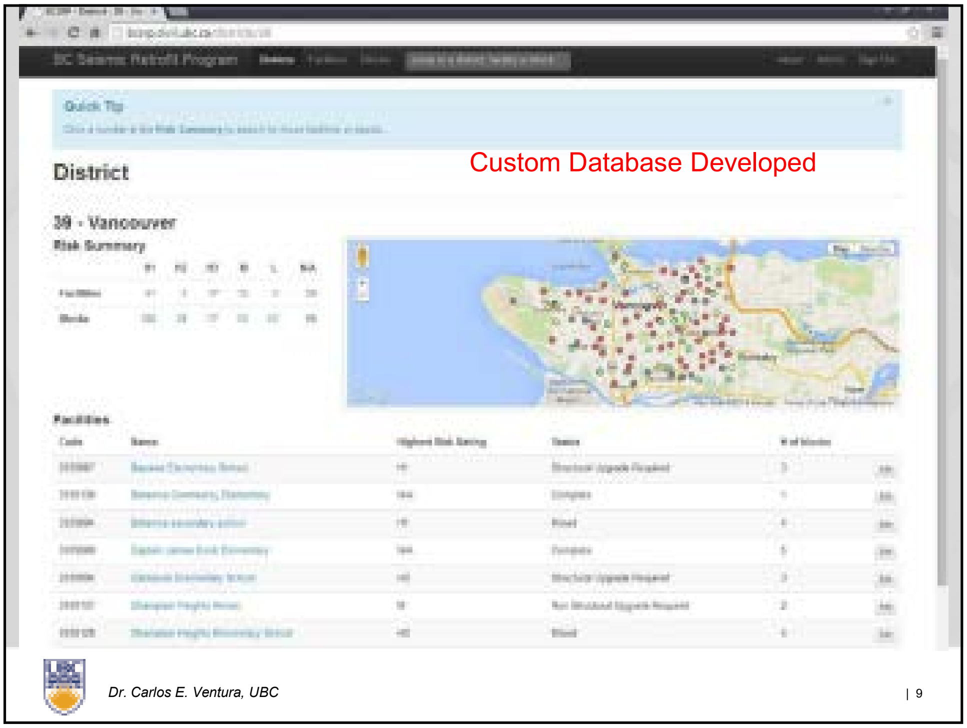
- **Project Definition Report (PDR)**
  - Cost Estimates to now include all indirect costs: phasing, staging, temp accommodation, moving costs
  - Cost comparison with school replacement

Assessment and Retrofit Steps

- **Seismic Project Identification Report (SPIR)**

- **Project Definition Report (PDR)**

- **Technical Review Board (TRB) Responsibilities**
  - 30+ structural engineers with retrofit experience and several geotechnical engineers with experience in liquefaction
  - Review every SPIR
  - Overview of PDR


BC Seismic Retrofit Program
Quick Tip
Custom Database Developed
District
39 - Vancouver
Risk Summary
Facilities
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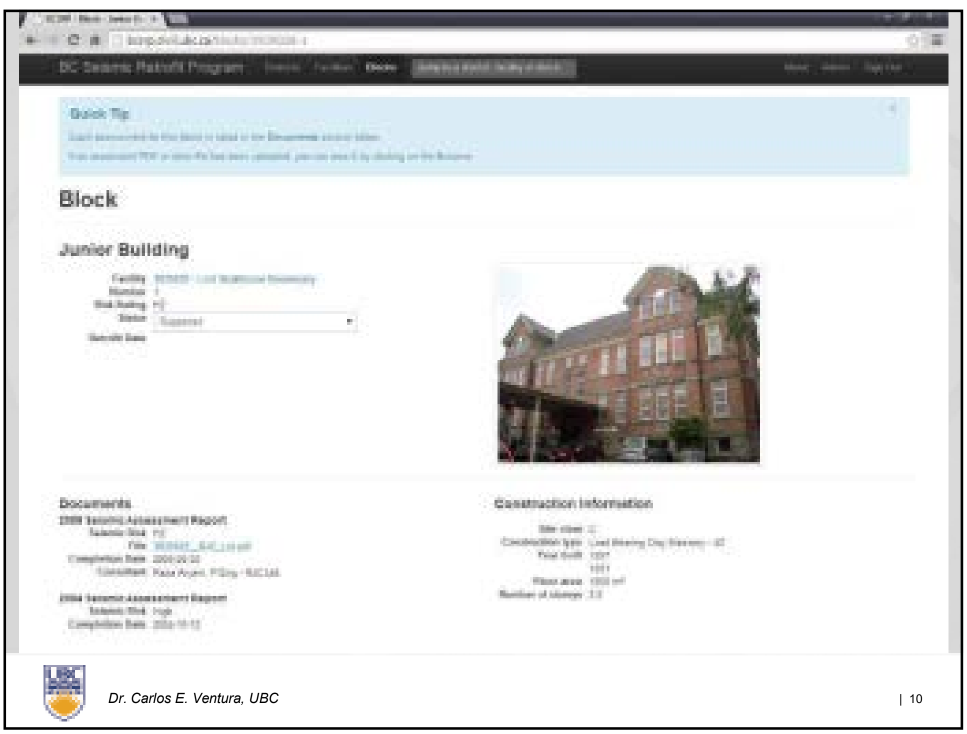
| 9


BC Seismic Retrofit Program
Quick Tip
Block
Junior Building
Documents
Construction Information
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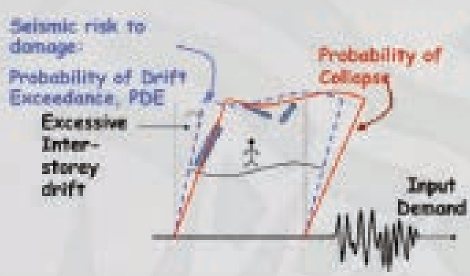
| 10

SRG Manual

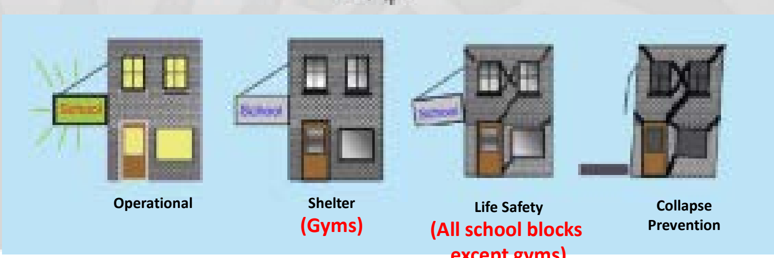
Vol.	Title
1	Overview
2	*The Guidelines and Commentary*
3	*Seismic Performance Analyzer I User Guide*
4	*Prototype Description Reports*
5	*Technical Background*
6	*Experimental Test Results*
7	*Library of Retrofit Details*
8	*Example Retrofit Strategies*
9	*Soil Hazard Maps*
10	*Post-Earthquake Evaluation Guidelines*
11	*Liquefaction Guidelines*
12	*Mid-rise Buildings (Analyzer II User Guide)*

Philosophy

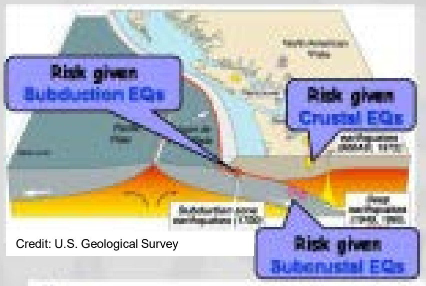


Performance-based Design

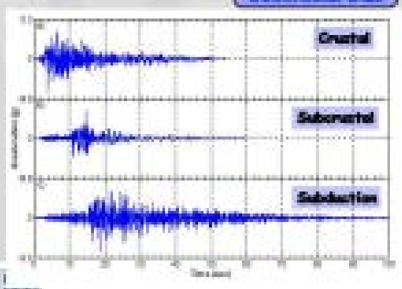
- **Reliance on Inelastic Deformation**
- **Probabilistic Analysis**

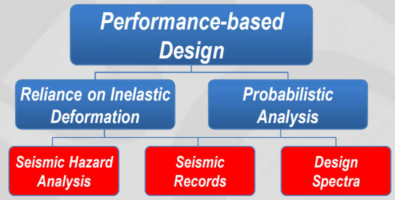


Seismic Hazard



Credit: U.S. Geological Survey



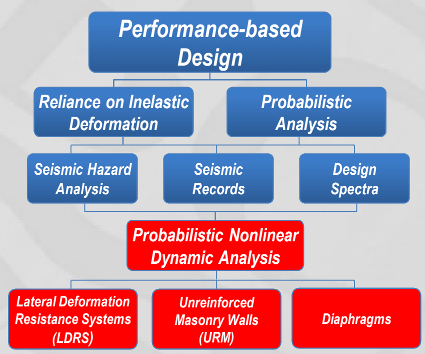


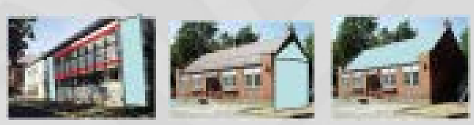
3 types of hazard

- Conditional Spectra (CS) used for selection and scaling of ground motions
- Record Database
  - Over 3309 records for subduction events (long duration)
  - Over 2562 records for subcrustal events
  - Over 6000 records for crustal events
- 120 EQ at different level of intensities were studied

Building Elements

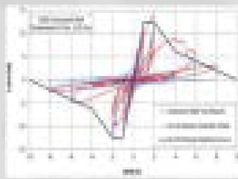
- 3 types of building elements are considered in the analysis:
  - Lateral Deformation Resistance Systems, LDRS (such as wood and concrete shear walls, concrete and steel frames, reinforced and unreinforced masonry walls) : 33 prototypes
  - Unreinforced masonry walls (URM): 5 prototypes
  - Flexible diaphragms (wood and steel deck diaphragms): 6 prototypes
- Wide range of
  - LDRS heights and resistances
  - URM thicknesses and heights
  - Diaphragm span lengths

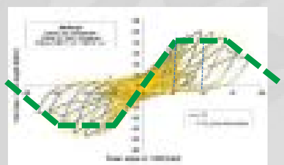




Building Elements Behavior

- The cyclic force-deformation of prototypes are based on experimental results





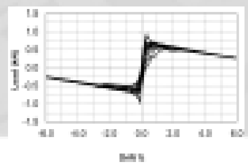
Performance-based Design

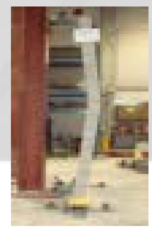
Reliance on Inelastic Deformation | Probabilistic Analysis

Seismic Hazard Analysis | Seismic Records | Design Spectra

Probabilistic Nonlinear Dynamic Analysis

Lateral Deformation Resistance Systems (LDRS) | Unreinforced Masonry Walls (URM) | Diaphragms





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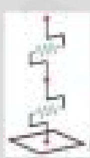
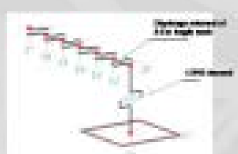
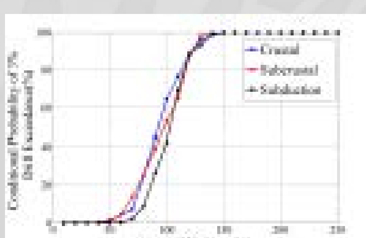
Structural Analysis

- A model is developed based on the cyclic force-deformation of obtained from experimental results







Performance-based Design

Reliance on Inelastic Deformation | Probabilistic Analysis

Seismic Hazard Analysis | Seismic Records | Design Spectra

Probabilistic Nonlinear Dynamic Analysis

Lateral Deformation Resistance Systems (LDRS) | Unreinforced Masonry Walls (URM) | Diaphragms

- Incremental non-linear dynamic analysis is performed for a wide range of ground motions and intensities

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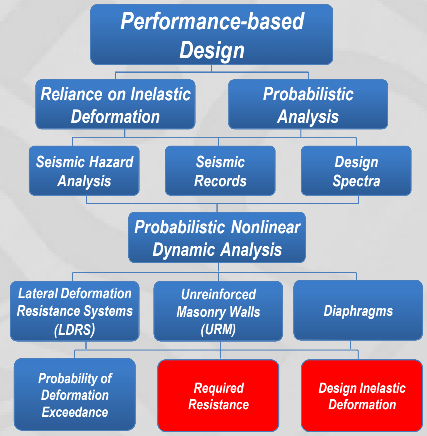
| 16

Life Safety Performance Objective

- ❑ Analysis is performed for wide range of resistances and drifts.



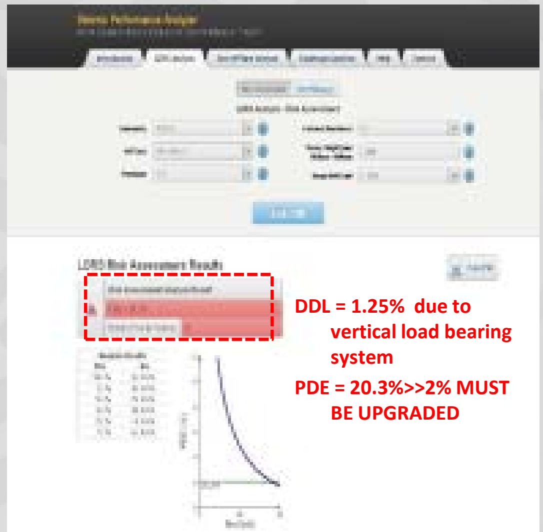
<u>Life Safety Performance Objective for LDRS:</u>

- ❑ Probability of CDL exceedance in 50 years PDE < 2%
- ❑ Conditional probability of near failure drift (CDL) exceedance (CPDE) ≤ 25% for 2% in 50 year of each hazard type

Seismic Analyzer

- ❑ User friendly access to pre-analyzed non-linear dynamic analysis results
- ❑ Ability to perform risk analysis and provide retrofit resistance for different performance objectives

Example



DDL = 1.25% due to vertical load bearing system

PDE = 20.3%>>2% MUST BE UPGRADED

Assessment:

Existing Prototype: Non-ductile R/C moment frame

Community: Victoria

Soil type: Site Class C

Factored resistance: 5%W

Clear storey height: 3200 mm

Example

Option A

Option B

Retrofit:

C-3: Upgrade the R/C moment frame

DDL = 1.25%

PDE = 2%

Rm = 44.5% W

C-5: Adding a new R/C shear wall

DDL = 1.00%

PDE = 2%

Rm = 23.3%W


High School – External Upgrade Scheme - Before
Photo courtesy of Mr. John Sherstobitoff (Ausenco)


High School – External Upgrade Scheme - After
Photo courtesy of Mr. John Sherstobitoff (Ausenco)

Photo courtesy of Dr. Graham Taylor (TBG Seismic Consultants)

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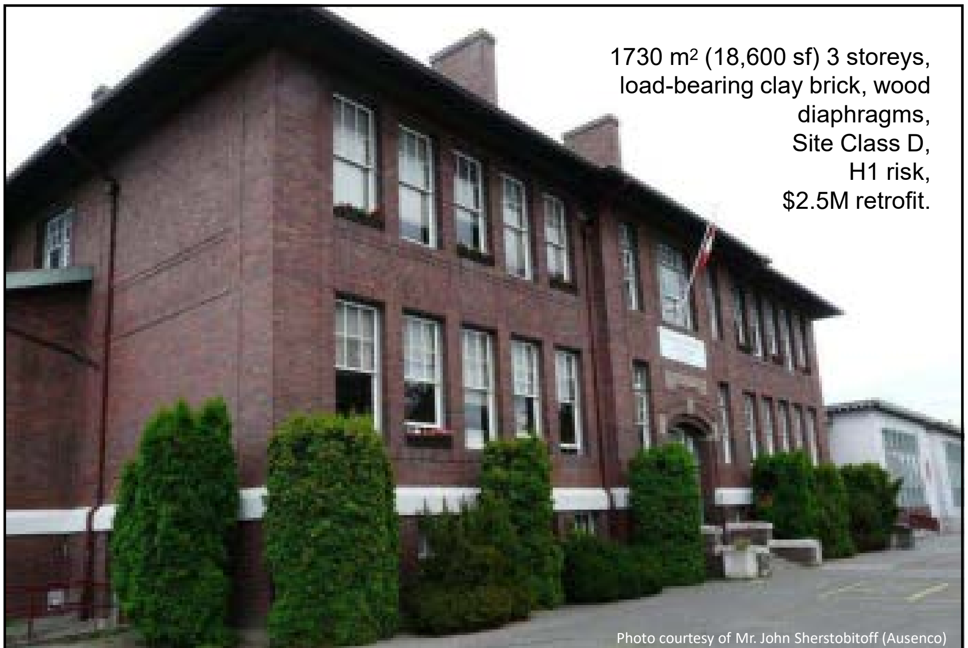
| 23

FRP to reinforce walls, stairwells

Photo courtesy of Mr. John Sherstobitoff (Ausenco)

Diaphragm Upgrade – FRP – in progress



1730 m[2] (18,600 sf) 3 storeys, load-bearing clay brick, wood diaphragms, Site Class D, H1 risk, $2.5M retrofit.

Photo courtesy of Mr. John Sherstobitoff (Ausenco)

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Photo courtesy of Mr. John Sherstobitoff (Ausenco)

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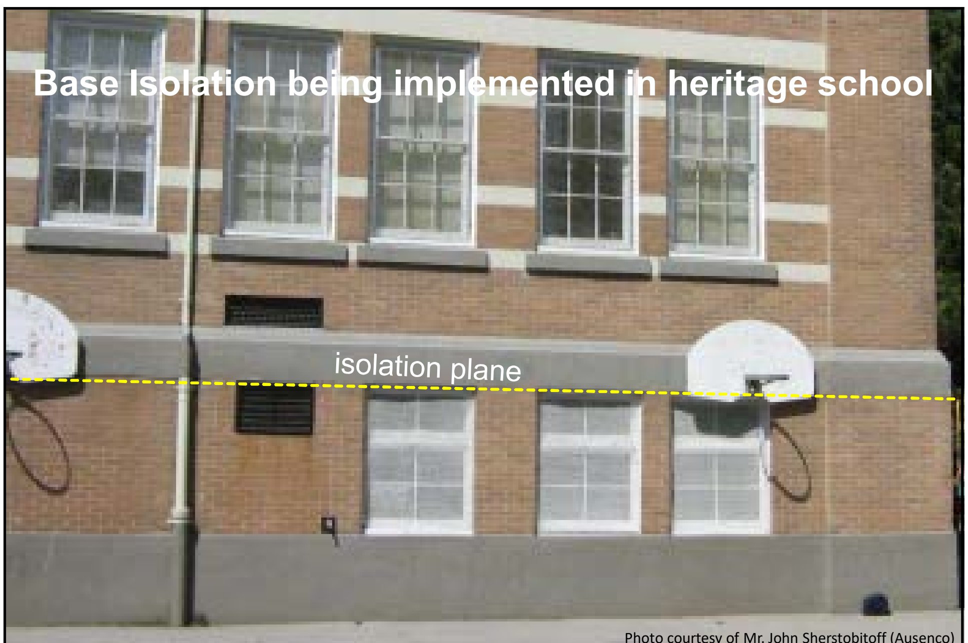
| 29



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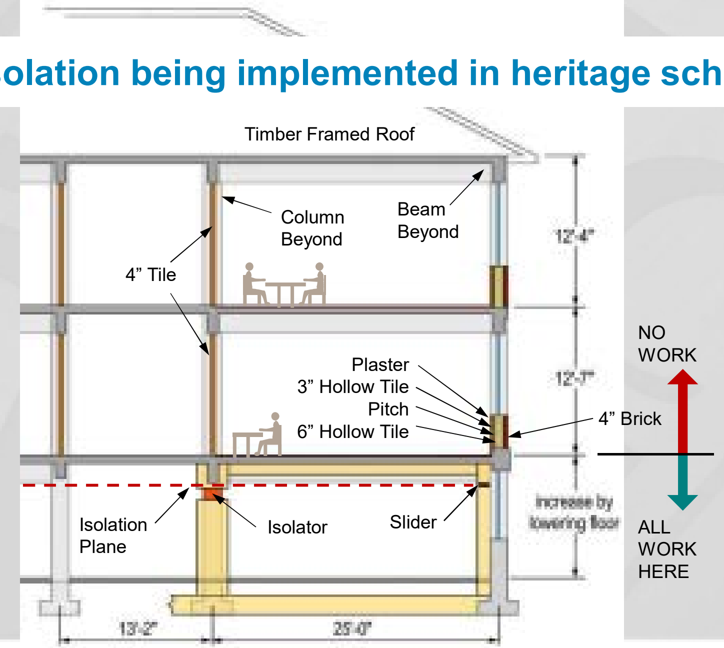
| 30

Base Isolation being implemented in heritage school



Testing at UBC – Bare 4" concrete block wall

Out-of-plane upgrade with simple Unistrut

In Summary

1. **New** rational tools for Earthquake Engineering
2. Technical advances and a **highly cooperative project**
3. **Better understanding of damage** associated to earthquakes
4. **Less conservative** seismic **hazard data**
5. **Quantifiable** seismic **risk** to damage
6. More information for **pre-earthquake preparedness** (Seismic retrofit)
7. More information for **post-earthquake** situations

QUESTIONS?

SEISMIC ASSESSMENT METHODS AND EXPERIMENTAL VERIFICATIONS OF REINFORCED CONCRETE BUILDINGS

By Dr. F.-P. Hsiao, National Cheng Kung University/ National Center for Research on Earthquake Engineering

Abstract

This study is prepared to demonstrate the relevant technology for detailed evaluation of school buildings. Procedures for detailed evaluation of school buildings are presented in this study. It is a reference to be consulted by the practicing engineers. The proposed method, called the Taiwan Earthquake Assessment for Structures by Pushover Analysis (TEASPA), is a modified capacity spectrum method developed in the NCREE handbook after the 1999 Chi-Chi earthquake. In this study, the evaluation of TEASPA is carried out using results from an experimental campaign comprised of pushover tests in low-rise reinforced concrete (RC) school buildings and capacity spectrum method. The base shear-roof displacement curve, peak ground acceleration, and failure mechanism are calculated from each analysis. The results show that TEASPA can provide accurate results for assessing a low-rise RC building's capacity and is more appropriate to pushover tests. Moreover, the solutions related to retrofitting problems are provided.

Keywords: reinforced concrete, seismic assessment, seismic retrofitting, nonlinear static analysis, nonlinear dynamic analysis, in-situ pushover test.

Biography

Dr. Fu-Pei Hsiao received his Ph.D. degree (2004) in Civil Engineering at National Cheng Kung University. Currently, he is a Research Fellow at National Center for Research on Earthquake Engineering and an Associate Professor (joint appointment) at Department of Civil Engineering, National Cheng Kung University. His present research interests include seismic assessment, seismic retrofitting, reinforced concrete structure and large-scale structural experiments.

Seismic Assessment Methods and Experimental Verifications of Reinforced Concrete Buildings

Dr. Fu-Pei Hsiao
Research Fellow, NCREE
Deputy Division Head, NCREE Tainan Lab
Associate Professor(Joint Appointment), NCKU

2019/10/7

www.narlabs.org.tw

1

Tragedies in Earthquake

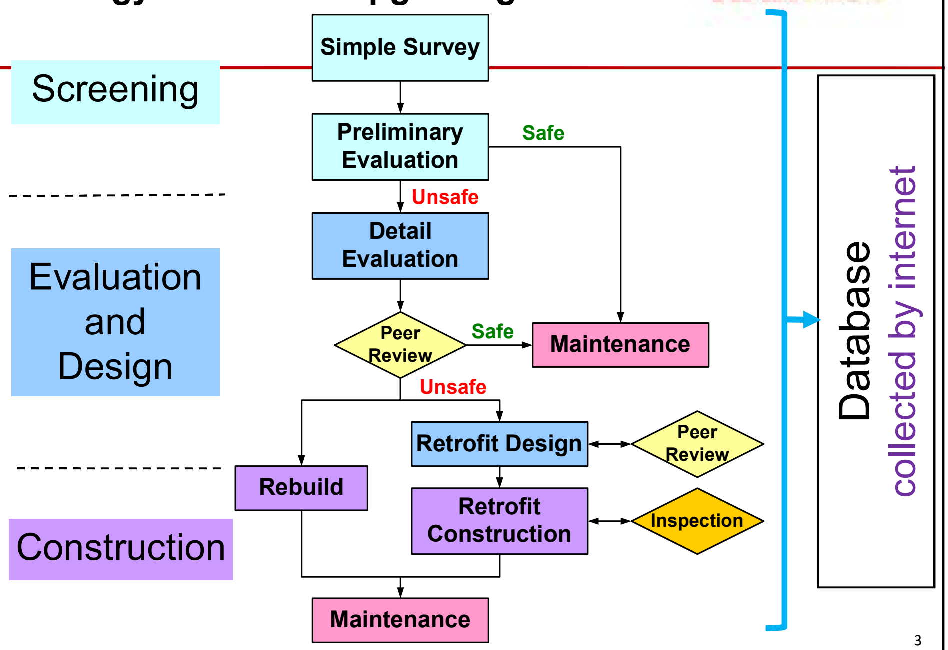
May 12, 2008, 14:28 pm
Magnitude: 8.0
Wenchuan Earthquake suffered heavy casualties of students

October 8, 2005, 08:50 am
Magnitude: 7.6
Pakistan Earthquake 19,000 death of students

2

Strategy for School Upgrading in Taiwan

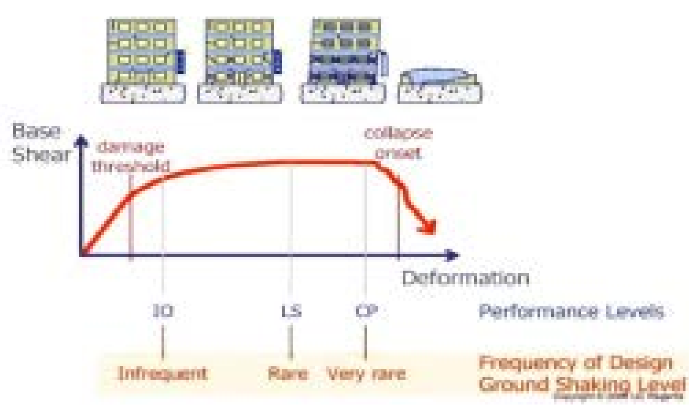
NARLabs



3

Performance Based Engineering

NARLabs

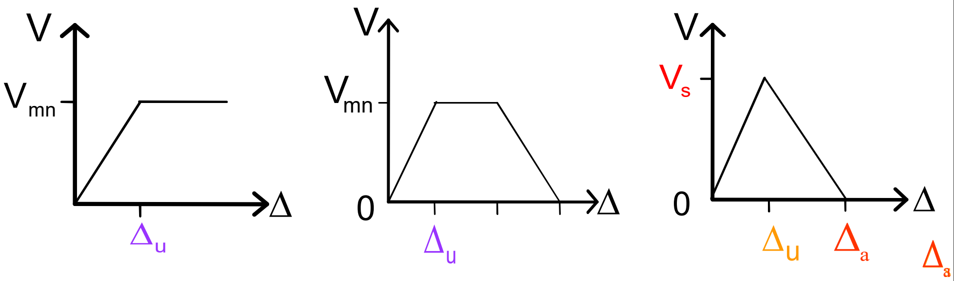


- Damage peak ground acceleration: a_c
- 475-yr design ground acceleration: a_g
- Acceptance criteria: $a_c \geq a_g$

4

Load-Deflection Curves of Column

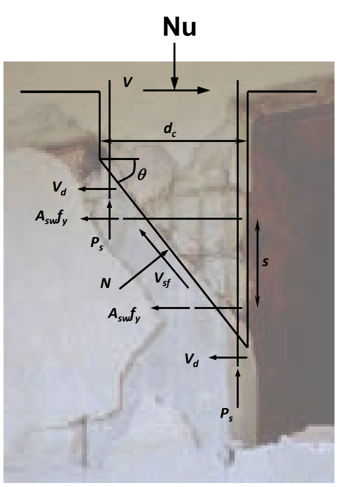
Taiwan Earthquake Assessment for Structures by Pushover Analysis (TEASPA)

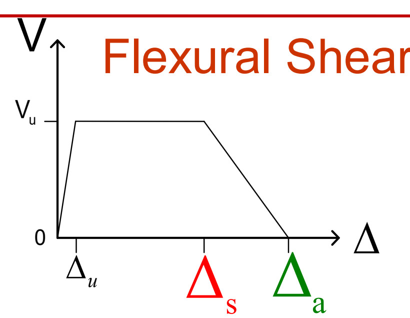


Flexure **Flexural Shear** **Shear**

5

Idealized Shear-Drift Backbone





Elwood & Moehle (Spectra 2005; ACI 2005)

$$\frac{\Delta_s}{H_n} = \frac{3}{100} + 4\rho'' - \frac{1}{40}\frac{\upsilon}{\sqrt{f'_c}} - \frac{1}{40}\frac{N_u}{A_g f'_c} \geq \frac{1}{100}$$

(MPa)

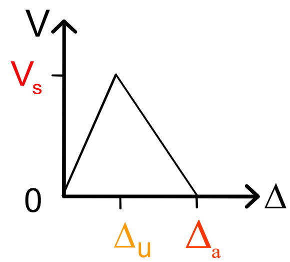
$$\frac{\Delta_a}{H_n} = \frac{4}{100}\frac{1+(\tan\theta)^2}{\tan\theta + N_u\left(\frac{s}{A_{st} f_{yt} d_c \tan\theta}\right)}$$

6

NARLabs

Test of Column Failed in Shear

Shear Failure

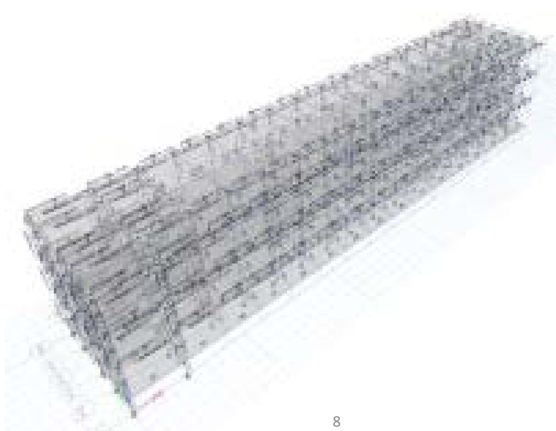


7

NARLabs

Pushover Analysis Using ETABS

- Modeling for School Building
- Properties of Plastic Hinges

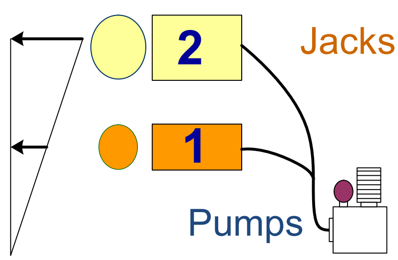


8

In-situ Pushover Tests

- Understanding the seismic capacity of existing school buildings
- Calibrating the detailed assessment method
- Verifying the seismic retrofitting methods

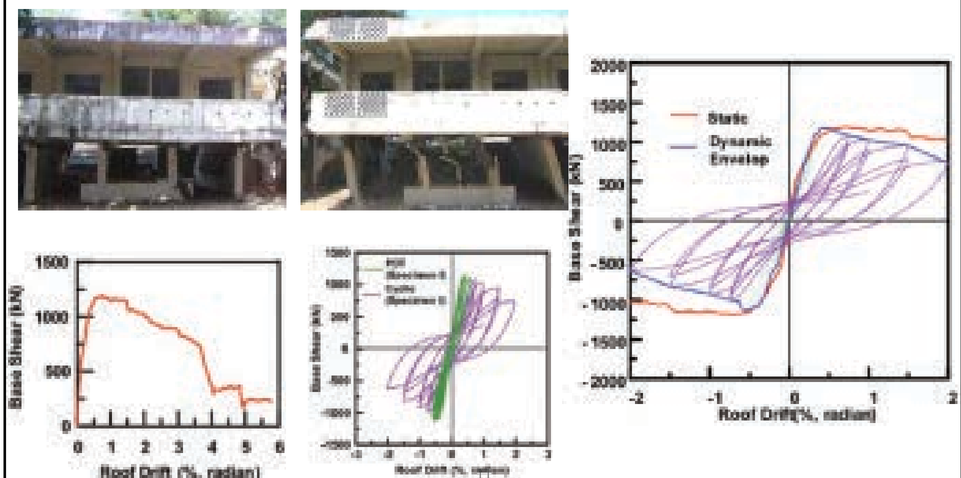
In-situ Pushover Tests



NARLabs

Correction the pushover curve with dynamic effect

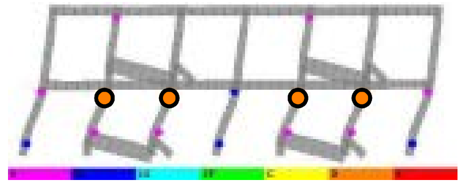
Monotonic pushover test | **Pseudo/cyclic dynamic test**

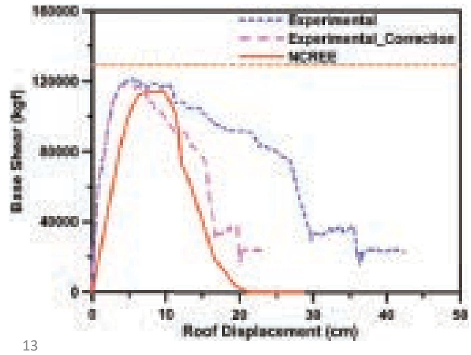


NARLabs

Pushover analysis and test result

Verifications of pushover curves with Reui-Pu elementary school

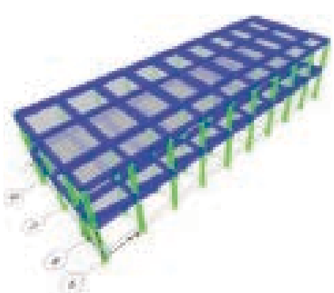


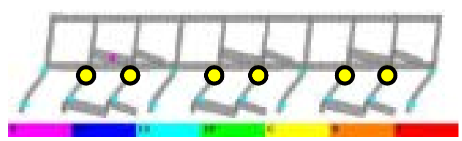


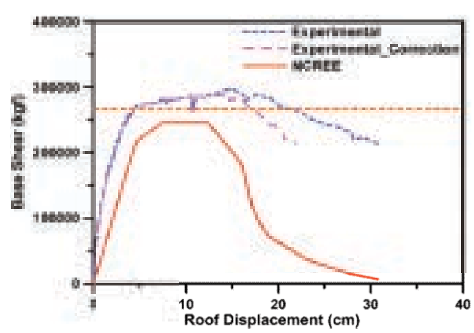
13

13

Verifications of pushover curves with Sin-Chen junior high school



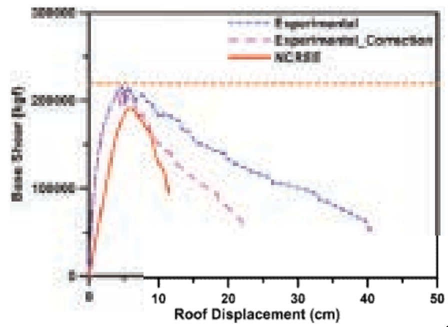




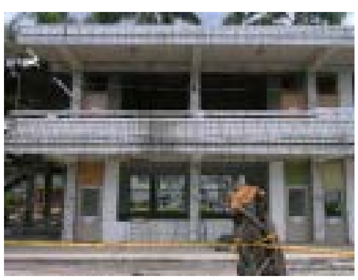
14

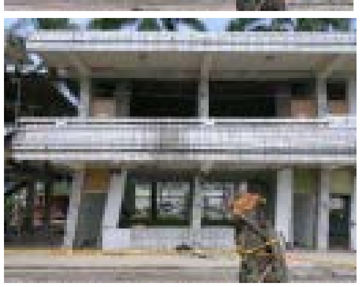
14

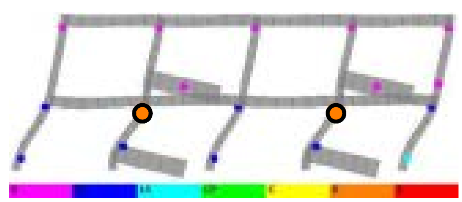
Verifications of pushover curves with Kao-Hu elementary school

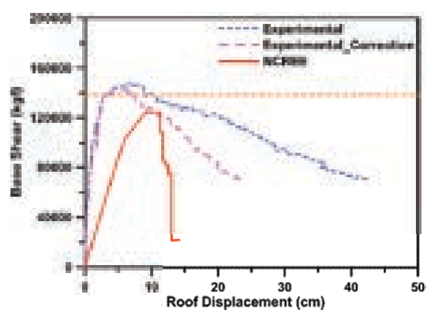


Verifications of pushover curves with Guan-Miao elementary school









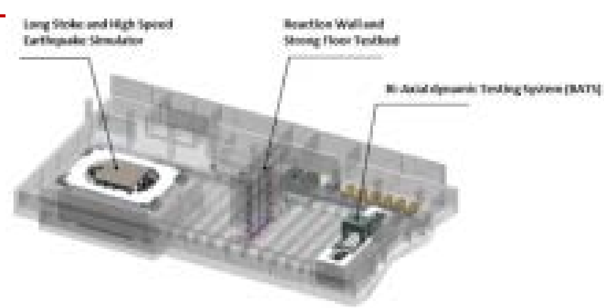
Remarks

For the next generation:
do something to
upgrade school buildings
before the next
disastrous earthquake.

BUT, will it be good enough?

17

NCREE Tainan Laboratory

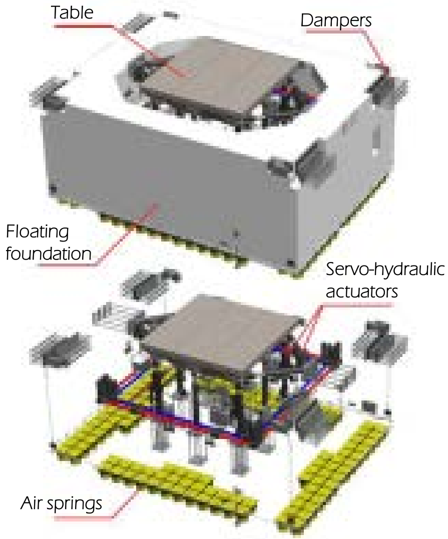


18

Long-Stroke and High-Speed Earthquake Simulator

NARLabs

Specifications of the earthquake simulator				
Table Size (m^2)	Max Stroke (m)	Max Velocity (m/s)	Max Acc. (g)	Max payload (ton)
8 x 8	H±1 V±0.4	H±2 V±1	H±2.5 V±3.0	250

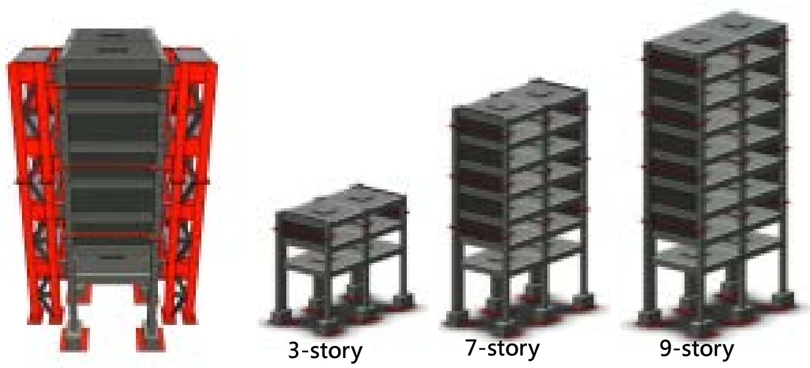


19

Study on Seismic Behavior with Mixed-use Residential and Commercial Building

NARLabs

- 1/2 scale RC structure with non-ductile detailing.
- Modulus design : 9-story, 7-story, 5-story and 3-story structures...
- High ceiling at 1st floor and soft story behavior.



20

Grand Opening on Aug. 9, 2017

NARLabs

Left camera

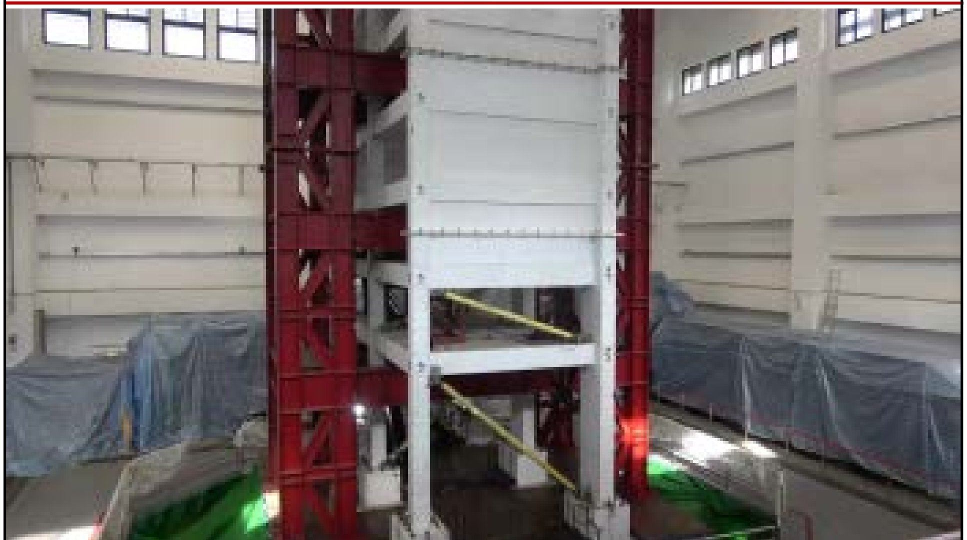
NARLabs

Near-fault earthquake test with 7F RC building

Mei-Nong EQ (CHY063)

NAR Labs

NF earthquake test with retrofitted 7F RC building



Mei-Nong EQ (CHY063)

23

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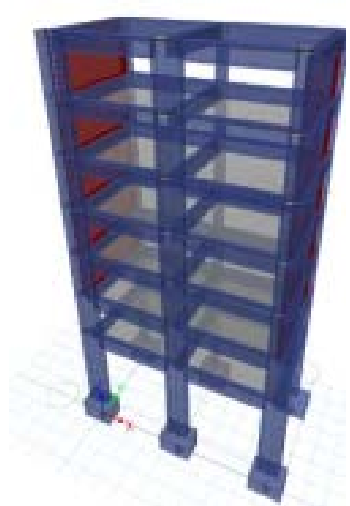
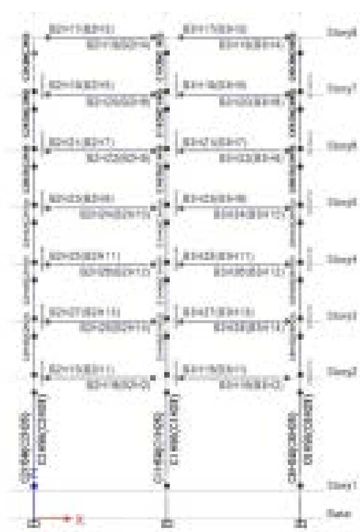
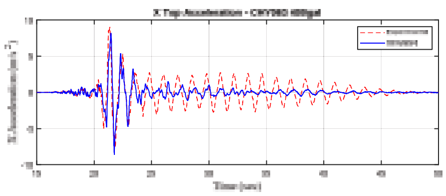
Numerical analysis with hinges model



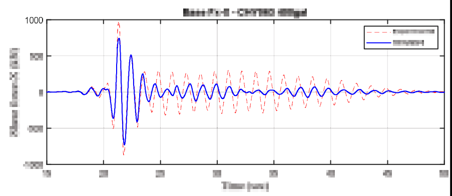


24

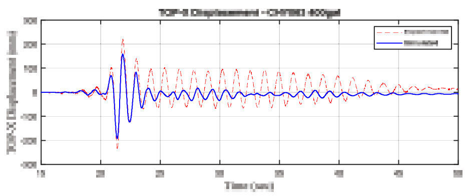
Comparison of analytical and experimental results



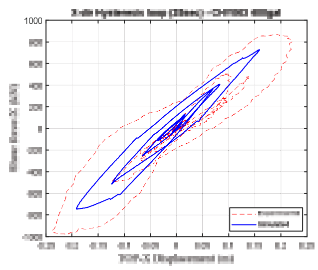
Roof Acceleration



Base Shear



Roof Displacement

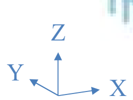


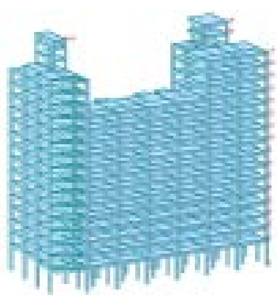
Hysteresis Loop

25

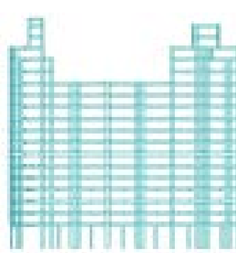
Nonlinear Response History Analysis

- A numerical model that are able to simulate dynamic nonlinear hysteretic behavior of a RC structure has to be established by using a structural analysis program. In this study, we used Midas.
- Plastic-hinges with hysteretic properties have to be considered for all major RC components.

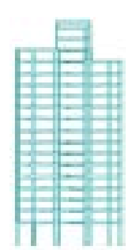




Sample building



Front view

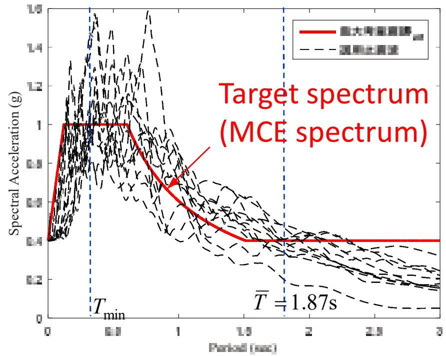


Side view

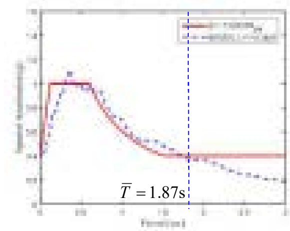
26

Ground Motions Selection

- The geo-mean response spectrum of each selected GM must be compatible with a target spectrum (usually the MCE spectrum) within the range of $T_{\min} \le T \le T_{\max}$, where $T_{\min} = (0.2)\min(T_x, T_y)$, $T_{\max} = (2)\max(T_x, T_y)$

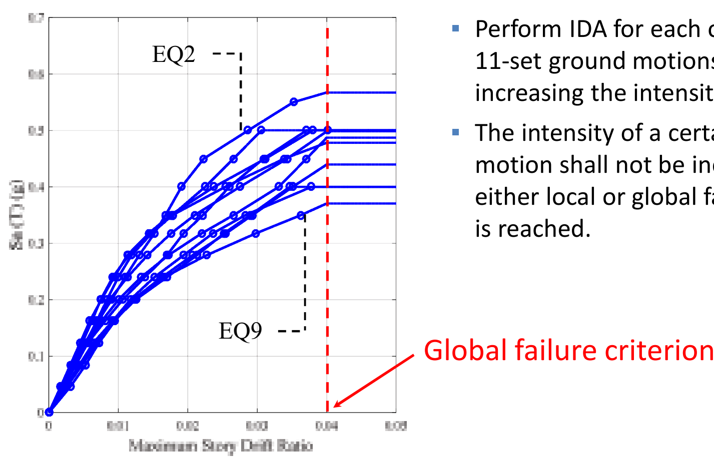


Geo-mean spectra of selected 11 sets of GMs



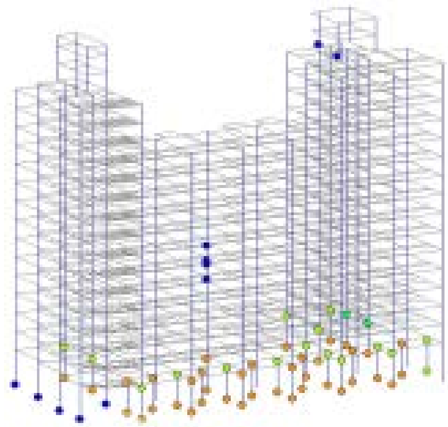
Average spectrum of selected GMs

Perform incremental dynamic analysis (IDA)

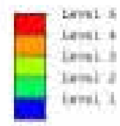


- Perform IDA for each of pre-selected 11-set ground motions by gradually increasing the intensity of each GM.
- The intensity of a certain ground motion shall not be increased when either local or global failure criteria is reached.

Check local failure criterion in IDA by using computer program



EQ#9($S_a(\bar{T}) = 0.4g$)



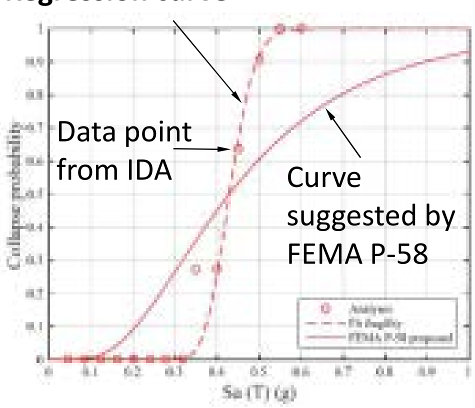
Colors of plastic hinge

- In many commercial program, the different statuses of a plastic hinge can be shown by different colors.
- This will make the user more easily to check weather a plastic hinge has reached its local failure criteria.

29

Establish collapse fragility curve

Regression curve



- ✓ A collapse fragility curve (CFC) represents collapse probability at a given earthquake intensity.
- ✓ A CFC is usually defined by two parameters: the median μ and logarithmic standard deviation β.
- ✓ The median μ of the CFC can be obtained by using the data from IDA, while the standard deviation β suggested by FEMA P-58 will be adopted in this study.

$$\beta = \sqrt{\beta_{a\Delta}^2 + \beta_q^2 + \beta_c^2}$$
$$= \sqrt{(0.45)^2 + (0.25)^2 + (0.25)^2}$$
$$= 0.5723$$

30

Determine collapse index (CI)

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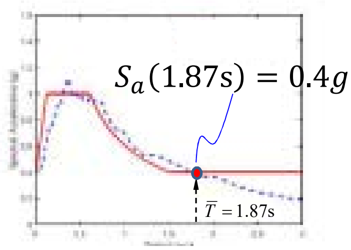
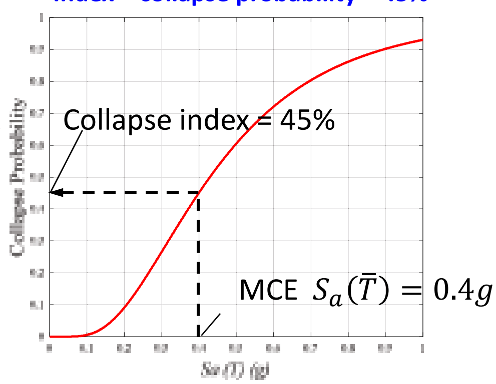
- Collapse index
  = Collapse probability under MCE-level earthquake
- Determine MCE-level seismic intensity at Yong-Kang Dist., Tainan, in terms of $S_a(\bar{T})$



MCE-level response spectrum

- **Index = collapse probability = 45%**



31

Check index acceptance level

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- In this study, the acceptable collapse probability proposed by **FEMA P-695** (2009) is adopted, i.e.,

Collapse probability must be less than 10%

- For the example building, the collapse index is 45% , which is much higher than the above acceptable level of 10%, therefore, the building is not safe and needs seismic retrofitting.

Collapse index (CI)	Collapse probability under MCE
Index of example building	45%
Acceptable level	10%

32

Conclusions

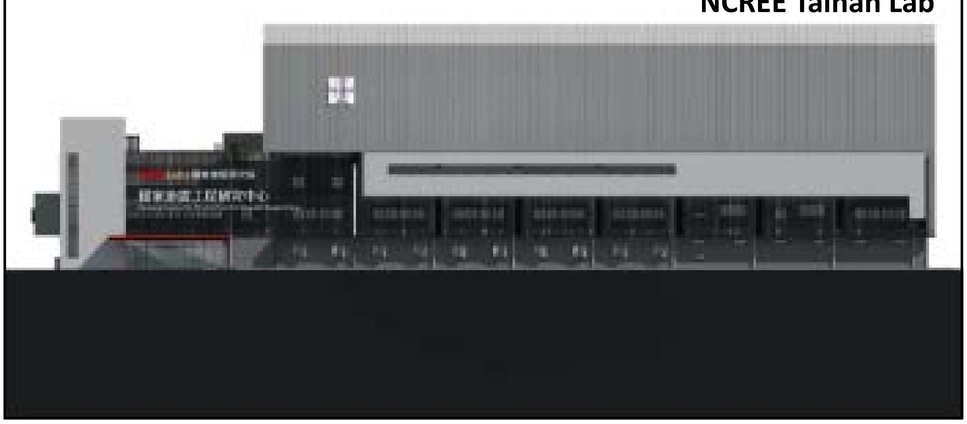
- A practical procedure and methodology for collapse assessment of a RC building is proposed. The proposed method is able to identify the RC building of high collapse risk and their possible failure components.

- The proposed method, which is developed based on FEMA P-58 framework, is composed of operational steps that can be easily followed by engineers.

33

Thank You

NCREE Tainan Lab



EVALUATION AND RETROFIT OF SEISMICALLY DEFICIENT STEEL BRACED FRAMES IN CANADA

By Dr. R. Tremblay, Polytechnique Montréal

Abstract

Steel structures constructed in seismic active areas of Canada prior to the implementation of the seismic design provisions in the CSA S16 steel design standard may sustain non-ductile failures under a severe earthquake, which may affect the structure integrity and pose a hazard to life safety. Potential deficiencies that have been investigated in recent research projects will be briefly reviewed, including brace fracture due to local buckling and low-cycle fatigue, failure of brace connections in tension and compression, and failure of steel roof deck diaphragms. Studies on the seismic response of multi-storey braced frames will also be presented, including soft-storey response, global frame stability and flexural demands imposed on columns. Seismic evaluation techniques will be reviewed and commented, and possible retrofit schemes will be introduced.

Keywords: brace fracture, local buckling, connection instability, steel deck diaphragm, soft-storey mechanism.

Biography

Dr. Robert Tremblay is Professor of Structural Engineering and former Canada Research Chair in Earthquake Engineering at Polytechnique Montreal, Canada. Before undertaking his doctoral studies, Dr. Tremblay worked for 10 years in the industry. His current research activities are mainly directed towards the seismic design and response of steel structures for buildings and bridges, with focus on innovative structural systems for enhanced seismic performance. He is a member of several code technical committees including the CSA-S16 Technical Committee on Structural Steel Design (Chair of the Work Group on Seismic Design) and the Standing Committee on Earthquake Design of the National Building Code of Canada.

Evaluation and Retrofit of Seismically Deficient Steel Braced Frames in Canada

R. Tremblay
Polytechnique Montreal, Montreal, QC

Joint NRC-Taiwan Workshop on Earthquake Engineering
Ottawa, Ontario

7-8 October 2019

Group for Research in STRUCTURAL ENGINEERING

POLYTECHNIQUE MONTRÉAL

Plan

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

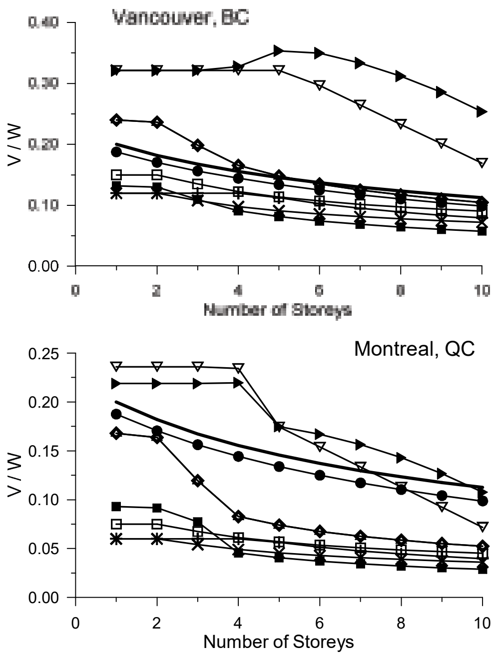
Plan

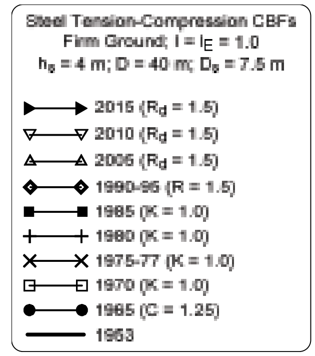
- **Context**
- Bracing members
- Brace Connections
- Multi-Storey Braced Frames
- Metal Roof Deck Diaphragms
- Conclusions

History of Codes and Standards in Canada

NBCC:	CSA-S16 :
	• 1924
	• 1930
• 1941 (E/Q in appendix)	• 1940
• 1953 (E/Q in code)	• 1954
• 1960	• 1961
• 1965	• 1965
• 1970 (PGA – 1%/an)	• 1969
• 1975	• 1974 (Limit States Design)
• 1977	• 1978 (SI)
• 1980	• 1984
• 1985 (Z_a & Z_v - 10%/50 yrs)	• 1989 (Seismic Provisions)
• 1990	• 1994
• 1995	• 2001
• 2005 (UHS - 2%/50 yrs)	• 2005
• 2010	• 2009
• 2015	• 2014
• 2020	• 2019

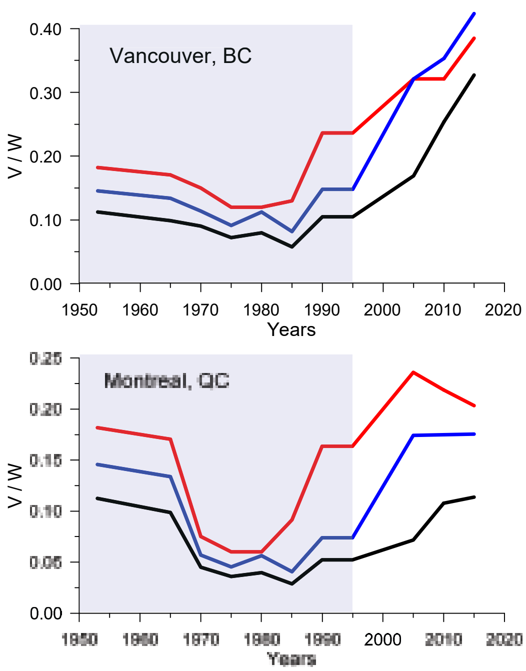
Evolution of seismic design loads

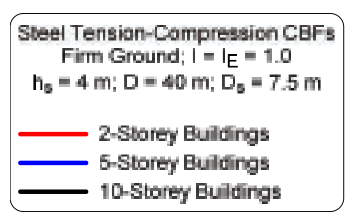




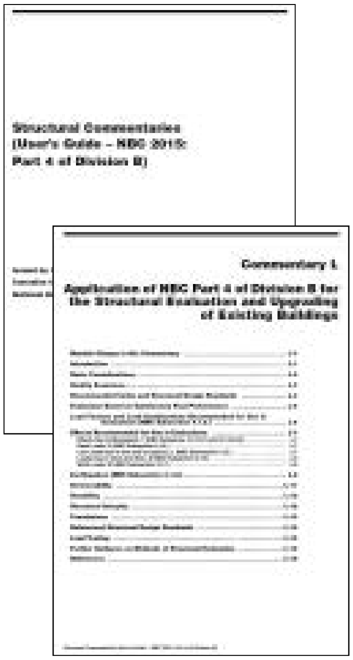
- ***Static Equivalent Force Procedure***
- ***Empirical T***

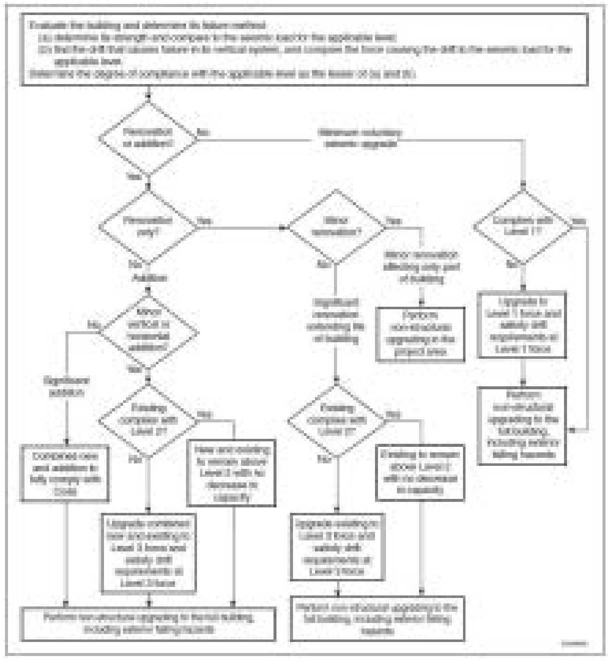
Evolution of seismic design loads





- ***Static Equivalent Force Procedure***
- ***Empirical T***

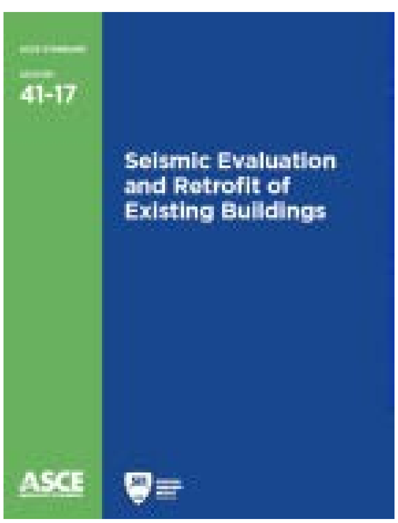




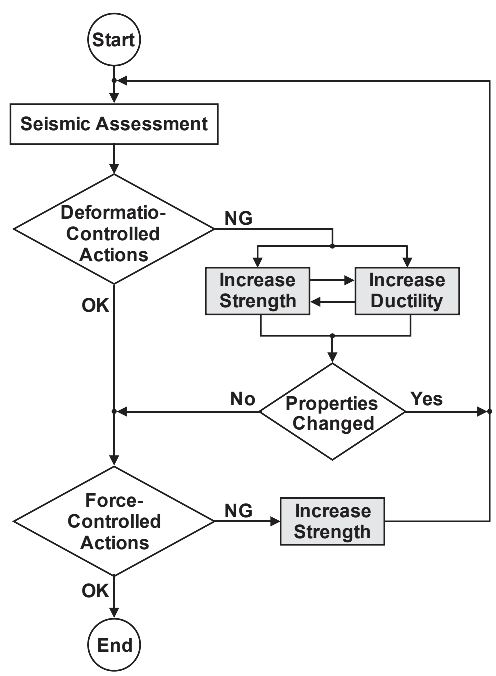
Force-based approach

4 Levels :

- ***1: 0.5 x 5%-50 yrs***
- ***2: 10%-50 yrs***
- ***3: 5%-50 yrs***
- ***4: 2%-50 yrs***



Component Based Approach



Evaluation using linear procedure (force-based approach):

$$m\,Q_{CE} \overset{?}{\geq} Q_{UD}$$

m = Ductility factor

Q_{CE} = Expected Strength

Q_{UD} = Seismic Force Demand from Linear Analysis

Table 9-8 (Continued). Acceptance Criteria for Linear Procedures—Structural Steel Components

	m-Factors for Linear Procedures[a]				
		Primary		Secondary	
Component/Action	IO	LS	CP	LS	CP
Braces in Compression (except EBF braces)					
a. Slender[...] $\frac{Kl}{r} \geq 4.2\sqrt{E/F_y}$					
1. W, I, 2L in-plane[...], 2C in-plane[...]	1.25	6	8	7	9
2. 2L out-of-plane[...], 2C out-of-plane[...]	1.25	5	7	6	8
3. HSS, pipes, tubes, L	1.25	5	7	6	8
b. Stocky[...] $\frac{Kl}{r} \leq 2.1\sqrt{E/F_y}$					
1. W, I, 2L in-plane[...], 2C in-plane[...]	1.25	5	7	6	8
2. 2L out-of-plane[...], 2C out-of-plane[...]	1.25	4	6	5	7
3. HSS, pipes, tubes	1.25	4	6	5	7
Braces in Tension (except EBF braces)[...]	1.25	5[...]	7[...]	8[...]	10[...]

ASCE 41-17

Evaluation using nonlinear procedure

- ***Plastic deformations for deformation-controlled actions***

  Capacity $\overset{?}{\geq}$ Demand

- ***Force demand for force-controlled actions***

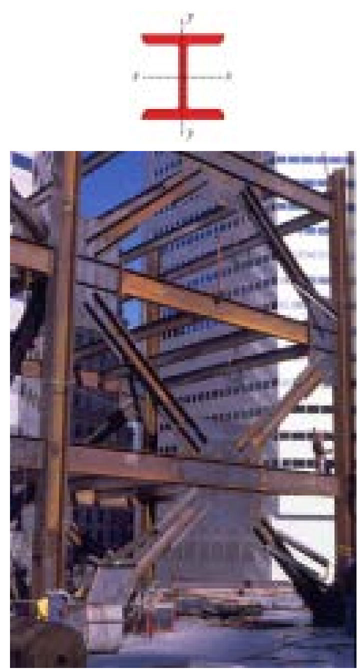
Table 9-8. Modeling Parameters and Acceptance Criteria for Nonlinear Procedures—Structural Steel Components—Axial Actions

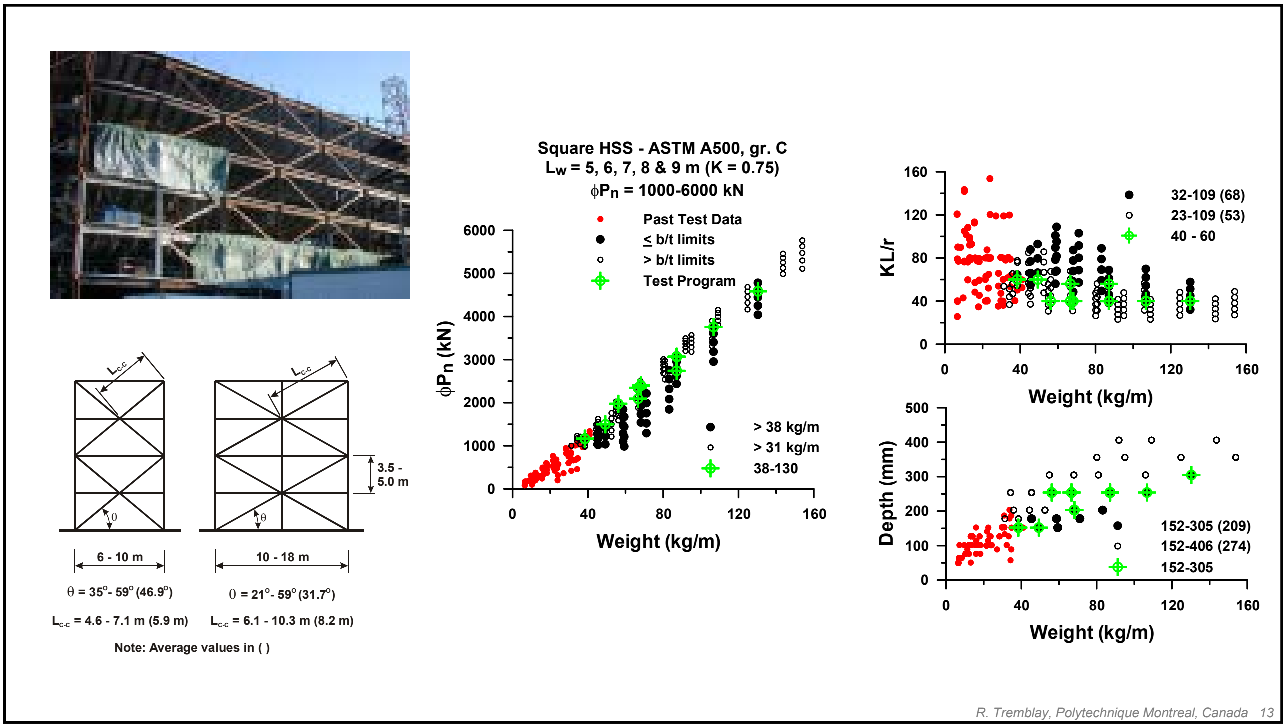
	Modeling Parameters			Acceptance Criteria		
	Plastic Deformation		Residual Strength Ratio	Plastic Deformation		
Component/Action	a	b	c	IO	LS	CP
Braces in Compression (except EBF braces)[...]						
a. Slender $\frac{Kl}{r} \geq 4.2\sqrt{E/F_y}$						
1. W, I, 2L in-plane[...], 2C in-plane[...]	$0.5\Delta_c$	$10\Delta_c$	0.3	$0.5\Delta_c$	$8\Delta_c$	$10\Delta_c$
2. 2L out-of-plane[...], 2C out-of-plane[...]	$0.5\Delta_c$	$9\Delta_c$	0.3	$0.5\Delta_c$	$7\Delta_c$	$9\Delta_c$
3. HSS, pipes, tubes	$0.5\Delta_c$	$9\Delta_c$	0.3	$0.5\Delta_c$	$7\Delta_c$	$9\Delta_c$
4. Single angle	$0.5\Delta_c$	$12\Delta_c$	0.3	$0.5\Delta_c$	$9\Delta_c$	$12\Delta_c$
b. Stocky[...] $\frac{Kl}{r} \leq 2.1\sqrt{E/F_y}$						
1. W, I, 2L in-plane[...], 2C in-plane[...]	$1\Delta_c$	$8\Delta_c$	0.5	$0.5\Delta_c$	$7\Delta_c$	$8\Delta_c$
2. 2L out-of-plane[...], 2C out-of-plane[...]	$1\Delta_c$	$7\Delta_c$	0.5	$0.5\Delta_c$	$6\Delta_c$	$7\Delta_c$
3. HSS, pipes, tubes	$1\Delta_c$	$7\Delta_c$	0.5	$0.5\Delta_c$	$6\Delta_c$	$7\Delta_c$
c. Intermediate	Linear interpolation between the values for slender and stocky braces (after application of all applicable modifiers) shall be used.					
Braces in Tension (except EBF braces)[...]						
1. W	$10\Delta_T$	$13\Delta_T$	0.6	$0.5\Delta_T$	$10\Delta_T$	$13\Delta_T$
2. 2L	$9\Delta_T$	$12\Delta_T$	0.6	$0.5\Delta_T$	$9\Delta_T$	$12\Delta_T$
3. HSS	$9\Delta_T$	$11\Delta_T$	0.6	$0.5\Delta_T$	$8\Delta_T$	$11\Delta_T$
4. Pipe	$8\Delta_T$	$9\Delta_T$	0.6	$0.5\Delta_T$	$7\Delta_T$	$9\Delta_T$
5. Single angle	$10\Delta_T$	$11\Delta_T$	0.6	$0.5\Delta_T$	$8\Delta_T$	$10\Delta_T$

Plan

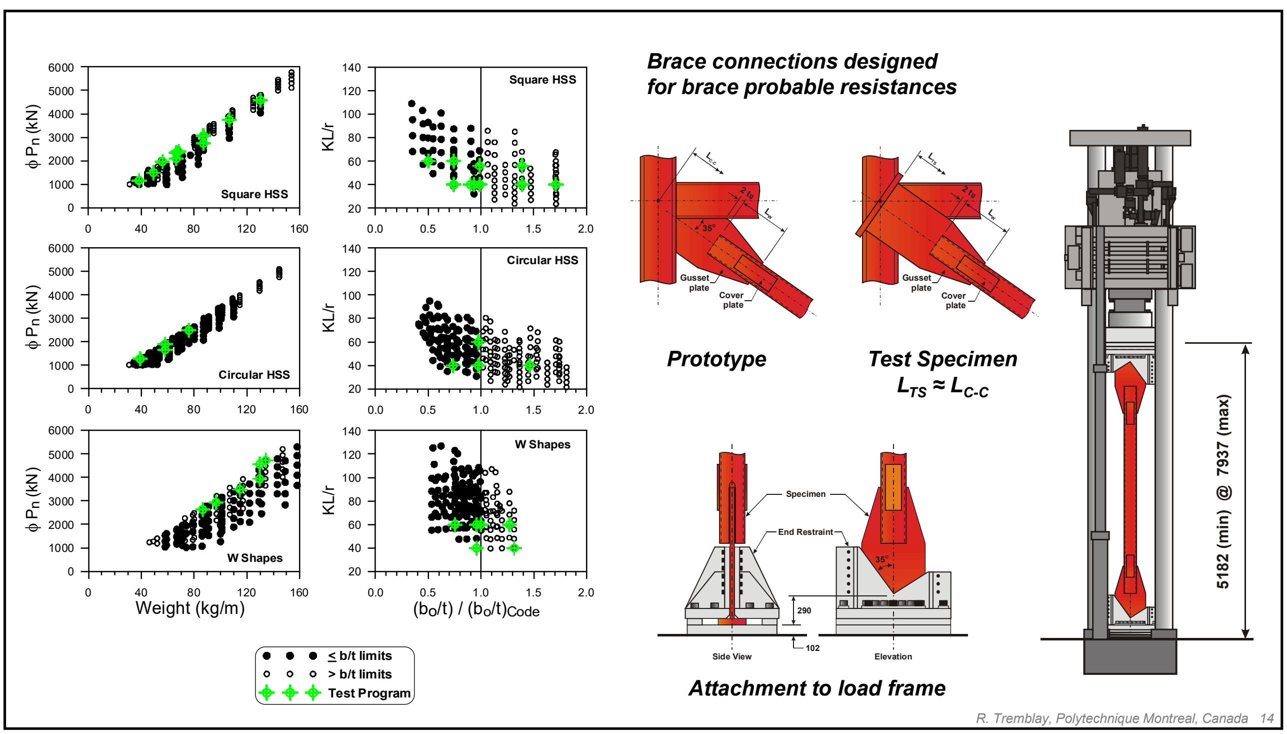
- Context
- **Bracing members**
- Brace Connections
- Multi-Storey Braced Frames
- Metal Roof Deck Diaphragms
- Conclusions

Plastic deformation capacity of bracing members

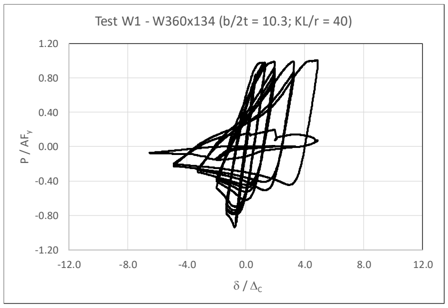


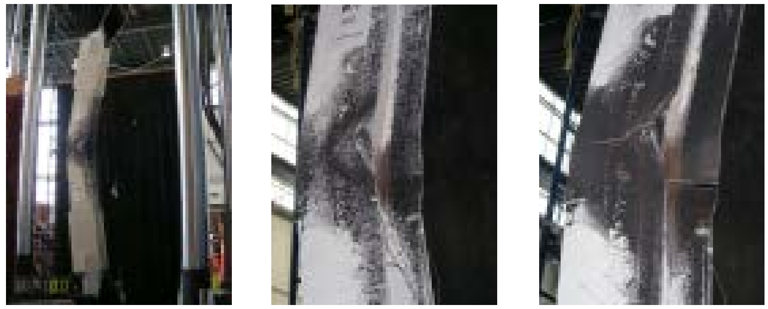


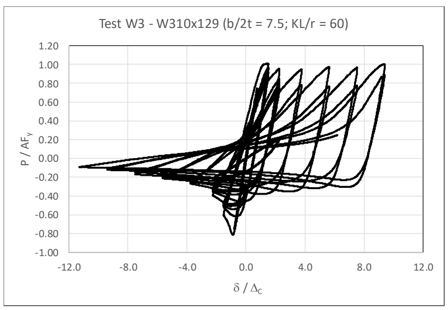
Square HSS - ASTM A500, gr. C
Lw = 5, 6, 7, 8 & 9 m (K = 0.75)
φPn = 1000-6000 kN
Past Test Data
≤ b/t limits
> b/t limits
Test Program
> 38 kg/m
> 31 kg/m
38-130
φPn (kN)
Weight (kg/m)
KL/r
32-109 (68)
23-109 (53)
40 - 60
Depth (mm)
152-305 (209)
152-406 (274)
152-305
Lc-c
3.5 - 5.0 m
6 - 10 m
10 - 18 m
θ = 35°- 59° (46.9°)
θ = 21°- 59° (31.7°)
Lc-c = 4.6 - 7.1 m (5.9 m)
Lc-c = 6.1 - 10.3 m (8.2 m)
Note: Average values in ( )
R. Tremblay, Polytechnique Montreal, Canada 13

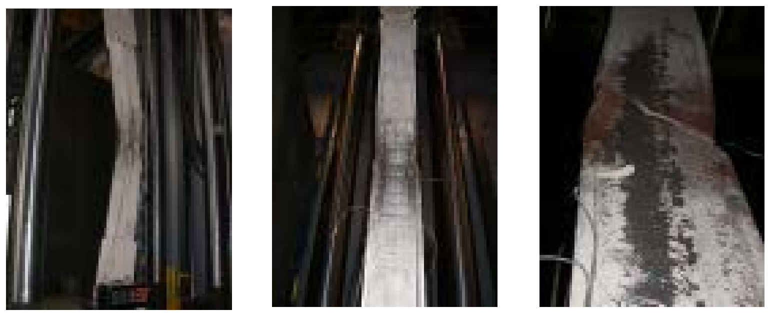


Brace connections designed
for brace probable resistances
φ Pn (kN)
Square HSS
Circular HSS
W Shapes
Weight (kg/m)
KL/r
(bo/t) / (bo/t)Code
≤ b/t limits
> b/t limits
Test Program
Gusset plate
Cover plate
Prototype
Test Specimen
LTS ≈ LC-C
Specimen
End Restraint
290
102
Side View
Elevation
Attachment to load frame
5182 (min) @ 7937 (max)
R. Tremblay, Polytechnique Montreal, Canada 14

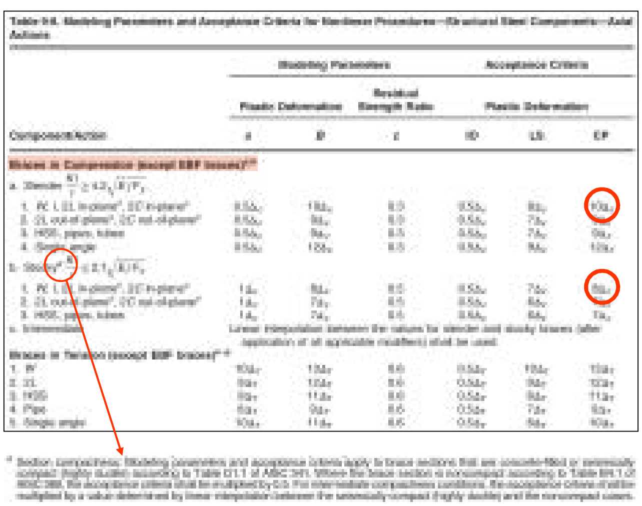


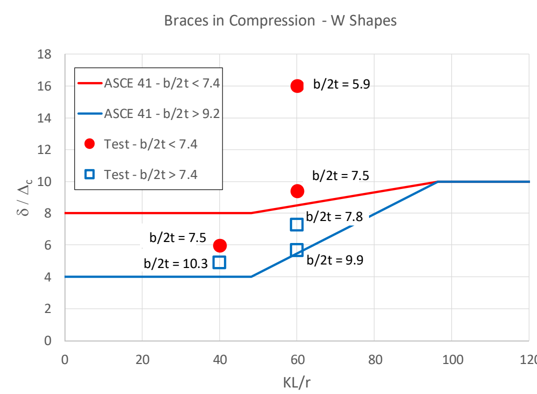


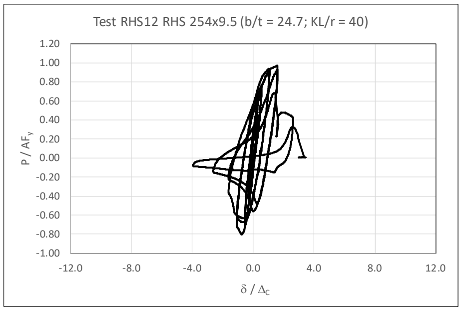


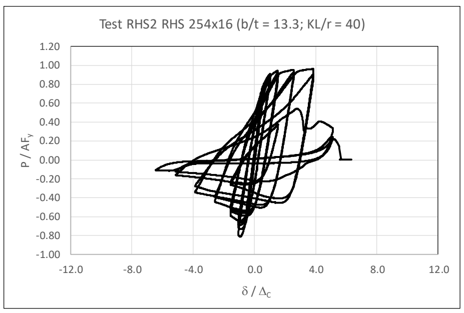


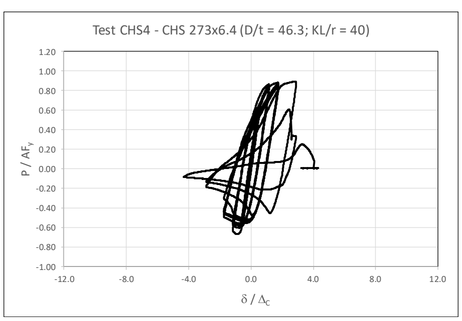
ASCE 41-17
Plastic deformation capacities

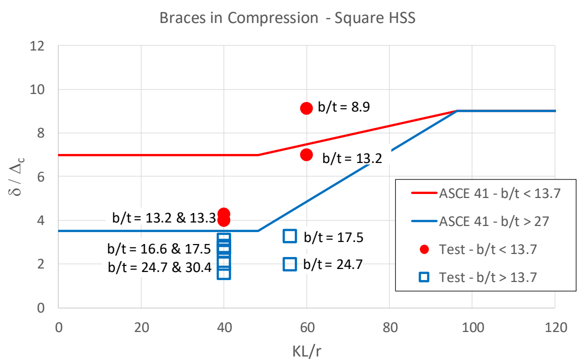


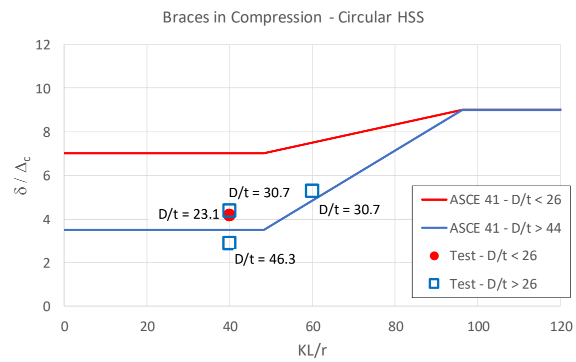



Test RHS12 RHS 254x9.5 (b/t = 24.7; KL/r = 40)
P / AFy
δ / Δc


Test RHS2 RHS 254x16 (b/t = 13.3; KL/r = 40)
P / AFy
δ / Δc


Test CHS4 - CHS 273x6.4 (D/t = 46.3; KL/r = 40)
P / AFy
δ / Δc





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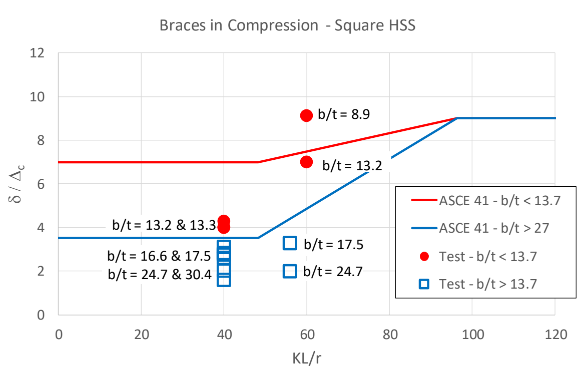

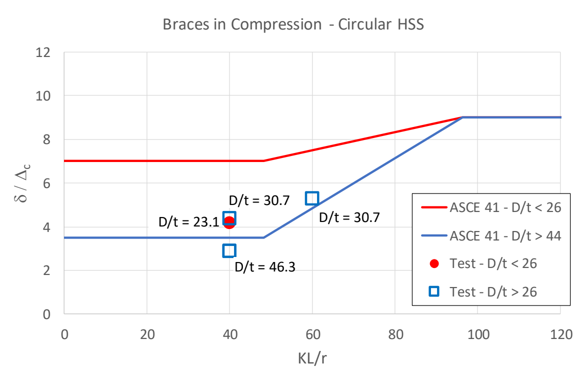

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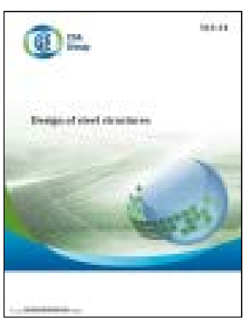
Brace failures observed in past earthquakes

Northridge 1994
Photos from Peter Maranian, Brandow and Associates (P. Uriz Thesis, 2005)



27.5.3 Diagonal bracing members

Note: *Where possible, at every storey, the two discontinuous bracing members in every K-bracing bay should be fabricated and installed from the same heat.*

27.5.3.1 Brace slenderness

The slenderness ratio, KL/r, of bracing members shall not exceed 200.

When the specified short-period spectral acceleration ratio ($I_E F_a S_a(0.2)$) is equal to or greater than 0.75 or the specified 1 s spectral acceleration ratio ($I_E F_v S_a(1.0)$) is equal to or greater than 0.30, the slenderness ratio of HSS bracing members shall not be less than 70.

Note: *The effects of translational and rotational restraints at the brace ends or along the brace length should be accounted for in the calculation of KL.*

27.5.3.2 Width (diameter)-to-thickness ratios

When the specified short-period spectral acceleration ratios ($I_E F_a S_a(0.2)$) are equal to or greater than 0.35, width-to-thickness ratios shall not exceed the following limits:

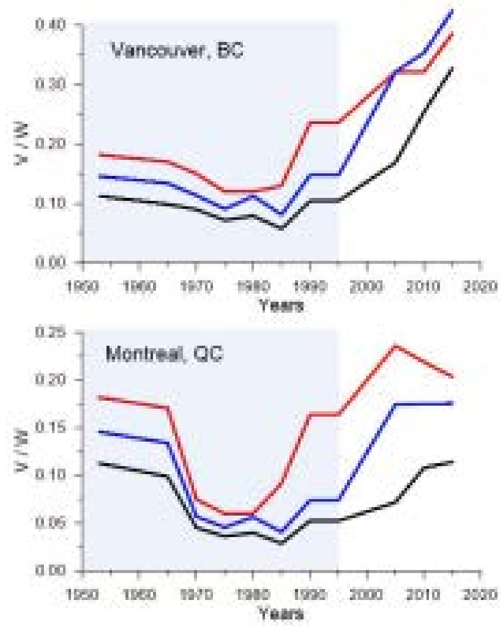
a) when $KL/r \le 100$:
   i) for rectangular and square HSS: $330 / \sqrt{F_y}$;
   ii) for circular HSS: $10\,000/F_y$;
   iii) for legs of angles and flanges of channels: $145 / \sqrt{F_y}$; and
   iv) for other elements: Class 1;
b) when $KL/r = 200$
   i) for HSS members: Class 1;
   ii) for legs of angles: $170 / \sqrt{F_y}$; and
   iii) for other elements: Class 2; and
c) when $100 < KL/r < 200$, linear interpolation may be used.

Possible situations:

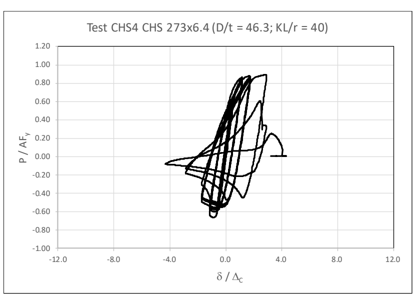
- ***Braces with high local slenderness (high b/t) have been commonly used because of their relatively higher efficiency in compression***
- ***Large inelastic deformation demand expected because of lower original design seismic loads***
- ***Force-based approach alone not sufficient to evaluate existing structures; detailing must also be examined***

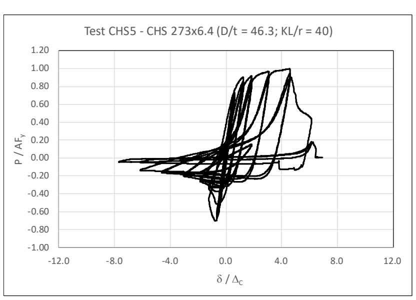
Possible retrofit schemes:

- ***Replace braces using members that meet KL/r and b/t ratio limits (W shapes)***
- ***Use more effective braces (buckling restrained braces, friction dampers, ductile plastic hinges, …)***



Use of a ductile W-shaped plastic hinge for enhanced ductility:



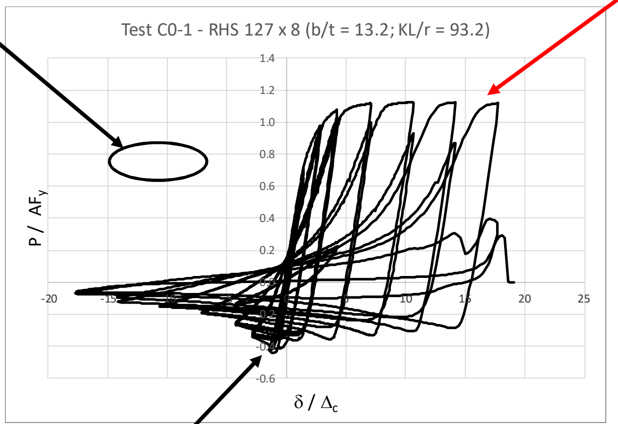


Plan

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

***Tension-Only Bracing* : brace connections designed for tension design loads**

Brace connections expected to sustain tension loads up to the brace probable axial yield strength



***Tension-Compression Bracing* : brace connections designed for compression design loads**