# Seismic Evaluation and Retrofitting of RC Building Structures

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## Introduction

- Why seismic evaluations?
- Methods for seismic evaluations
- FEMA 310 / ATC 40 Procedures
- Euro Code seismic evaluation and retrofitting requirements
- Why retrofitting?
- Typical deficiencies of masonry buildings
- Typical deficiencies of RC buildings
- Typical failures of RC columns



## Seismic Evaluation Methods

- Qualitative evaluation
  - Condition Assessment
  - Visual inspection
  - Non destructive testing
- Analytical evaluation
  - Linear static analysis Capacity/Demand
  - Non linear Static (Push over) Analysis
  - Inelastic THA

## Qualitative Methods

- Condition assessment is based on:
  - Available documentation specific to the building
  - Past performance of similar structures under EQ
- Visual inspection report
  - Structural layout and geometry
- Non-destructive testing
  - Material strengths
  - Detail of the structural system



## Analytical Method

- Linear Static Analysis (ELF or RSA)
  - Demand Capacity ratio (DCR)
- Nonlinear Static (Push over) Analysis
  - Conventional, Modal, Adaptive pushover
  - Software: SAP2000, ETABS, Seismostruct, …
- Nonlinear Time History analysis
  - Software: IDARC, DRAIN, SOFISTIK, …

## Seismic Evaluation Methods

- US standard framework for evaluation and retrofitting
- FEMA 154/ATC-21/1988
  - Rapid visual screening of buildings for potential seismic hazard
- ATC 40/1996
  - Seismic evaluation and retrofitting of concrete buildings
- ASCE 31-02/FEMA 310/1998
  - Seismic evaluation of buildings in three steps (tiers) of higher detail & accuracy
- ASCE/SEI 41-06/FEMA 356/2000
  - Seismic rehabilitation of buildings is the 3rd step of FEMA 310, together with detailed procedure for rehabilitation

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## Seismic Evaluation Methods

- Similar evaluation and retrofitting procedures other countries, such as:
- UNIDO/UNDP 1985; Japan 1990; New Zealand 1996; Italy 1998; Greece 2000. In most cases the procedure is articulated in three successive steps of higher detail and accuracy from first step to the third.
- EN 1998-3: 2005 is relevant to ASCE/SEI 41-06/FEMA 356 and refers to a detailed quantitative assessment and retrofitting of buildings.

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# Information Required for Seismic Evaluation

- According to ATC-40/1996 for the evaluation of reinforced concrete buildings , the information required depends on the evaluation stage (preliminary or detailed) and the availability of original data (calculations or drawings). The following list of tables are recommended

| Level of evaluation | Original drawings available | Original drawings not available |
|---|---|---|
| Preliminary evaluation | Table 5.1 (slide 10) | Table 5.2 (slide 11) |
| Detailed evaluation | Table 5.3 (slide 12) | Table 5.4 (slide 13) |

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# Information Required for Seismic Evaluation (ATC 40/1996)

*Table 5-1. Information Required For Preliminary Seismic Evaluation When Original Construction Drawings are Available*

| Item | Required Yes | Required No | Comment |
|---|---|---|---|
| Structural calculations | | X | Helpful but not essential |
| Site seismicity, geotechnical report | | X | Helpful but updated report should be done |
| Foundation report | | X | Helpful but not essential |
| Prior seismic assessment reports | | X | Helpful but not essential |
| Condition survey of building | X | | |
| Alteration and as built assessment | X | | |
| Walk through dimensioning | | X | Unless required by undocumented alterations |
| Nonstructural walk through | X | | Identify falling hazards, weight. |
| Core testing | | X | Unless concrete appears substandard |
| Rebound hammer testing | | X | Unless concrete appears substandard |
| Aggregate testing | | X | |
| Reinforcement testing | | X | |
| Reinf. location verification | | X | Unless insufficient info. on drawings |
| Nonstructural exploration | | X | |

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## Information Required for Seismic Evaluation (ATC 40/1996)

*Table 5-2. Information Required For Preliminary Seismic Evaluation When Original Construction Drawings are Not Available*

| Item | Required Yes | Required No | Comment |
|---|---|---|---|
| Structural calculations | | X | Could minimize scope of site work |
| Site seismicity, geotechnical report | | X | Could minimize scope of site work |
| Foundation report | | X | Could minimize scope of site work |
| Prior seismic assessment reports | | X | Could minimize scope of site work |
| Condition survey of building | X | | |
| Alteration and as built assessment | X | | |
| Walk through dimensioning | X | | Sufficient to define primary elements |
| Nonstructural walk through | X | | Identify falling hazards, weight |
| Core testing (limited) | X | | Minimum 2 per floor, 8 per building |
| Rebound hammer testing | | X | Could be helpful, especially if concrete appears substandard |
| Aggregate testing | X | | Several cores |
| Reinforcement testing | | X | |
| Reinforcement location verification | | X | Could be helpful |
| Nonstructural exploration | | X | |

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## Information Required for Seismic Evaluation (ATC 40/1996)

*Table 5-3. Information Required For a Detailed Seismic Evaluation When Original Construction Drawings are Available*

| Item | Required Yes | Required No | Comment |
|---|---|---|---|
| Structural calculations | | X | Could be very helpful |
| Site seismicity, geotech rpt. | | X | Helpful but not essential |
| Foundation report | | X | Helpful but not essential |
| Prior seismic assessment reports | | X | Helpful but not essential |
| Condition survey of building | X | | |
| Alteration and as built assessment | X | | |
| Walk through dimensioning | | X | Spot checking is appropriate |
| Nonstructural walk through | X | | Identify falling hazards, weight |
| Core testing | X | | Minimum 2 per floor, 8 per building |
| Rebound hammer testing | X | | Minimum 8 per floor, 16 per building |
| Aggregate testing | X | | Each core |
| Reinforcement testing | | X | Optional |
| Reinforcement location verification | X | | Pachometer @ 10% of critical locations, visual @ 2 locations |
| Nonstructural exploration | X | | Verify anchorage and bracing conditions for components sensitive to Building Performance |

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## Information Required for Seismic Evaluation (ATC 40/1996)

*Table 5-4. Information Required For a Detailed Seismic Evaluation When Original Construction Drawings are Not Available*

| Item | Required Yes | Required No | Comment |
|---|---|---|---|
| Structural calculations | | X | Could be very helpful |
| Site seismicity, geotech rpt. | | X | Helpful but not essential |
| Foundation report | | X | Helpful but not essential |
| Prior seismic assessment reports | | X | Helpful but not essential |
| Condition survey of building | X | | |
| Alteration and as built assessment | X | | |
| Walk through dimensioning | X | | Must be done very thoroughly, particularly if structure will be retrofitted |
| Nonstructural walk through | X | | Identify falling hazards, weight |
| Core testing | X | | Minimum 2 per floor, 8 per building |
| Rebound hammer testing | X | | Minimum 8 per floor, 16 per building |
| Aggregate testing | X | | Each core |
| Reinforcement testing | X | | 2 per type |
| Reinforcement location verification | X | | Pachometer for all critical elements, visual on 25% |
| Nonstructural exploration | X | | Verify anchorage and bracing conditions for components sensitive to Building Performance |

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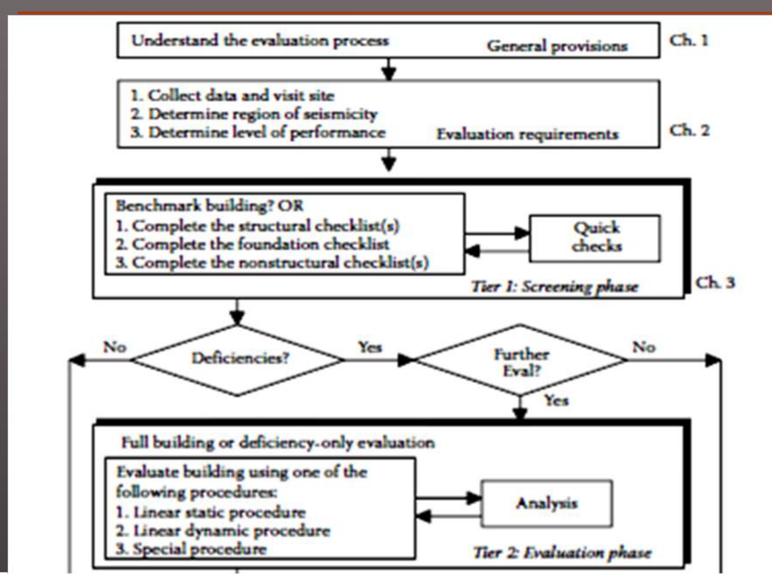
## Evaluation process according to ASCE 31-02/FEMA 310/1998

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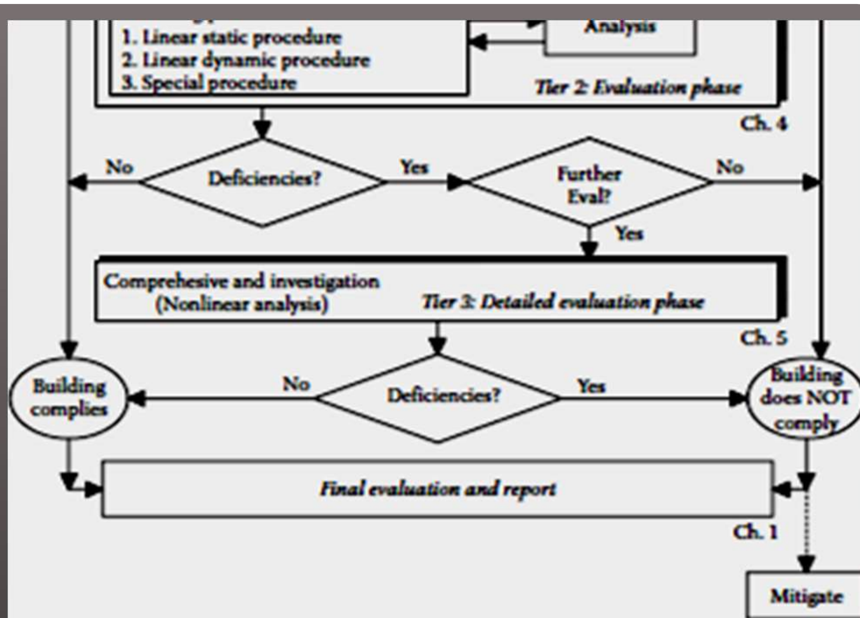


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## Euro-Code 8 (EN 1998-3:2005) Fundamental Requirements

- Limit State of Near Collapse (NC)
  - structure is heavily damaged, with low residual lateral strength and stiffness
  - Most non-structural components have collapsed
  - Large permanent drifts are present.
- Limit State of Significant Damage (SD)
  - structure is significantly damaged, with some residual lateral strength and stiffness
  - Most non-structural components are damaged, although partitions and infill have not failed out-of-plane
  - Moderate permanent drifts are present.

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## Euro-Code 8 (EN 1998-3:2005) Fundamental Requirements

- Limit State of Damage Limitations (DL)
  - structure is lightly damaged, with structural elements prevented from significant yielding and retaining their strength and stiffness properties.
  - Non-structural components, such as partitions and infills, may show distributed cracking, but the damage could be economically repaired
  - Permanent drifts are negligible.



## Euro-Code 8 (EN 1998-3:2005) Information for Structural Assessment

- General Information and History
  - Data from available documentations, relevant generic data sources, field investigation and laboratory tests
- Required Input data
  - Information about the structural system, foundations, ground condition, overall dimensions and cross sectional properties, identifiable material defects and inadequate detailing, type and extent of previous and present damages, …
- Knowledge levels
  - Limited knowledge level (KL1), Normal knowledge level (KL2), Full knowledge level (KL3)

## Euro-Code 8 (EN 1998-3:2005) Information for Structural Assessment

- Factors needed to define the knowledge levels
  - **Geometry**: the geometrical properties of the structural system, and of such nonstructural elements (e.g. masonry infill panels) as may affect structural response.
  - **Details**: these include the amount and detailing of reinforcement in reinforced concrete, connections between steel members, the connection of floor diaphragms to lateral resisting structure, the bond and mortar jointing of masonry and the nature of any reinforcing elements in masonry,
  - **Materials**: the mechanical properties of the constituent materials.

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| Knowledge Level | Geometry | Details | Materials | Analysis | CF |
|---|---|---|---|---|---|
| KL1 | From original outline construction drawings with sample **visual** survey *or* from **full** survey | Simulated design in accordance with relevant practice *and* from **limited** *in-situ* inspection | Default values in accordance with standards of the time of construction *and* from **limited** *in-situ* testing | LF- MRS | $CF_{KL1}$ |
| KL2 | | From incomplete original detailed construction drawings with **limited** *in-situ* inspection *or* from **extended** *in-situ* inspection | From original design specifications with **limited** *in-situ* testing *or* from **extended** *in-situ* testing | All | $CF_{KL2}$ |
| KL3 | | From original detailed construction drawings with **limited** *in-situ* inspection *or* from **comprehensive** *in-situ* inspection | From original test reports with **limited** *in-situ* testing *or* from **comprehensive** *in-situ* testing | All | $CF_{KL3}$ |

From EN1998-3: 2005
Part 3: Assessment and retrofitting of buildings

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## Euro-Code 8 (EN 1998-3:2005) Information for Structural Assessment

**Table 3.2: Recommended minimum requirements for different levels of inspection and testing.**

| | Inspection (of details) | Testing (of materials) |
|---|---|---|
| | For each type of primary element (beam, column, wall): | |
| Level of inspection and testing | Percentage of elements that are checked for details | Material samples per floor |
| Limited | 20 | 1 |
| Extended | 50 | 2 |
| Comprehensive | 80 | 3 |

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## Euro-Code 8 (EN 1998-3:2005) Information for Structural Assessment

- **Confidence Factors ($CF_{KLi}$)**
- To determine the properties of existing materials to be used in the calculation of the capacity, when capacity is to be compared with demand for safety verification, the mean values obtained from *in-situ* tests and from the additional sources of information, shall be divided by the confidence factor, CF, given in Table 3.1 for the appropriate knowledge level
- The recommended values are $CF_{KL1} = 1.35$, $CF_{KL2} = 1.20$ and $CF_{KL3} = 1.00$.

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## Euro-Code 8 (EN 1998-3:2005) Information for Structural Assessment

- Analysis Methods
  - LF – lateral force analysis (linear),
  - MRS – modal response spectrum analysis (linear),
  - non-linear static (pushover) analysis,
  - non-linear time history dynamic analysis.
  - q-factor approach.

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## Euro-Code 8 (EN 1998-3:2005) Decision for Structural Interventions

- **Criteria for a structural intervention**
  - On the basis of the conclusions of the assessment of the structure and/or the nature and extent of the damage, decisions should be taken for the intervention.
    - Note: As in the design of new structures, optimal decisions are pursued, taking into account social aspects, such as the disruption of use or occupancy during the intervention.
  - The selection of the type, technique, extent and urgency of the intervention shall be based on the structural information collected during the assessment of the building.

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## Euro-Code 8 (EN 1998-3:2005) Types of Interventions

- Local modification of damaged or undamaged elements
- Addition of new structural elements (bracing, infill walls, steel, timber or RC belts in masonry)
- Modification of structural systems (elimination of vulnerable elements)
- Addition of new structural systems
- Transformation of non-structural into structural elements
- Base isolation & energy dissipative devices
- Mass reduction
- Restriction or change of use of building
- Partial demolition



## Euro-Code 8 (EN 1998-3:2005) Retrofit design procedure

- The retrofit design procedure include the following steps
  - Conceptual design
  - Analysis
  - Verifications

## Retrofitting (Rehabilitation)

- Pre-earthquake strengthening of vulnerable buildings
  - Changes in the design philosophy
  - Changes in utilization of structures
- Post-earthquake repairing
  - Repairing of the damaged portion of the buildings

- Retrofitted structure shall comply to the current standard code requirements

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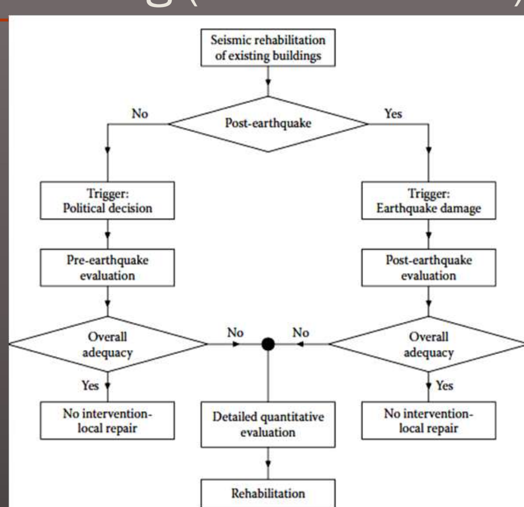
## Retrofitting (Rehabilitation)

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## Typical deficiencies of Masonry structures

- Unreinforced masonry
  - Not earthquake resistant
- Reinforced masonry (Generally performs well)
  - Under-reinforced
  - Ungrouted cells
  - connections


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## Typical deficiencies of RC frames

- Inadequate shear strength in beams, columns and joints
- Inadequate flexural strength and ductility of columns
  - Lack of adequate confinement
  - Insufficient lap length in the plastic hinge region
- Poor concrete quality

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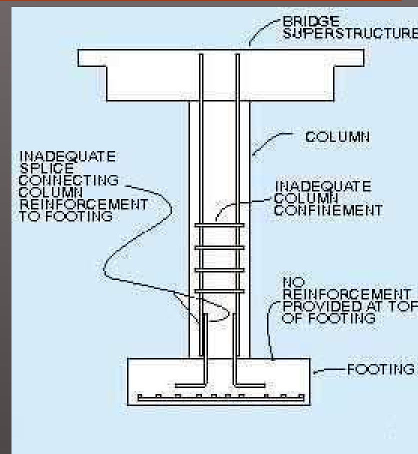
# Typical deficiencies of RC columns

- Inadequate shear strength
- Lack of adequate confinement
- Insufficient lap length in the plastic hinge region
- Strong beam-weak column
- Short (captive) column
- Poor concrete quality

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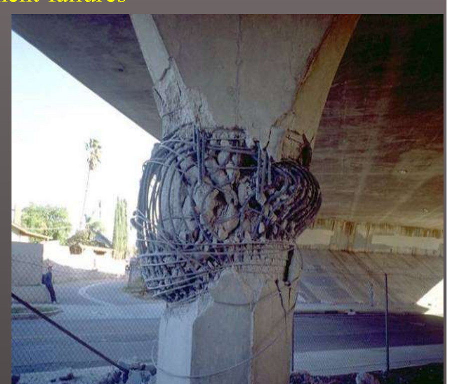
# Typical failures of RC columns

Confinement failures

Izmit, Turkey EQ (1999)



Imperial Valley EQ, California (1979)

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## Typical failures of RC columns

Strong beam – weak column

Izmit EQ, Turkey (1999)

Short (captive) column

Kalamata EQ, Greece (1996)

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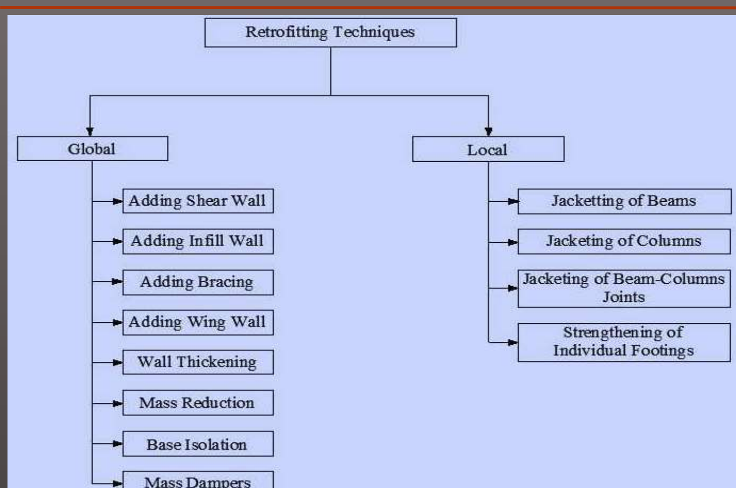
## Different retrofitting techniques

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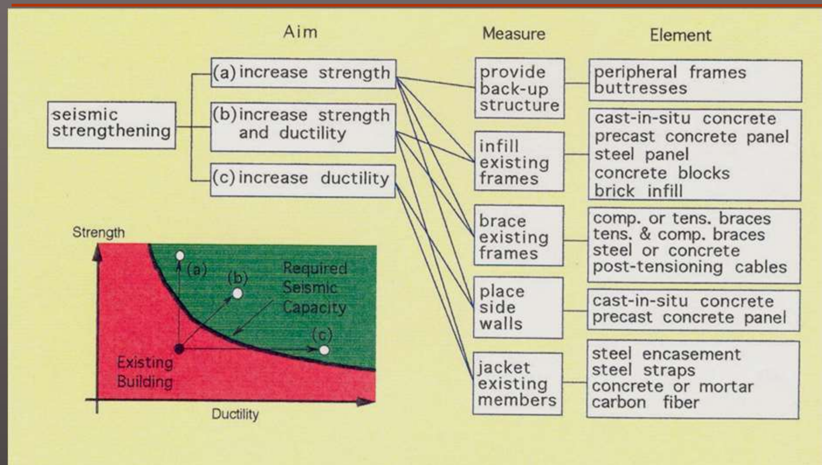
# Different retrofitting techniques

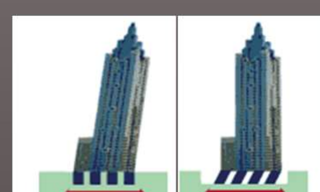


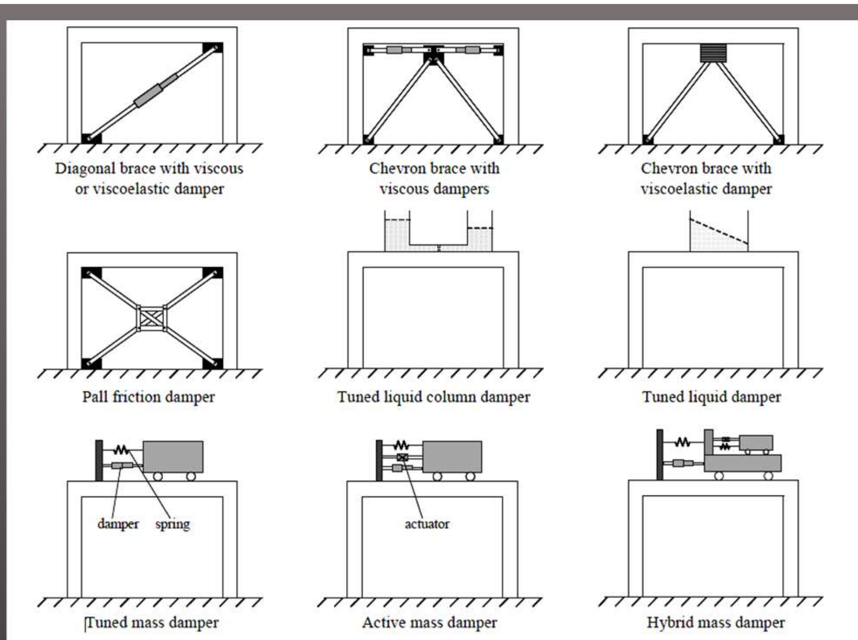
Typical Strengthening Methods



# Innovative Retrofitting Methods

- Base isolation
  - Elastomeric base isolators
  - Sliding base isolators
  - Friction pendulum systems
- Energy dissipating devices
  - Passive devices
  - Active devices
  - Hybrid devices
  - Semi active devices


not isolated isolated

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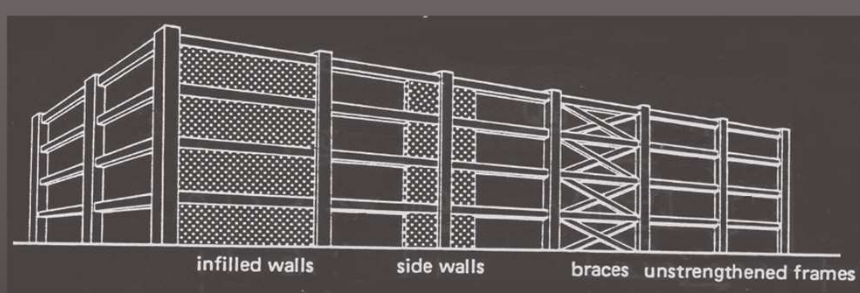
# Retrofitting techniques (cont'd)




Methods used for increasing strength

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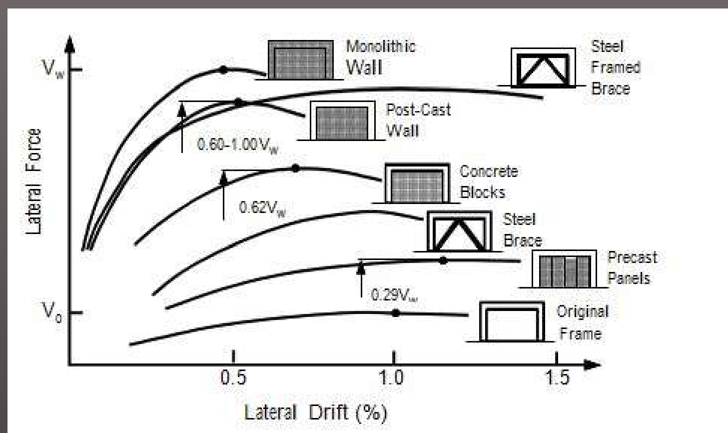
## Retrofitting techniques (cont'd)




(a) Effectiveness of structural walls and bracings

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## Retrofitting techniques (cont'd)

- Adding new shear walls
  - Frequently used for retrofitting of non-ductile RC frame buildings
  - The added elements can be either cast-in-place or precast elements
  - New elements preferably placed at the exterior frames

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## Retrofitting techniques (cont'd)

- Adding steel bracings
  - An effective solution when large openings are required
  - Potential advantage are:
    - Higher strength and stiffness
    - Opening for natural light
    - Amount of work is less since foundation cost is minimized
    - Adds much less weight to the existing structure

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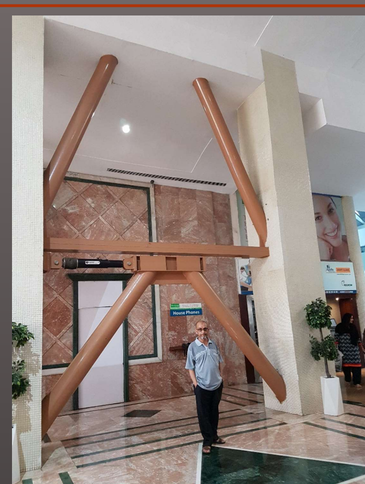
## Retrofitting techniques (cont'd)

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## Retrofitting techniques (cont'd)

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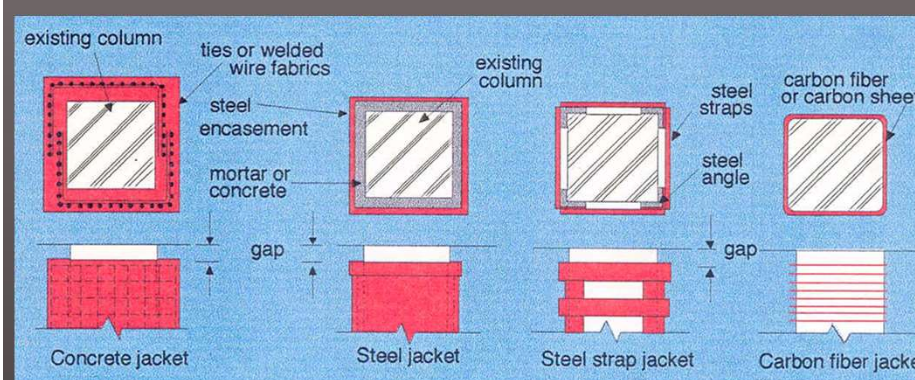
## Retrofitting techniques (cont'd)




Methods used for increasing ductility

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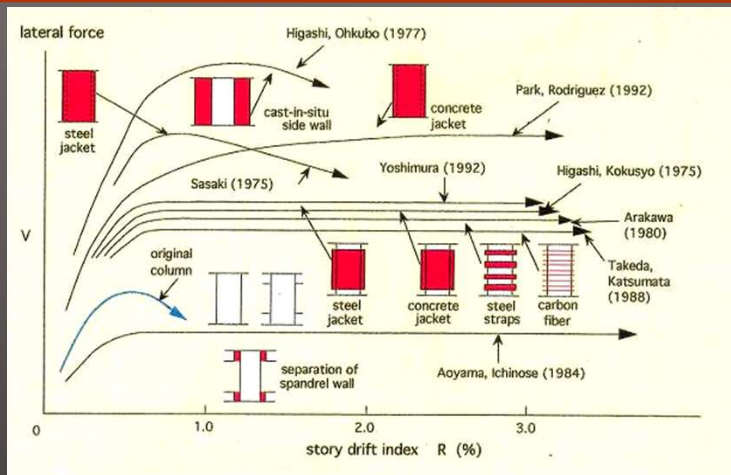
# Retrofitting techniques (cont'd)




Typical Load-displacement Relationships of Columns Reinforced with Various Techniques

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(a) (b)

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## Retrofitting techniques (cont'd)

- Column Jacketing
  - Most popular method of strengthening columns
  - Increases concrete confinement
  - Increases shear strength
  - Increases flexural strength

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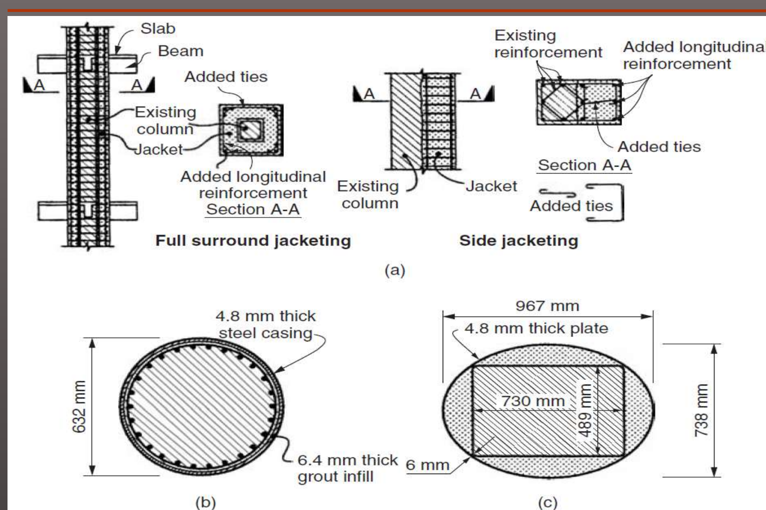
## Retrofitting techniques (cont'd)

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## Retrofitting techniques (cont'd)



## Retrofitting techniques (cont'd)

- Materials used for jacketing
  - Steel jackets
  - Steel straps
  - Fiber Reinforced Polymers (FRP)
- Drawbacks of the above mentioned materials are weight of steel, high cost, fire resistance and durability.

❖Alternative cost-effective material

- **Slurry Infiltrated Mat Concrete (SIMCON)**

## SIMCON (Slurry Infiltrated Mat Concrete)

- Recently developed type of HPFRC
- Produced by infiltration of cement slurry in a pre-placed multiple layers of fiber mesh
- Characteristics
  - high strength, high toughness and high degree of plasticity
  - very ductile behavior with multiple cracking before failure

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## SIMCON (cont'd)

- Mechanical properties
  - Normal strength fiber mesh, $f_{tm}$ = 380 MPa
  - Fiber volume, $V_f$ = 2.2 - 6.0 %

- Flexural strength 17 - 36 MPa
- Compressive strength 90 - 120 MPa
- Tensile strength 7 - 12 MPa
- Elastic modulus 22 - 32 GPa

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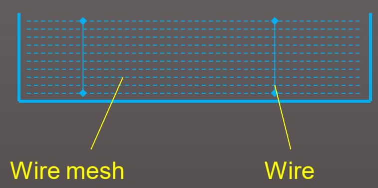
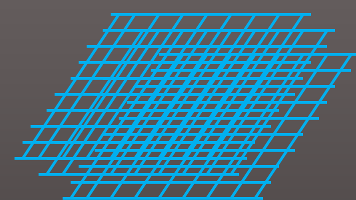
# SIMCON (cont'd)

## System 1

Multiple layer wire mesh



*section* *plan-view*

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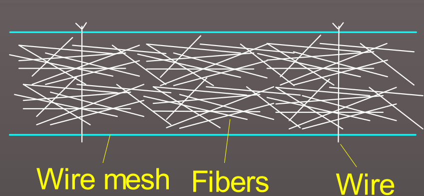
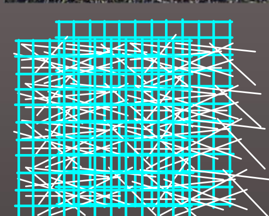
# SIMCON (cont'd)

## System 2

Discrete fibers + wire mesh layers



*section* *plan-view*

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## Research Approach

- Experimental and analytical studies
- Two main types of investigations
  - Confinement properties
    - different volume of fiber mesh layers
    - circular and square shaped cross-sections
  - Cyclical behavior of columns
    - different volume of fiber mesh layers
    - different axial load levels

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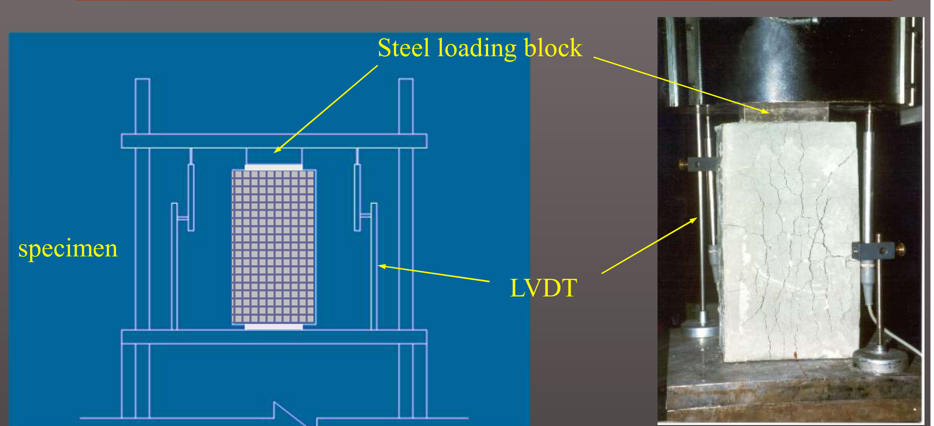
## Uniaxial compression test setup

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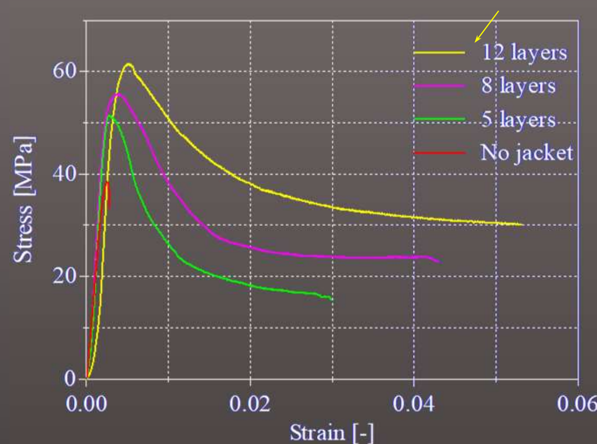
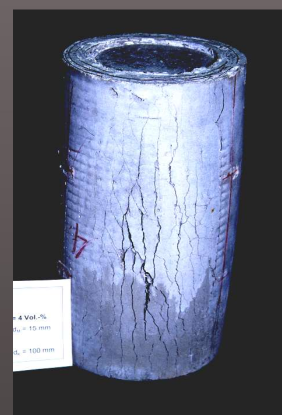
## Compressive stress-strain curves



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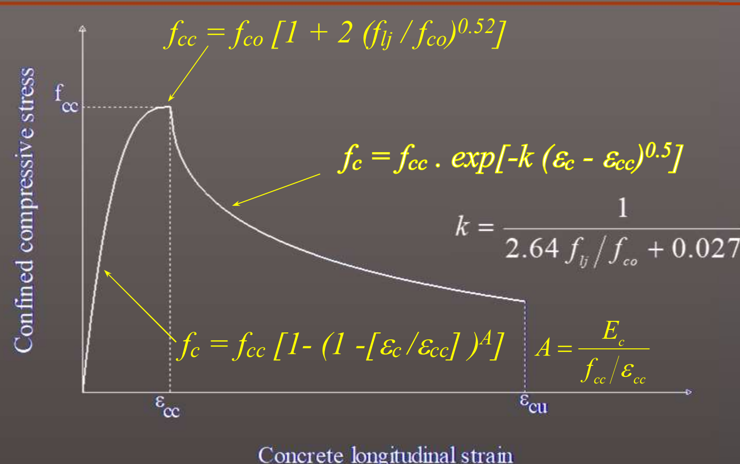
## Analytical confinement model

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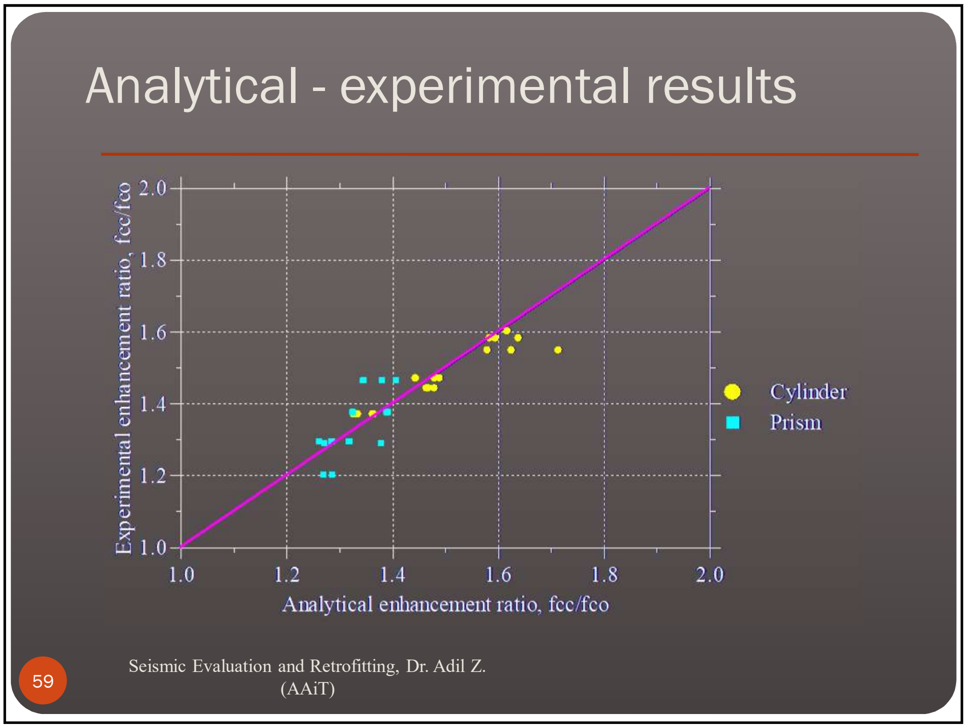
Analytical - experimental results
Experimental enhancement ratio, fcc/fco
2.0
1.8
1.6
1.4
1.2
1.0
1.0
1.2
1.4
1.6
1.8
2.0
Analytical enhancement ratio, fcc/fco
Cylinder
Prism
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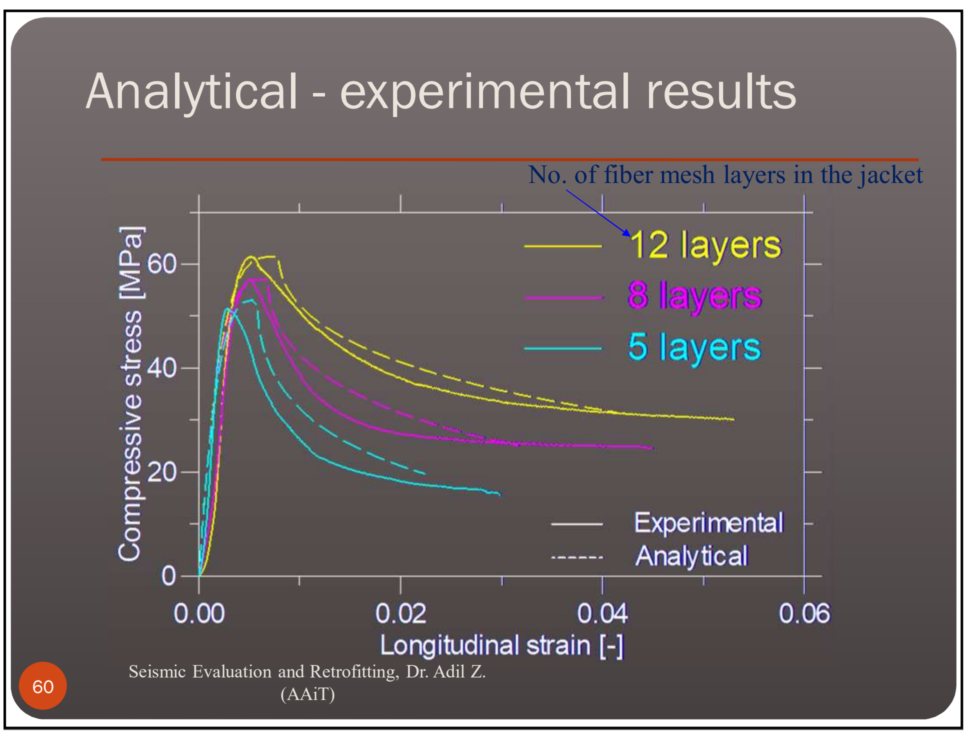
Analytical - experimental results
No. of fiber mesh layers in the jacket
12 layers
8 layers
5 layers
Compressive stress [MPa]
60
40
20
0
0.00
0.02
0.04
0.06
Longitudinal strain [-]
Experimental
Analytical
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## Cyclical loading test program

| Test Series | specimen | Specimen type | Axial load level* | SIMCON Jacket length [mm] | Fiber volume [%] |
|---|---|---|---|---|---|
| 1 | C1-N | 'as-built' | $0.20\ f_{c,cyl}A_g$ | - | - |
| | C1-R | Repaired | | 290 | 2.30 |
| | C2-S | Strengthened | | 290 | 3.82 |
| | C3-N | 'as-built' | | - | - |
| 2 | C4-S | Strengthened | $0.40\ f_{c,cyl}A_g$ | 290 | 3.17 |
| | C5-N | 'as-built' | | - | - |
| | C5-R | Repaired | | 440 | 1.75 |

* $f_{c,cyl}$ is the compressive cylinder strength and $A_g$ is the gross concrete cross section

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## Preparation of test specimen


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# Experimental setup


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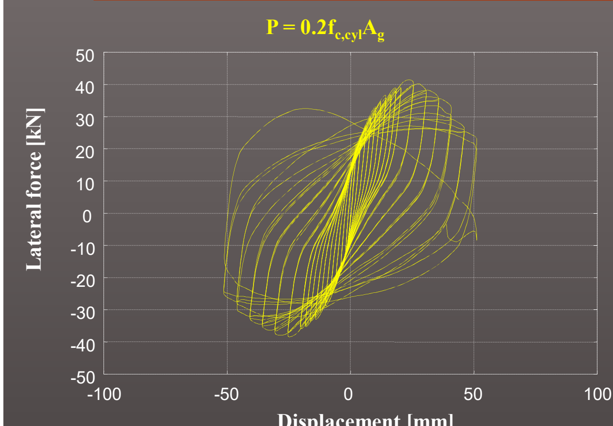
# Test results - "as-built" column - Series 1





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## Column C1-N at the end of test

West side

East side

65

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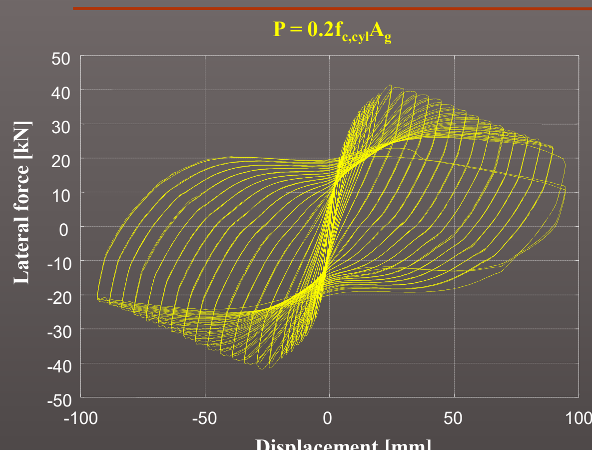
## Test results - retrofitted column - series 1





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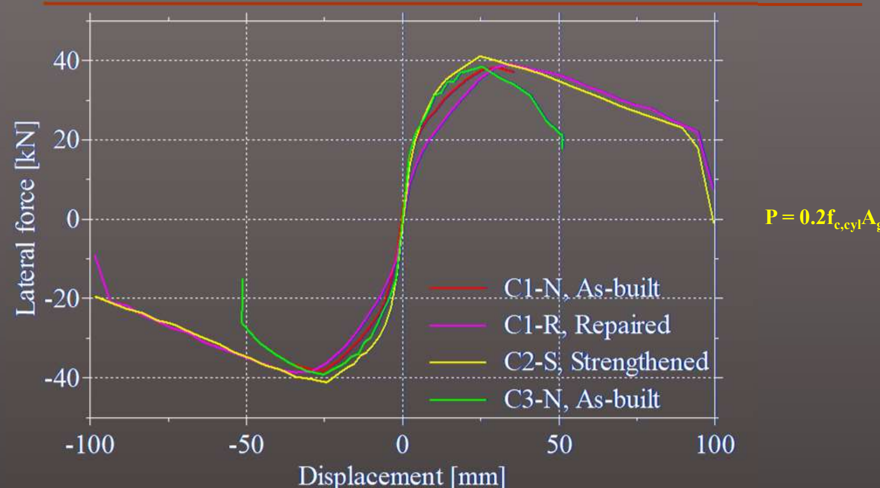
## Envelope curves - Series 1

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## Columns C2-S and C5-N at end of tests

C2-S


C5-N

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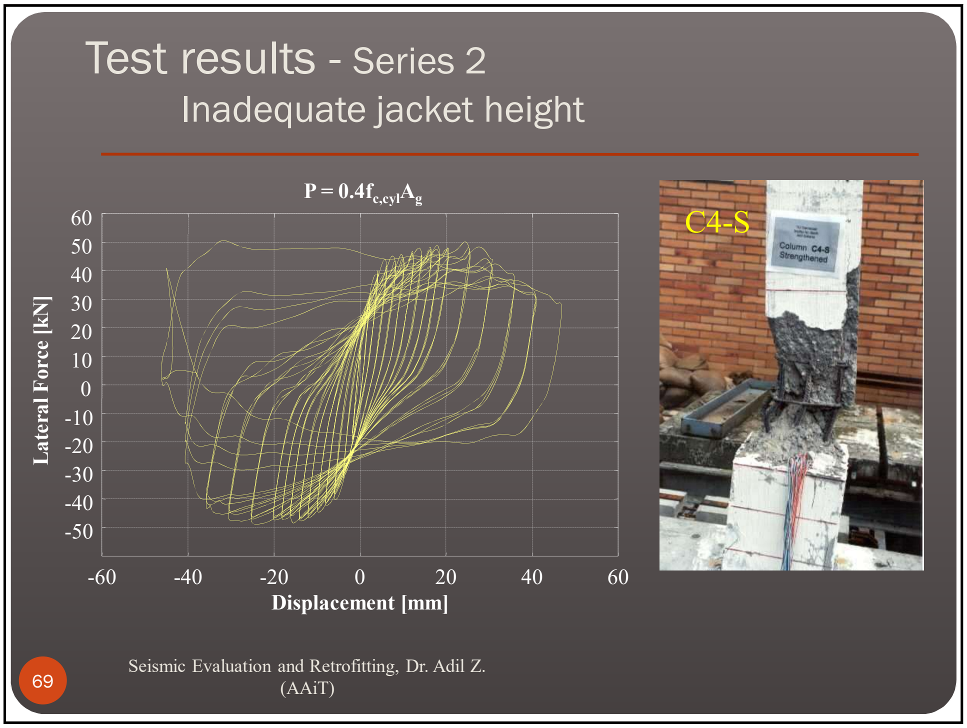
Test results - Series 2
Inadequate jacket height
P = 0.4f c,cyl A g
Lateral Force [kN]
60 50 40 30 20 10 0 -10 -20 -30 -40 -50
-60 -40 -20 0 20 40 60
Displacement [mm]
C4-S
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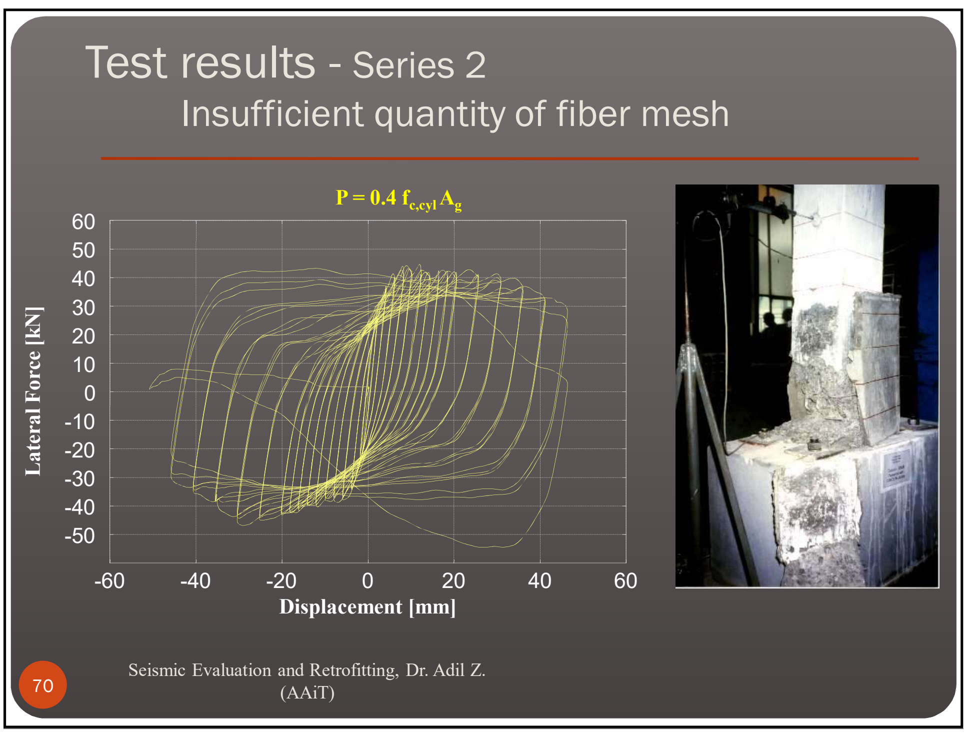
Test results - Series 2
Insufficient quantity of fiber mesh
P = 0.4 f c,cyl A g
Lateral Force [kN]
60 50 40 30 20 10 0 -10 -20 -30 -40 -50
-60 -40 -20 0 20 40 60
Displacement [mm]
70
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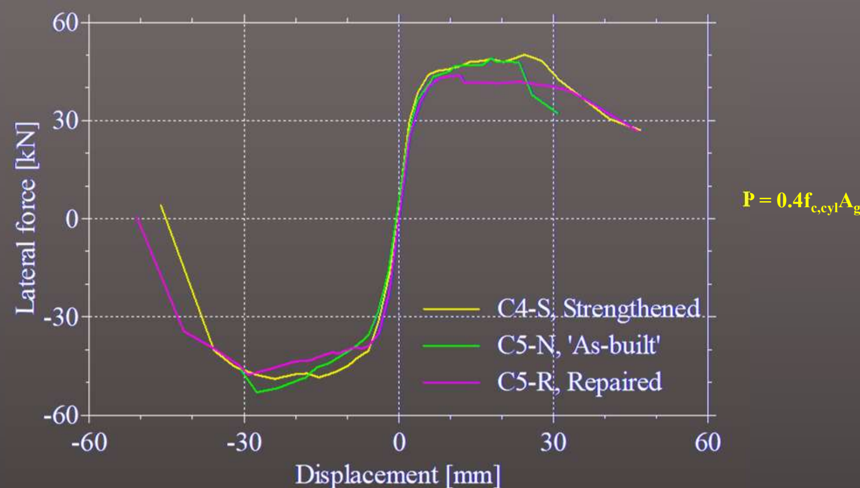
## Envelope curves - Series 2

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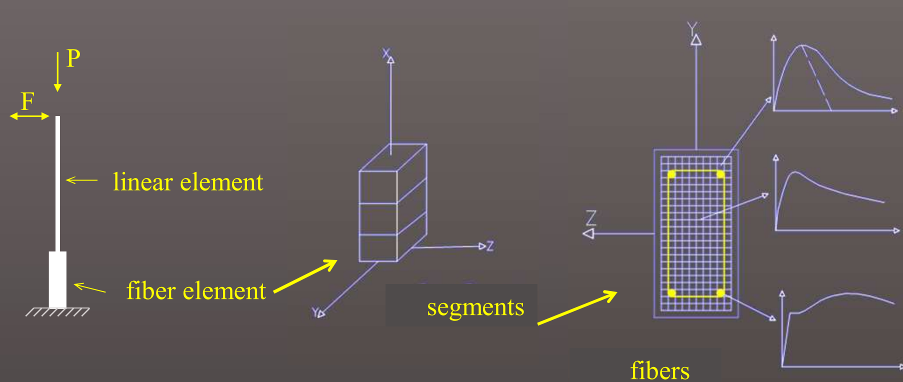
## Fiber element model

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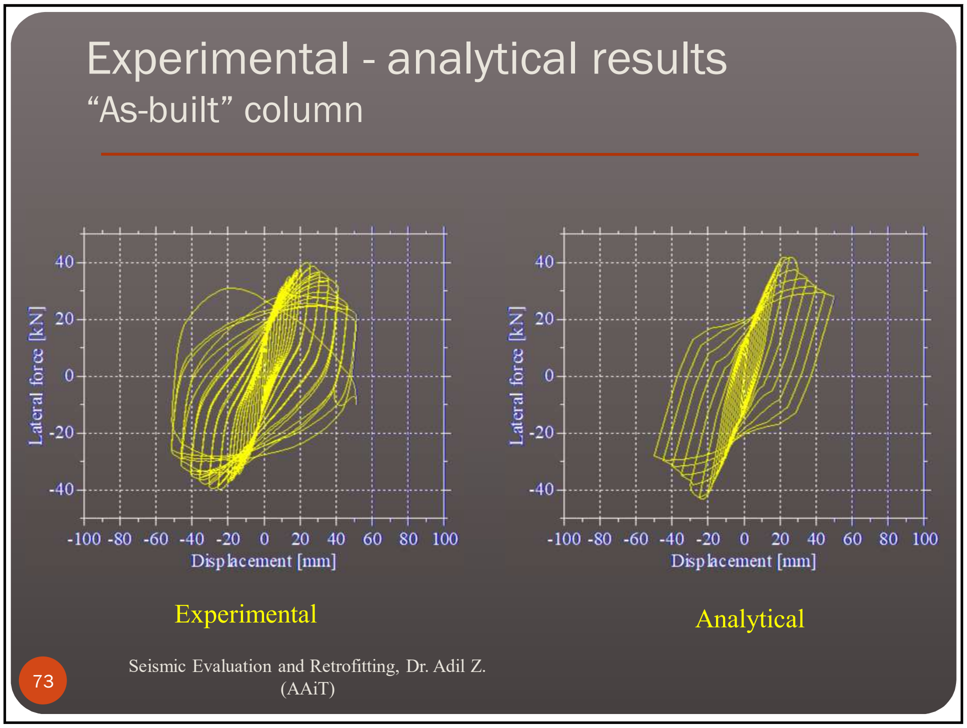

Experimental - analytical results
"As-built" column
Lateral force [kN]
Displacement [mm]
Experimental
Analytical
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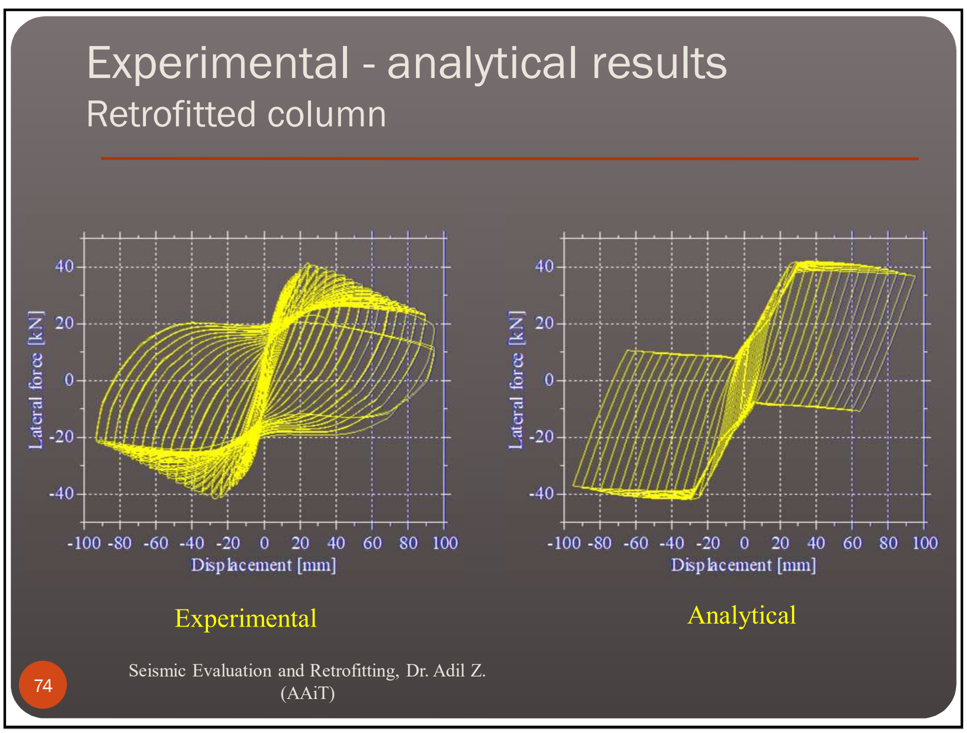

Experimental - analytical results
Retrofitted column
Lateral force [kN]
Displacement [mm]
Experimental
Analytical
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## Conclusions

- Significant enhancement in strength and ductility for axially loaded specimens
- Retrofitted columns behaved very well under reversed cyclic lateral loading. For low axial load level:
  - No spalling of cover concrete, no buckling of longitudinal bars,
  - The columns failed due to rupture of longitudinal bars.
- Height of jacket depends also on axial load level

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## Practical Applications

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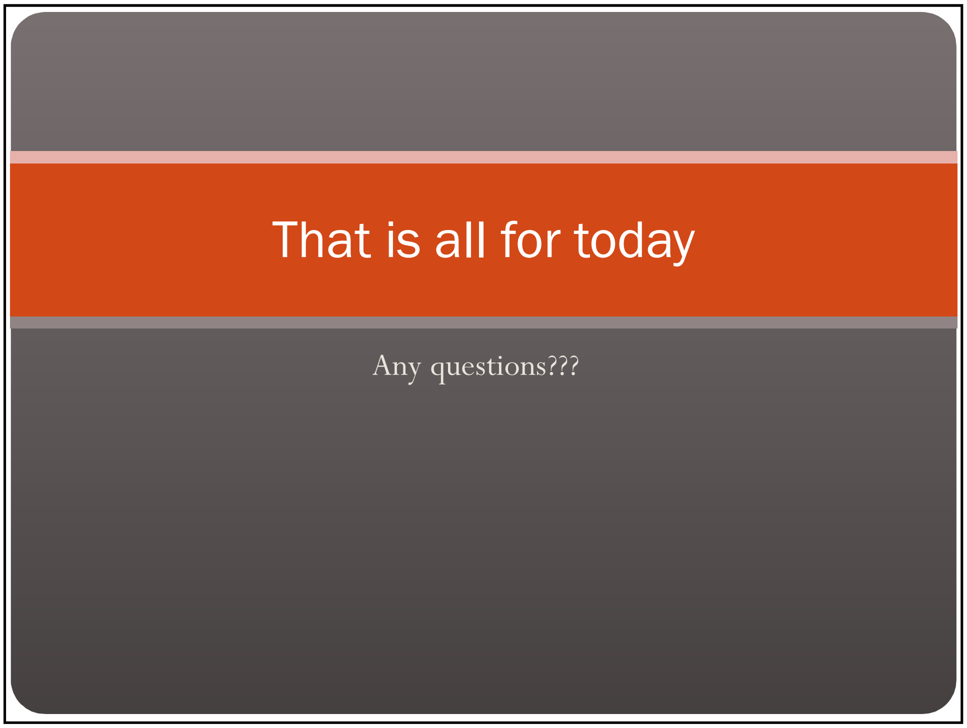
That is all for today
Any questions???