Towards Robust Behavioral Modeling of Reinforced Concrete Members

Kutay Orakçal **Boğaziçi University**

with contributions of:

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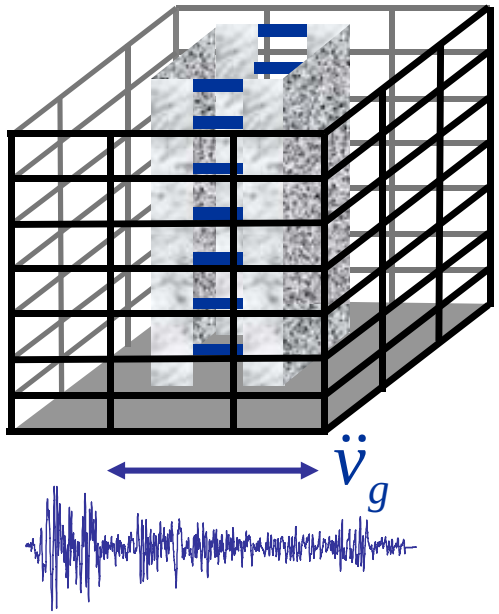
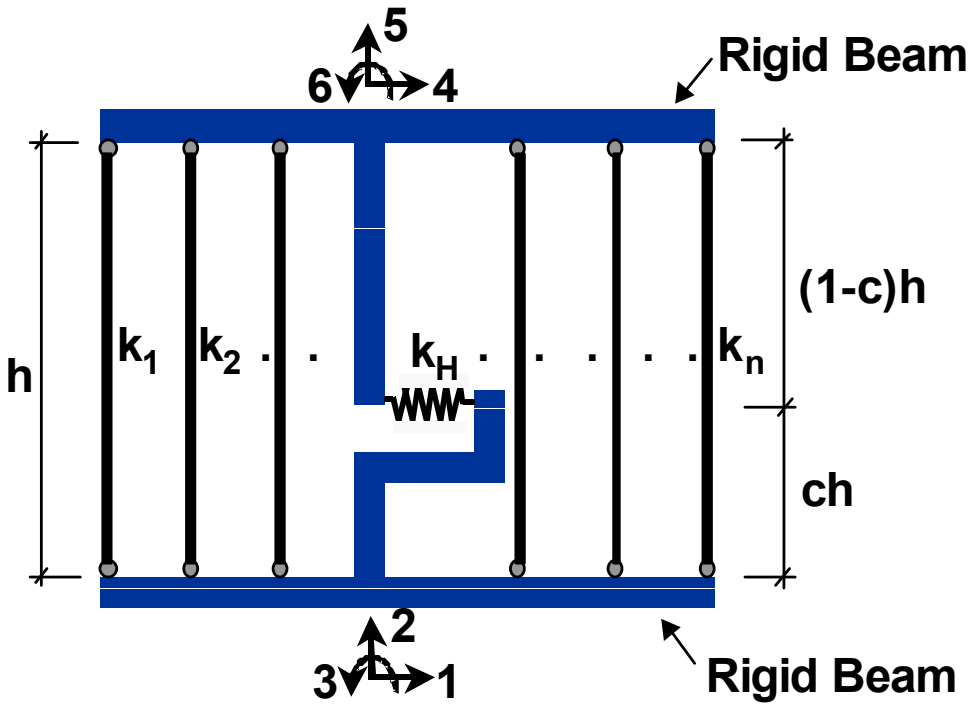
International Workshop on"Role of Research Infrastructures in Seismic Rehabilitation"

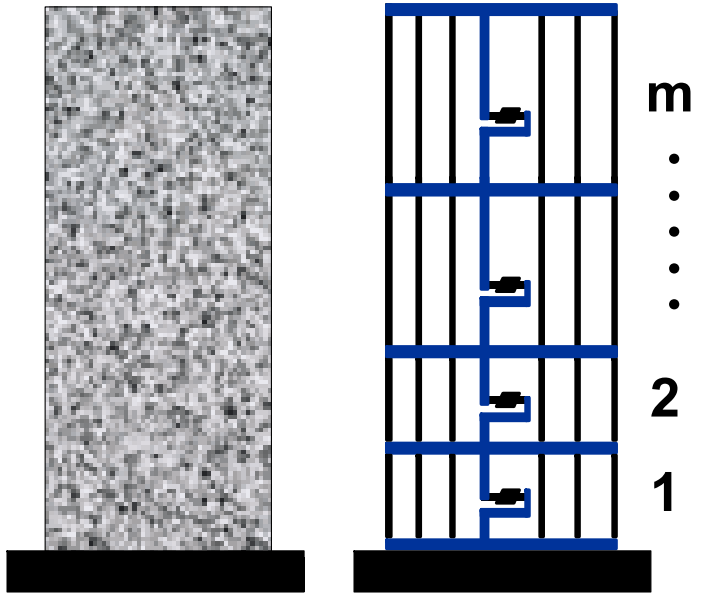
Structural Modeling

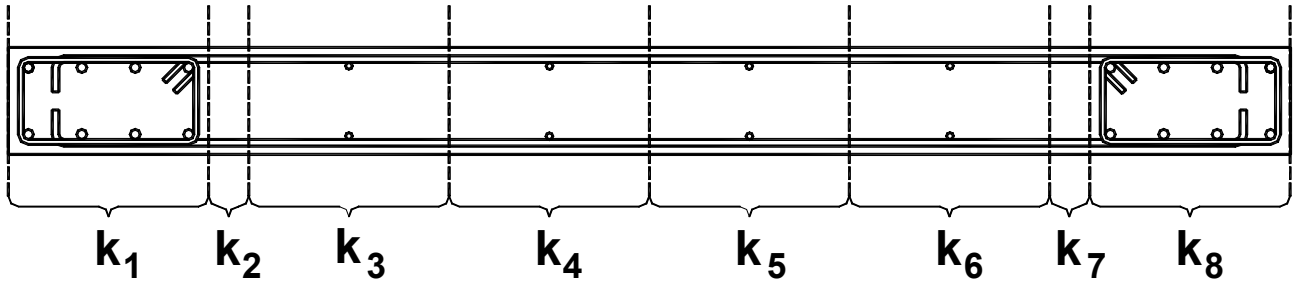
- Modern codes on performance-based seismic assessment and design require **nonlinear response analysis of structures**.
- Analytical models should represent the **behavioral characteristics** of the members **at both global and local response levels.**
- Examples of novel analytical modeling approaches to be presented for nonlinear response simulation of RC members.
- Emphasis on simulation of nonlinear **flexural, shear, and bond-slip responses** in RC columns and walls



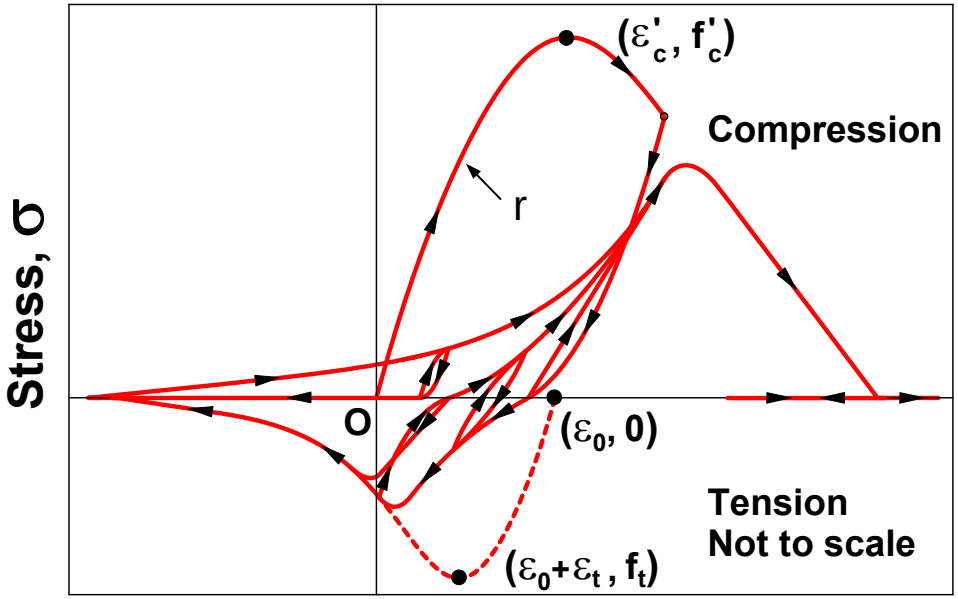
Modeling of Flexural Responses: The "MVLEM" for Structural Walls

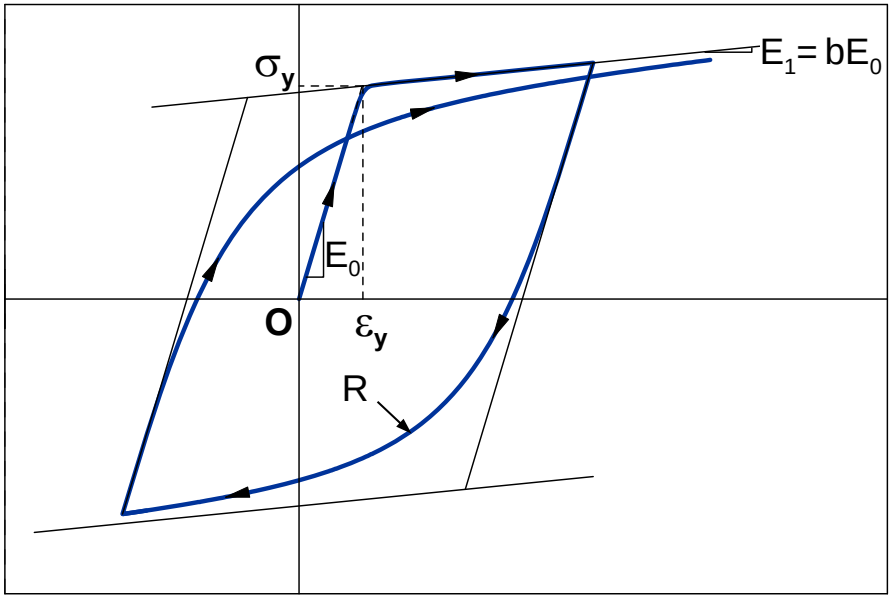






Material Constitutive Models





Concrete :

- Chang and Mander (1994)
  - Generalized (can be updated)
  - Allows refined calibration
  - Gap closure and tension stiffening
  - Validated with extensive data

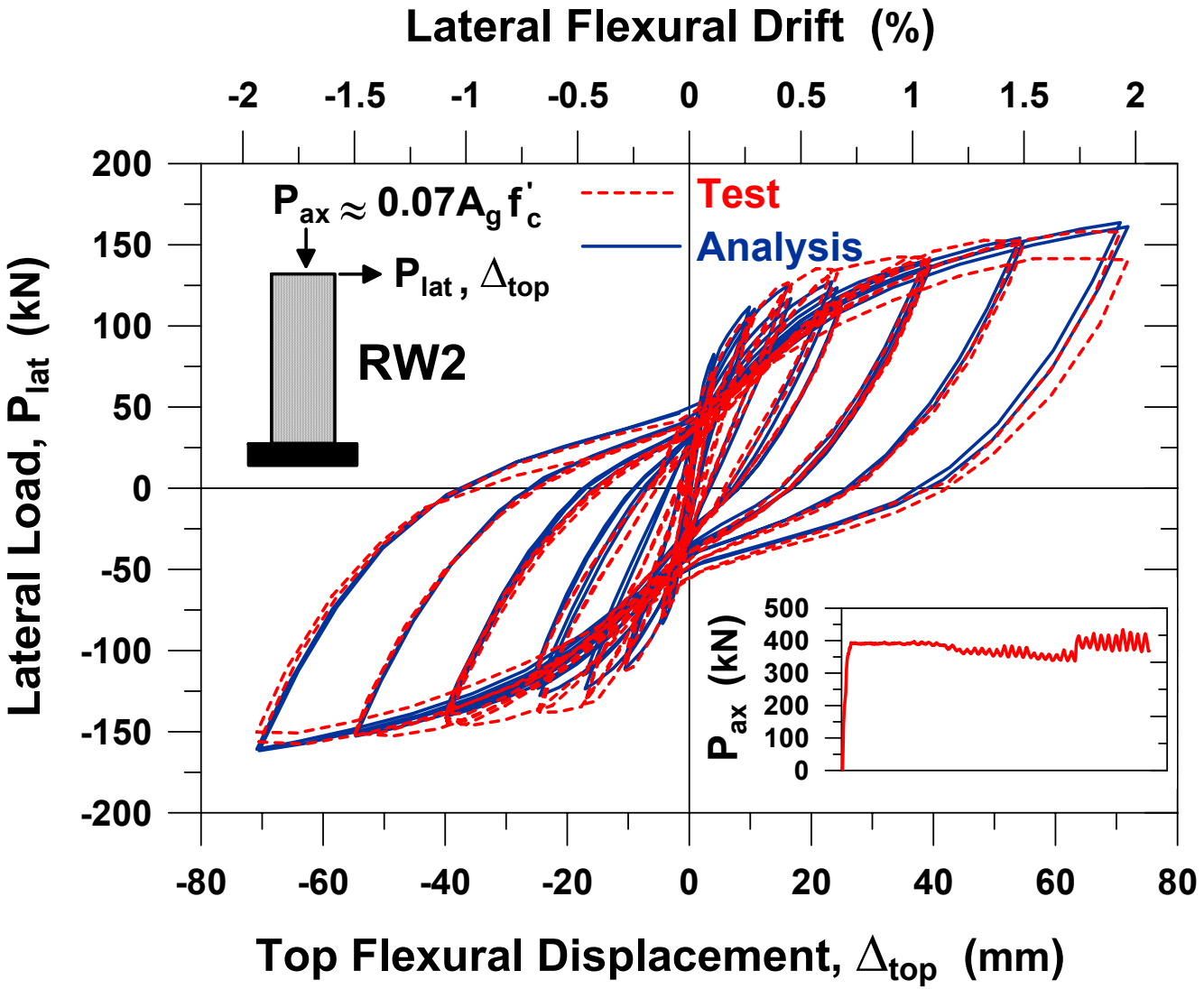
Reinforcing Steel :

- Menegotto and Pinto (1973)
- Filippou et al. (1984)
  - Simple but effective
  - Degradation of cyclic curvature

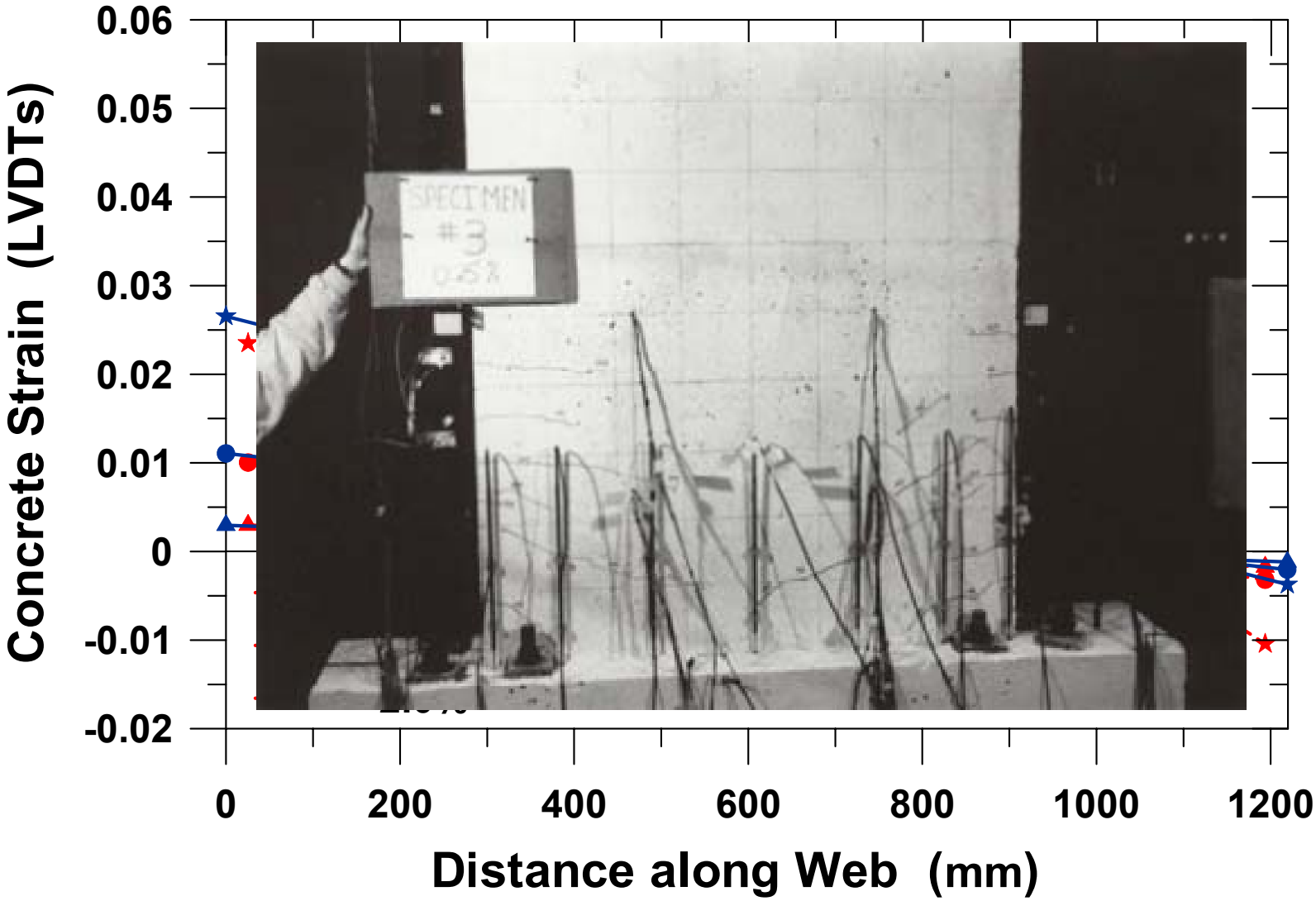
Experimental Verification of the Model

- Cyclic test results on slender rectangular and T-shaped wall specimens
  (Thomsen and Wallace, 1995)
  - Approximately 1/4 scale
  - Aspect ratio = 3
  - Prototype building design (UBC)
  - Displacement – based evaluation for detailing
  - 3.66 m x 122 cm x 10 cm
- Loading:
  - Constant axial load
  - Cyclic lateral load applied at top of walls

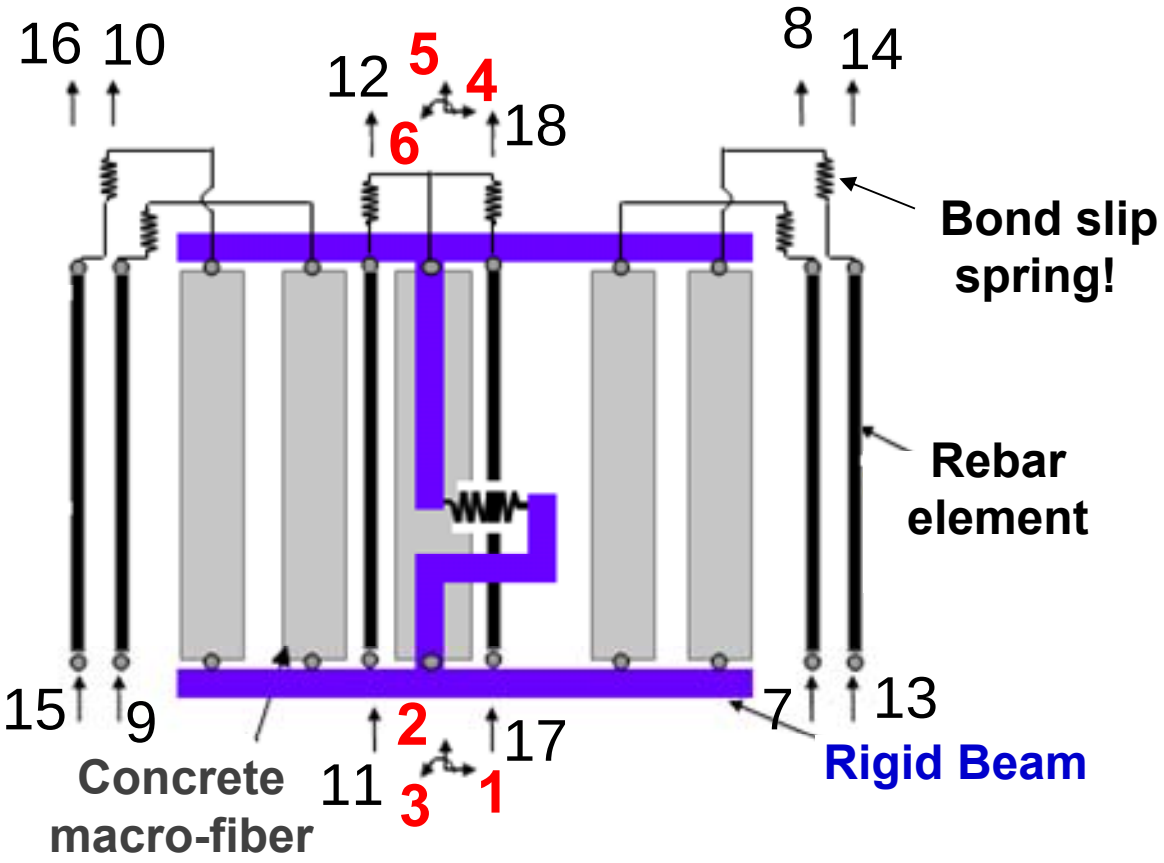
Model Predictions:
Lateral Load – Displacement Response



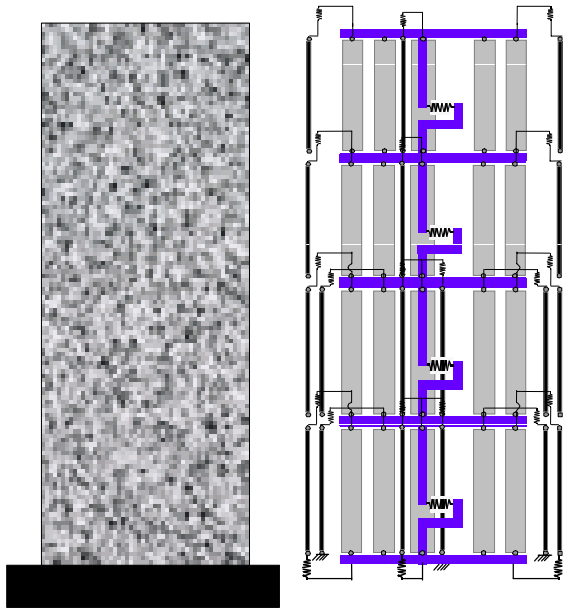
Strain Distribution and Curvatures



Modeling of Bond Slip Responses: MVLEM with Bond Slip Springs (Chowdhury, 2011)



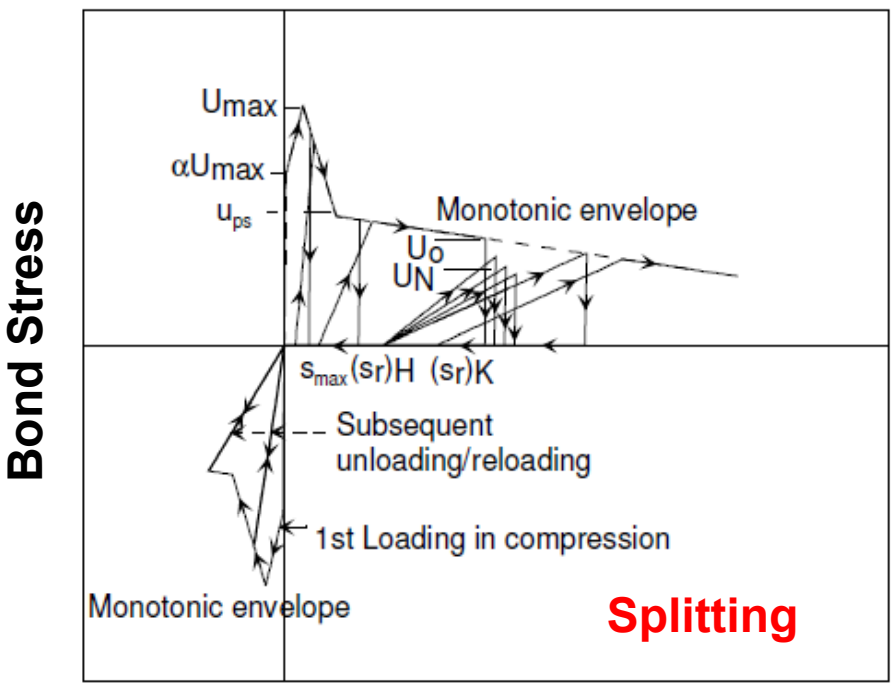
Modified Model Element

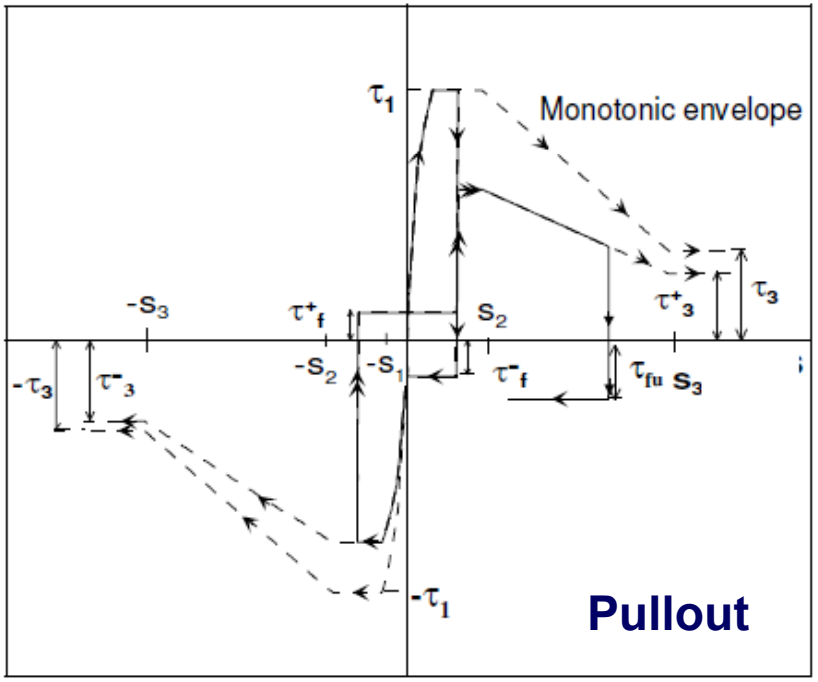


Column or Wall

Analytical model

Constitutive Bond Stress vs. Slip Models





Splitting

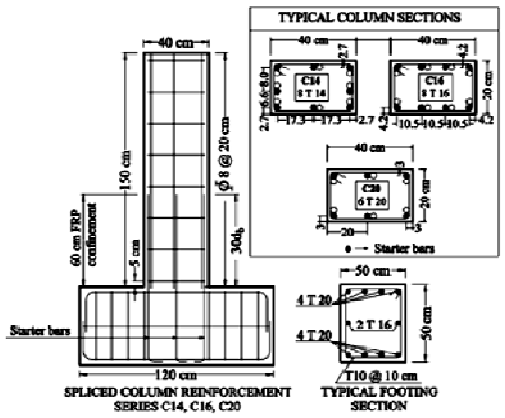
- Harajli et al. (2009)
- Unconfined and partially-confined concrete
- Experimentally-validated

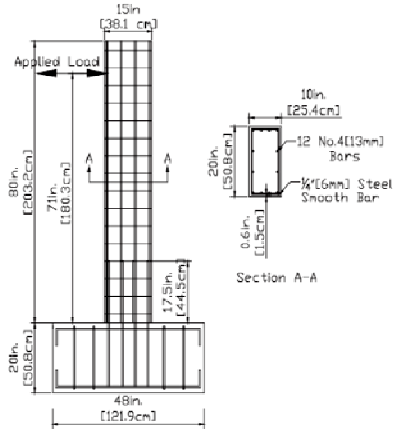
Pull-out

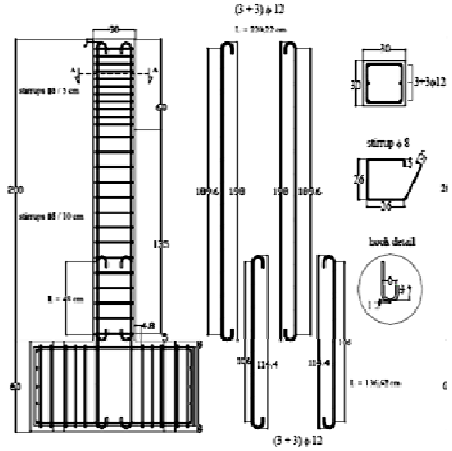
- Eligehausen et al. (1983)
- Confined concrete, in vicinity of ties
- Experimentally-validated

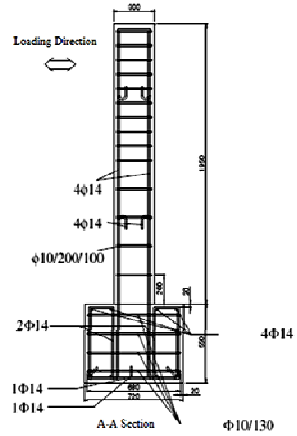
Experimental Verification

- Melek and Wallace (2006)
- Columns with inadequate lap splices
- Detailed local response measurements
- Also verified with various experimental results available in the literature:





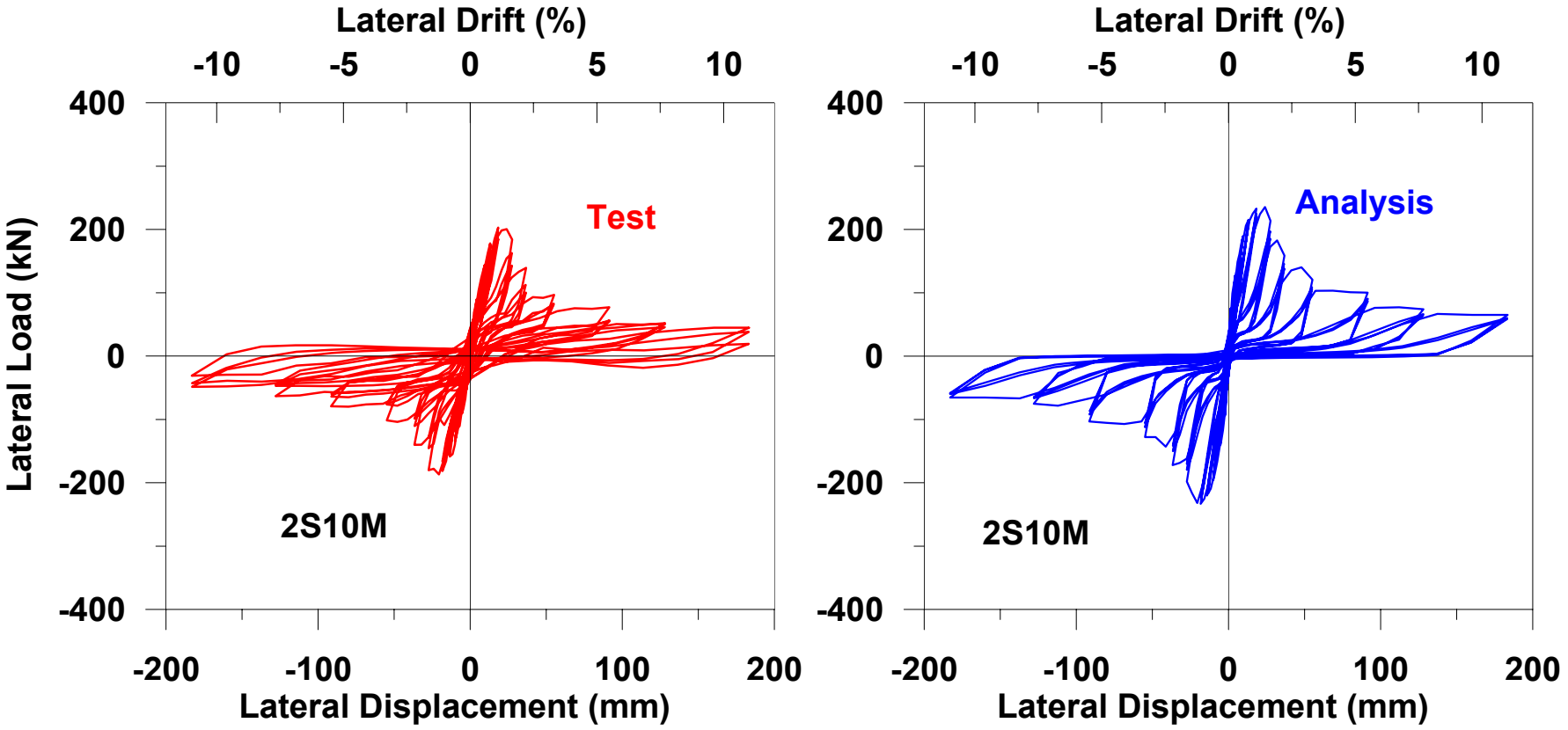




Harajli and Dagher (2008) Elgawady et al. (2010) Verderame et al. (2008) Yılmaz (2009) (ITU)

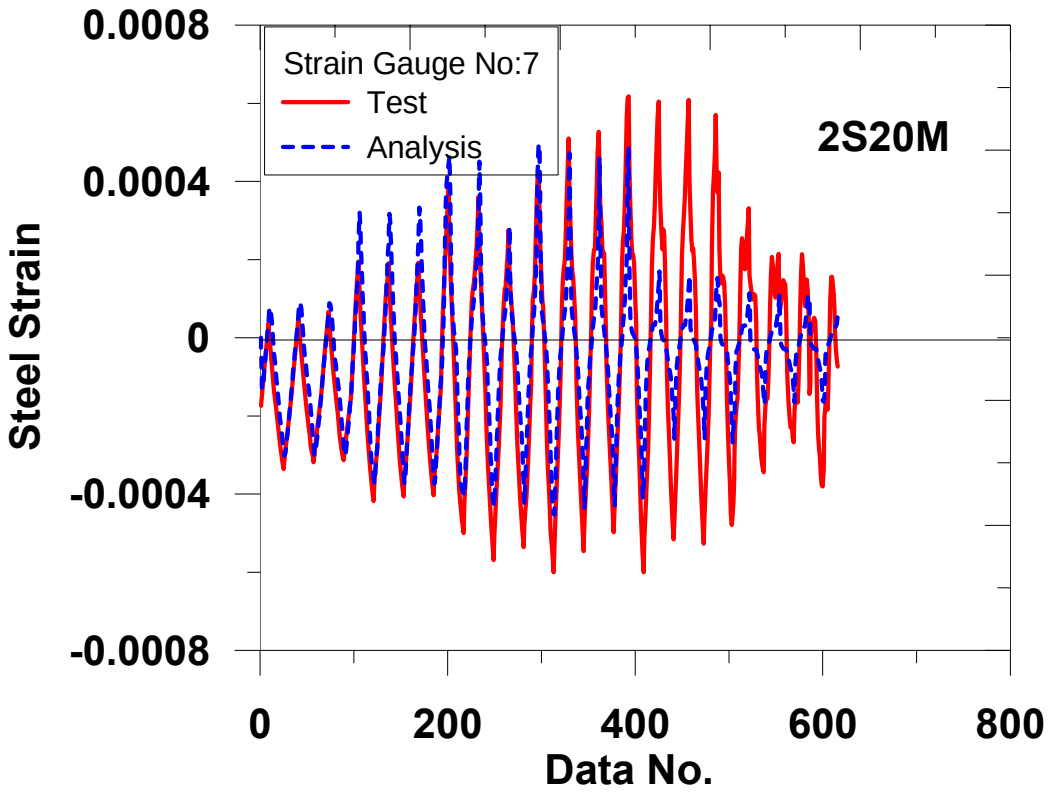
Model Predictions:
Lateral Load – Displacement Response

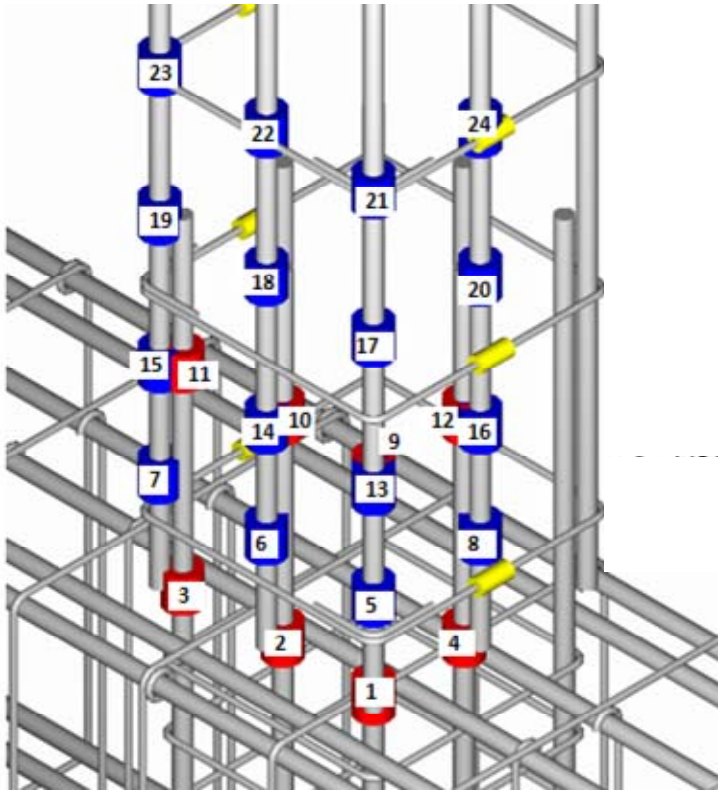
- **Specimen 2S10M** ($P_{axial} = 10\% A_g f_c$)



Steel Strain Histories

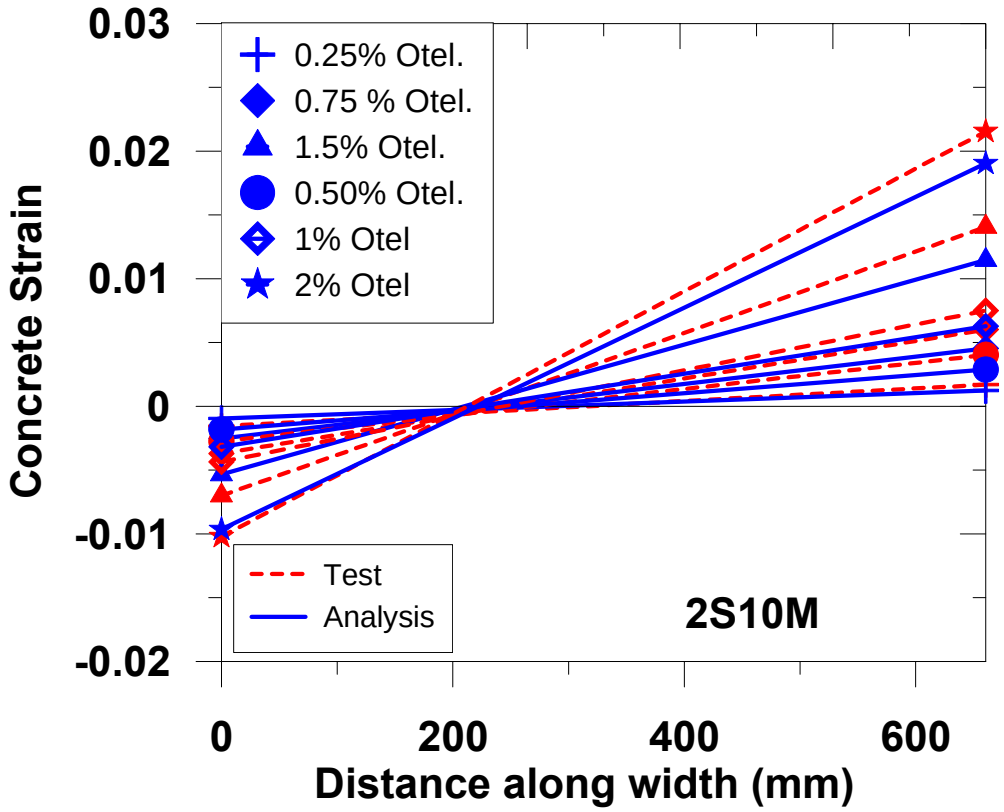
- **Specimen 2S20M** **(at straingauge no. 7)**

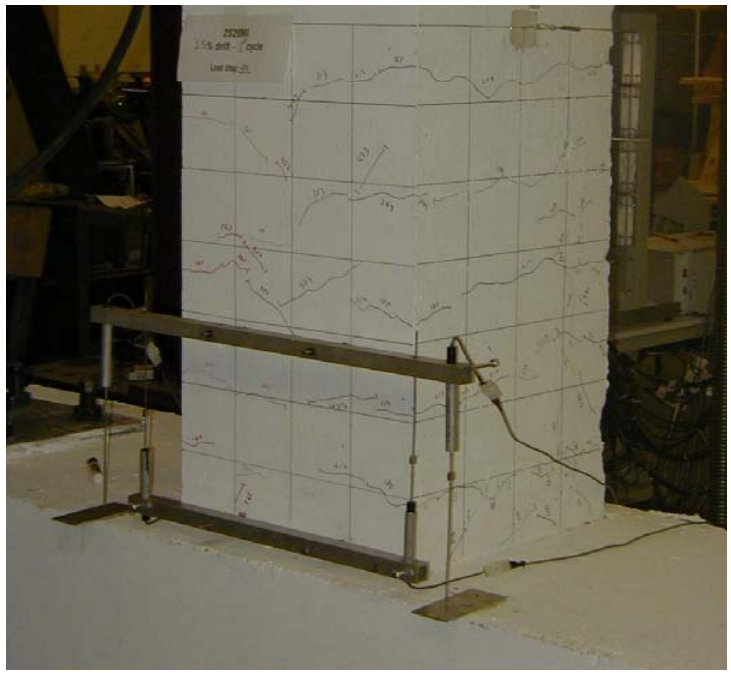




Concrete Strain Distribution

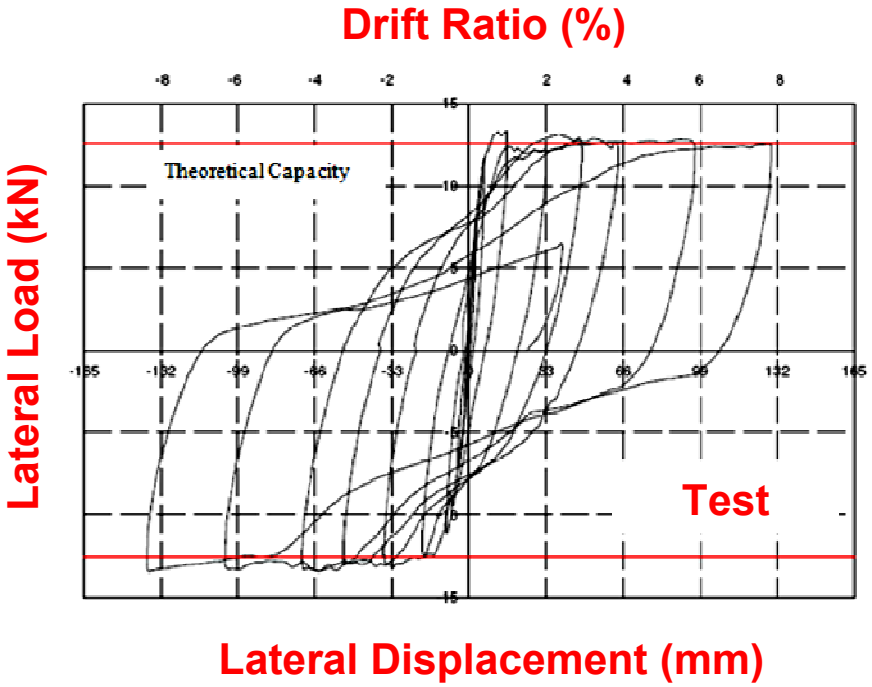
- **Specimen 2S10M** **(at halfway along lap splice length)**

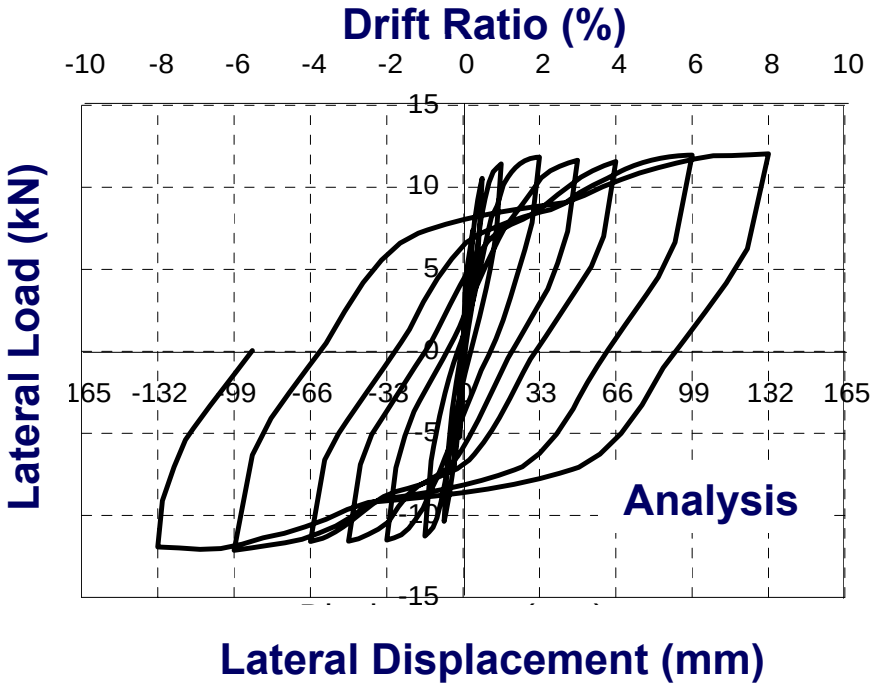




Columns with Plain Bars and 180° Hooks

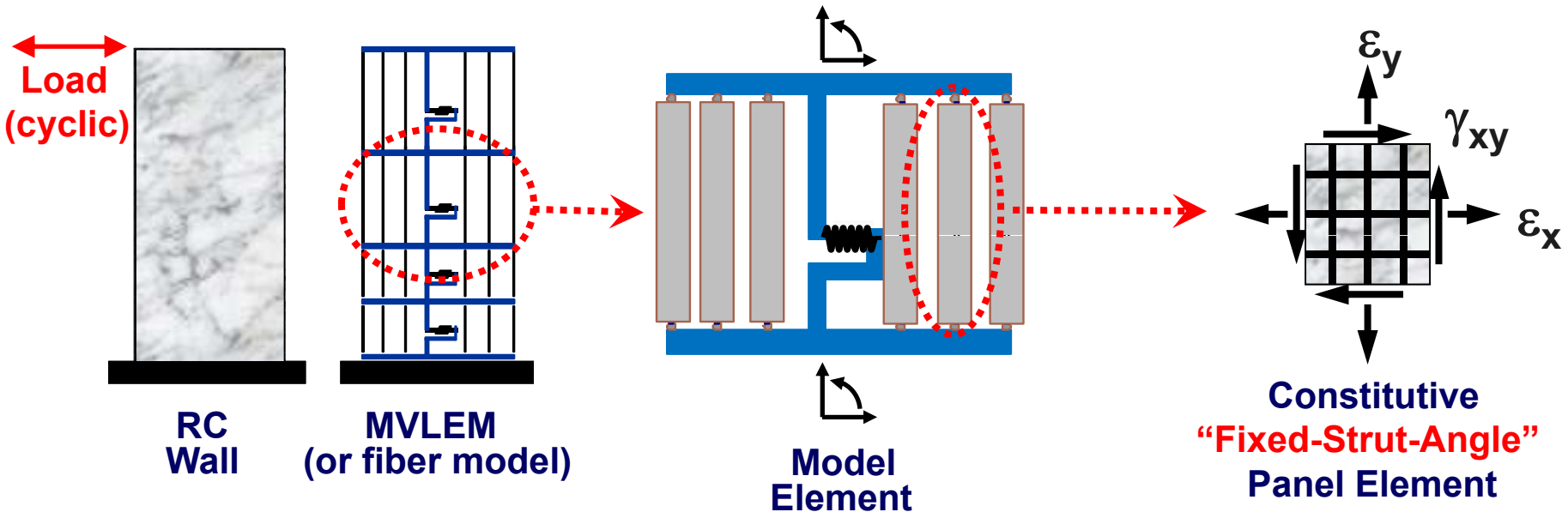
- Specimen **LS-44ϕ-N1** by Yılmaz and İlki (2009), İstanbul Tech. Univ.
- **Plain bar** Lap length = 44ϕ 180-degree hooks
- f_c = 10 MPa f_y = 285 MPa, P_{axial} = 0





➢ **Presence of 180-degree hooks prevents slip failure!!**

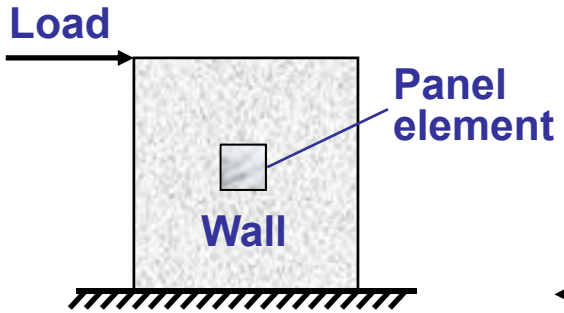
Modeling of Shear-Flexure Interaction (SFI): MVLEM with Panel Sub-Elements

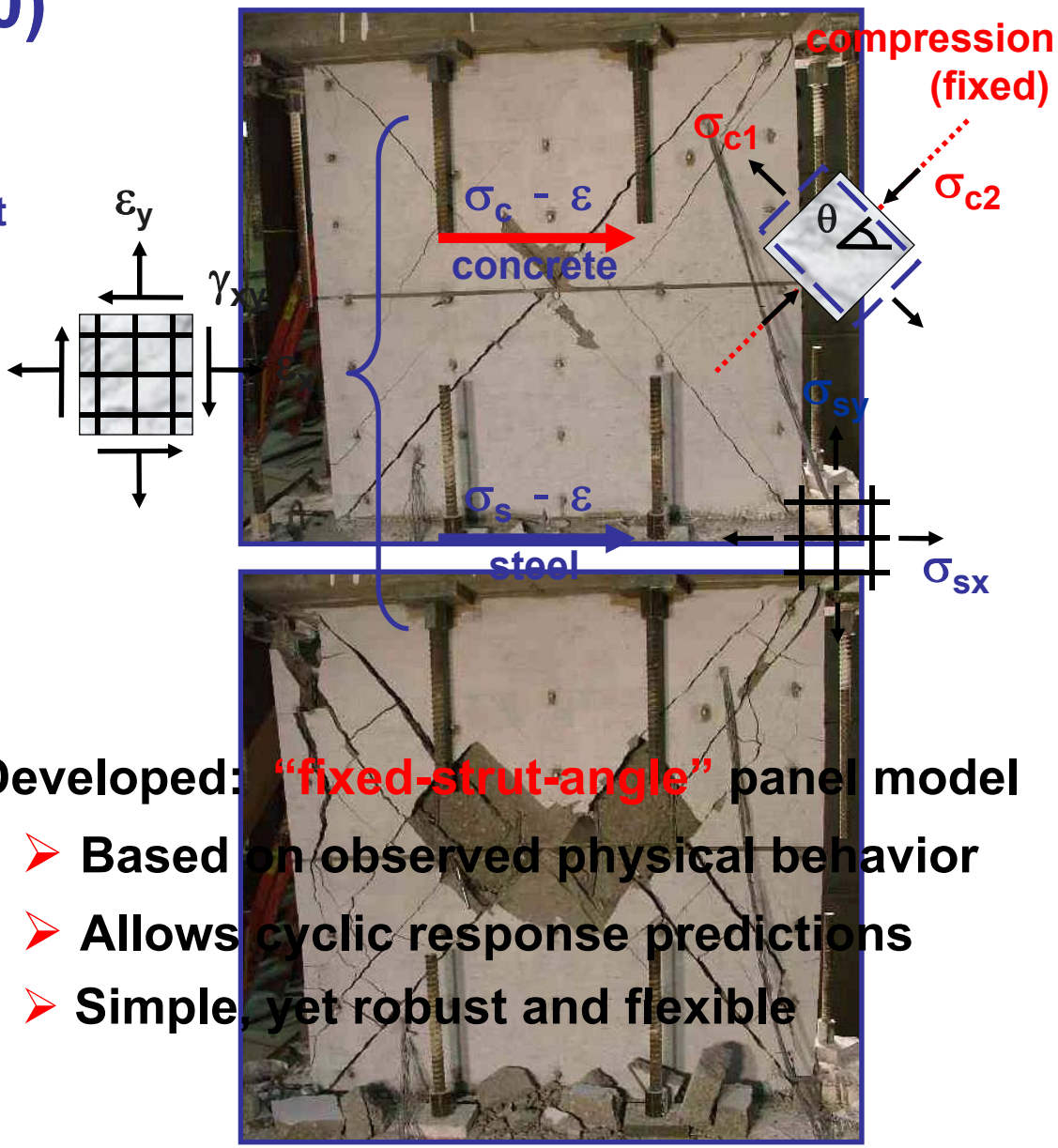


Assumptions:

- Plane sections remain plane
- Shear strains (γ_{xy}) are uniformly distributed along l_w
- Resultant horizontal stress (σ_x) is equal to zero for each panel element (agrees with boundary condition at sides)
- Assumptions are valid for $h_w/l_w \geq 1.0$

Constitutive RC Panel Model Developed (Ulugtekin, 2010)

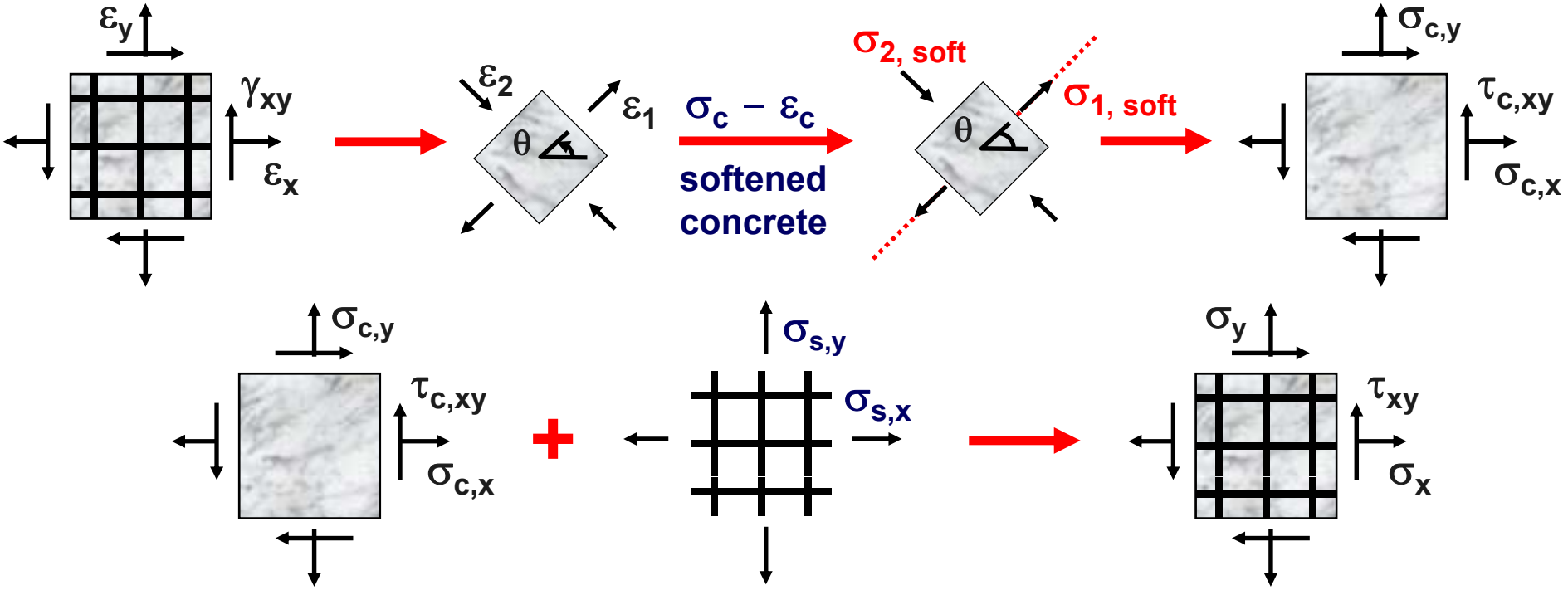




- Developed: "fixed-strut-angle" panel model
  - Based on observed physical behavior
  - Allows cyclic response predictions
  - Simple, yet robust and flexible

The Fixed-Strut-Angle Panel Model

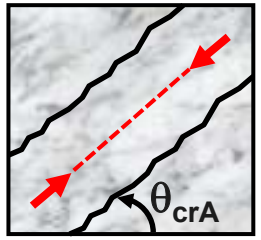
- **Uncracked Panel Response:**
  - **Rotating principal stress angle approach**
  - **Monotonic stress-strain relationships**
  - **Behavior mostly in the linear elastic range**



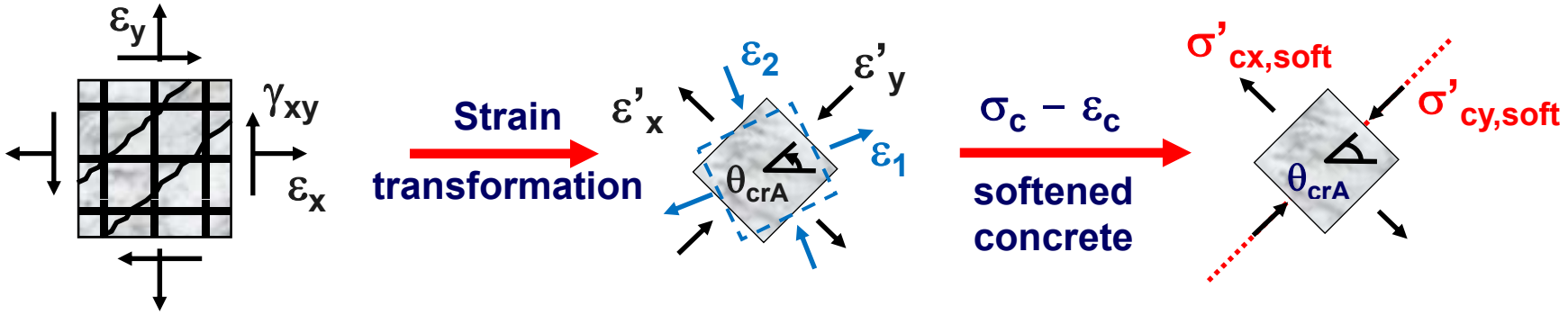
The Fixed-Strut-Angle Panel Model

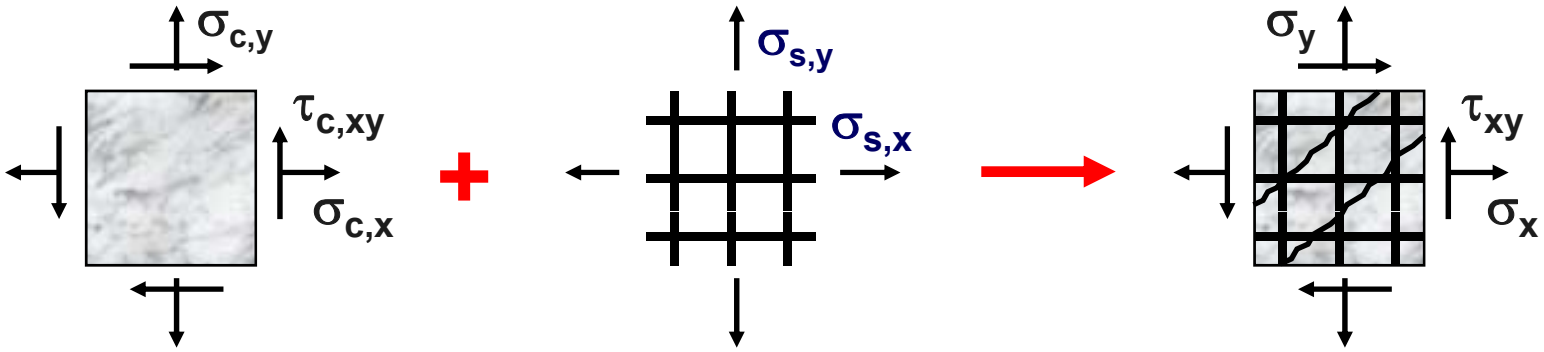
Cracked Panel Response

- $\varepsilon_1 > \varepsilon_{cr,mon} \rightarrow \theta_{crA}$ (principal strain direction)
- σ_1 and σ_2 are || and $\perp$ to θ_{crA}
- $\gamma_{x'y'} \rightarrow \tau_{x'y'} = 0$ (zero aggregate interlock)



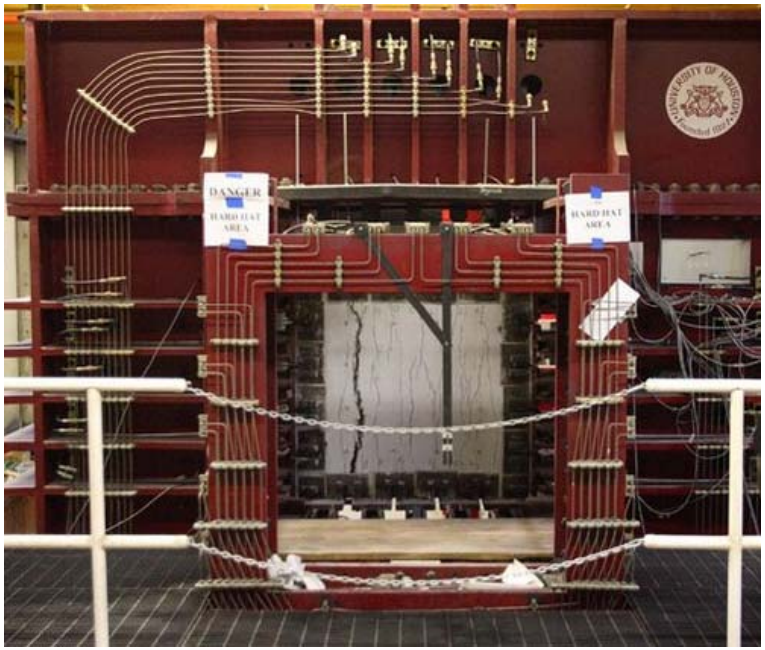
Compression strut
(direction fixed)



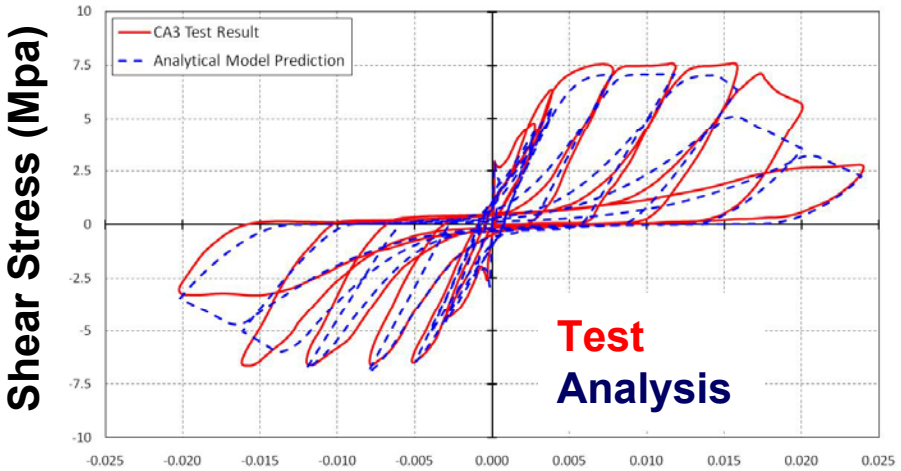


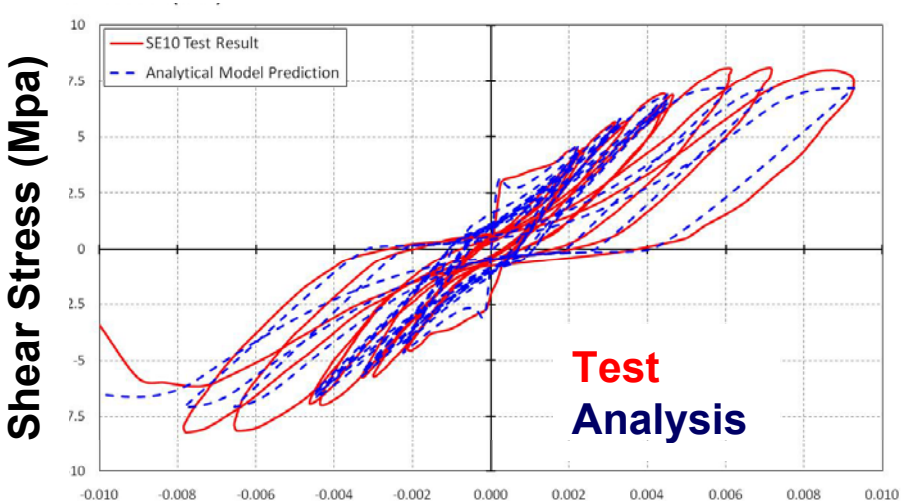
Experimental Verification of the Panel Model

- Cyclic panel test results by:
  - Mansour and Hsu (2001)
  - Stevens and Collins (1987)
- Accurate response predictions

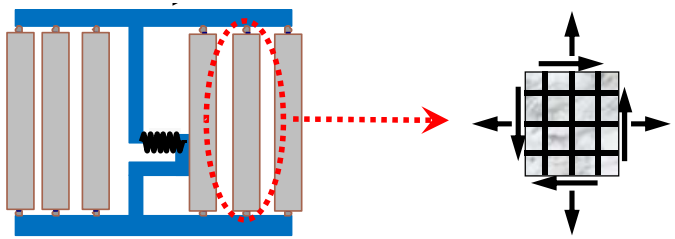


Panel Tester
at Univ. Of Houston



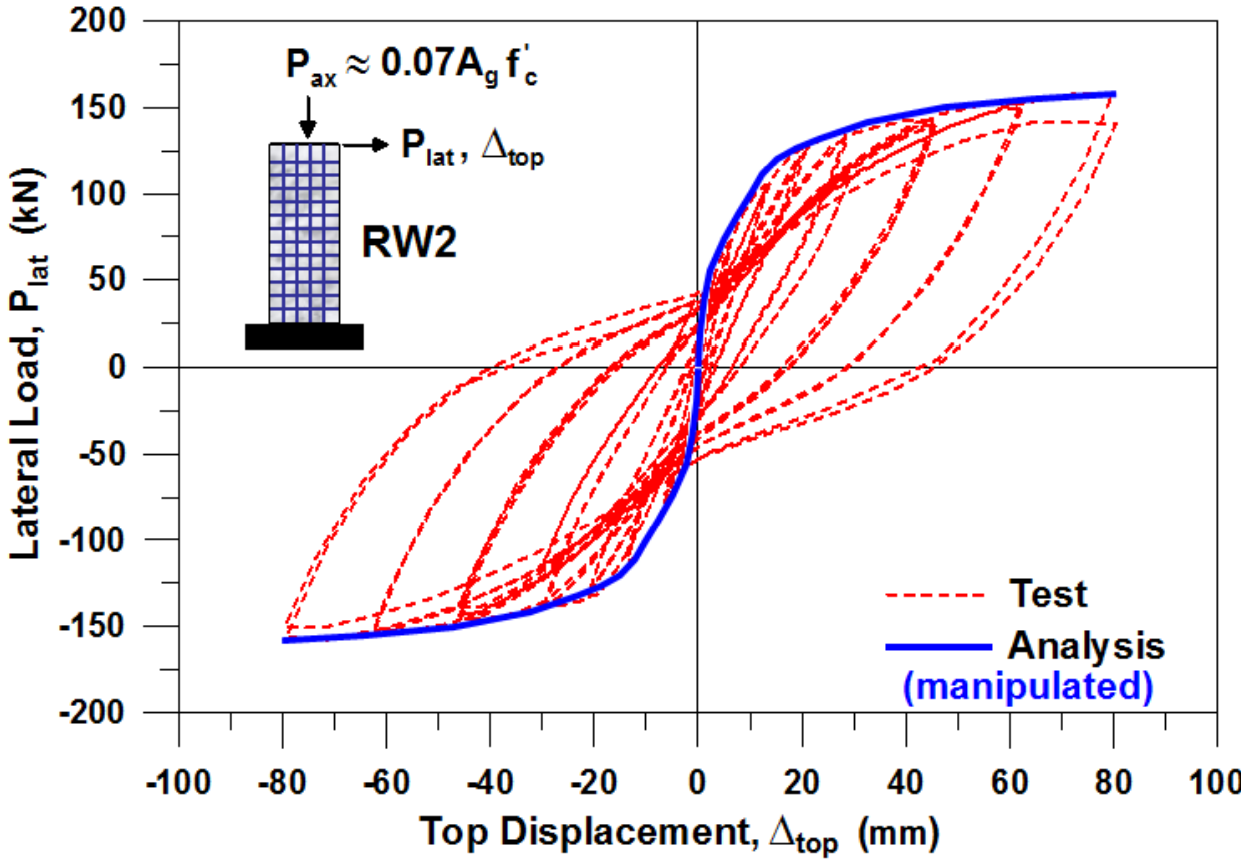


SFI Model Prediction for Slender Walls: Lateral Load – Displacement Response



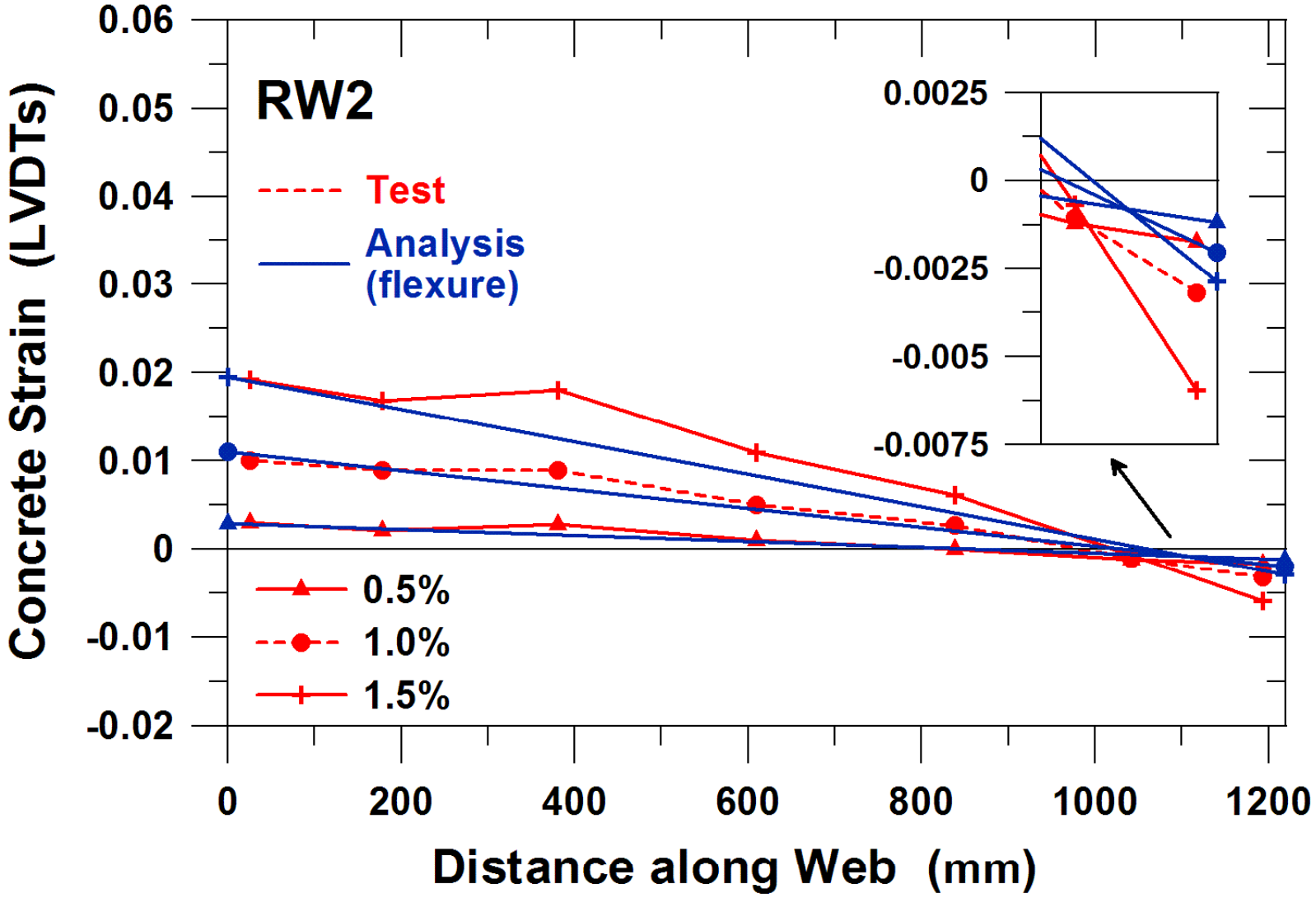
MVLEM – SFI

($\sigma_x = 0$)



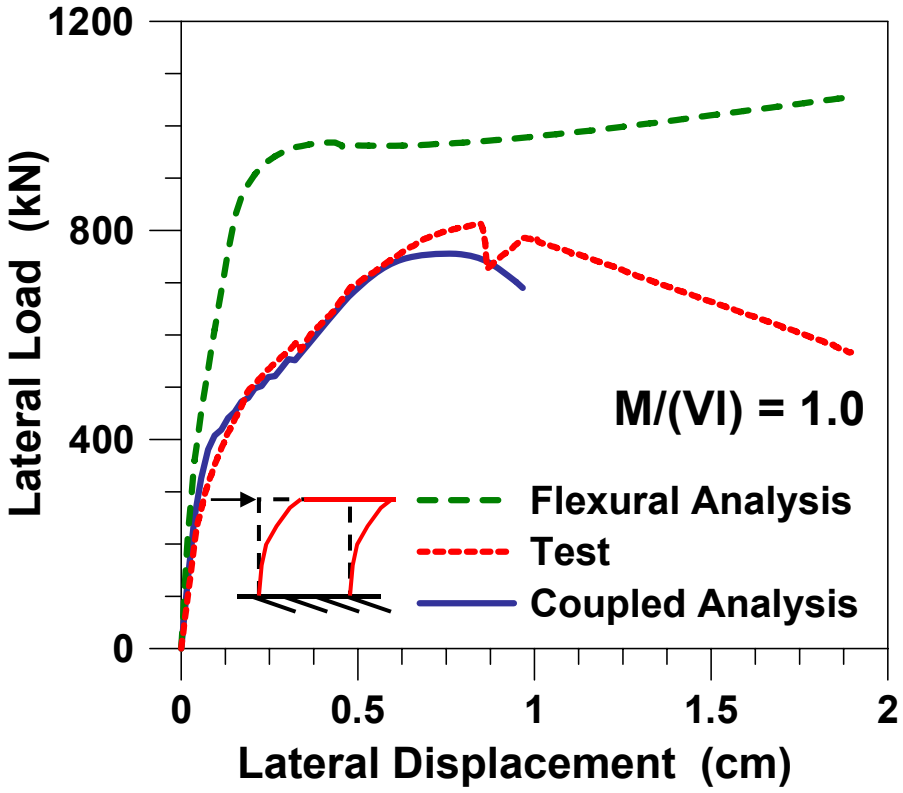
Specimen RW2
Thomsen and Wallace (1995)

Strain Distribution and Curvatures

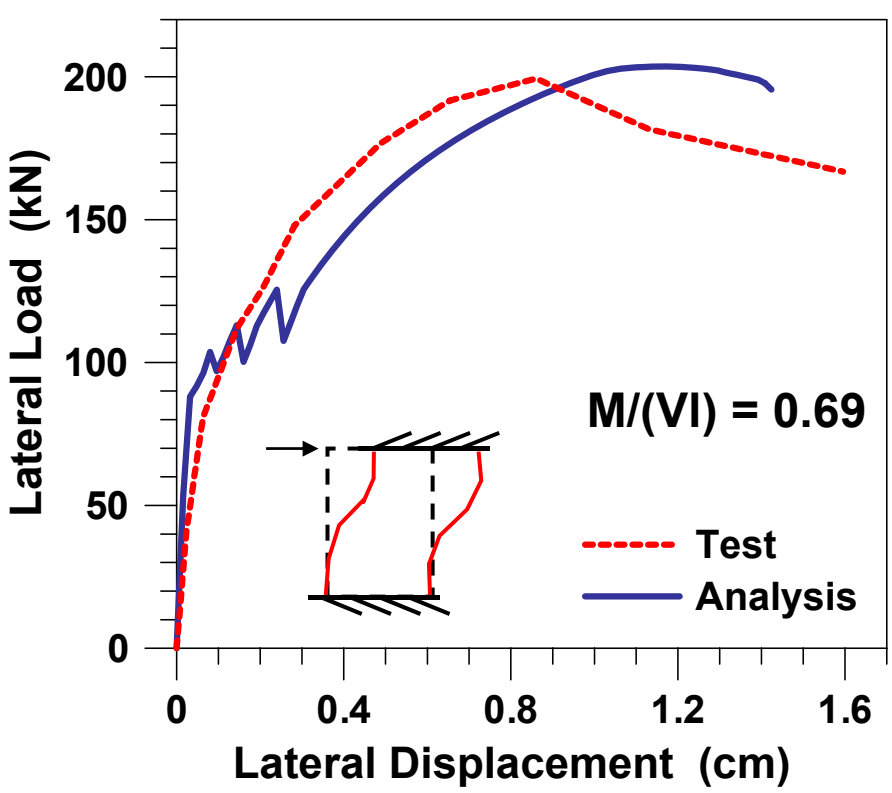


SFI Model Prediction for Short Walls:

- Hirosawa (1975)
  - Cantilever wall
  - Shear cap. ≈ Flex. cap.



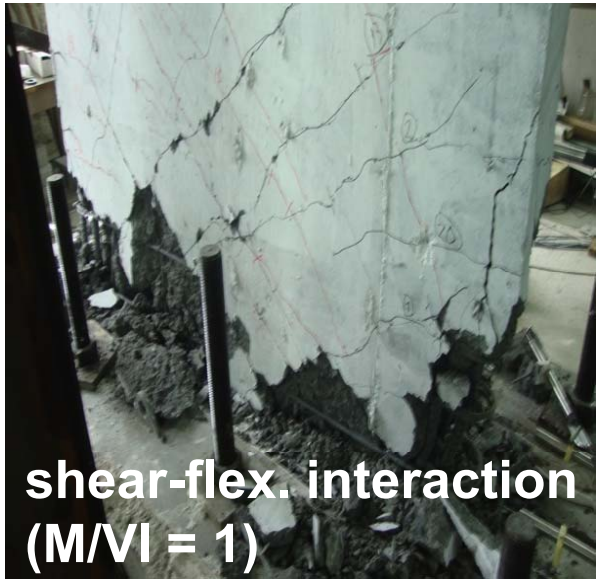
- Hidalgo et al. (2002)
  - Fixed–Fixed wall
  - Shear cap. ≈ 0.5 Flex. Cap.



Short Wall Test Program at B.U. (Terzioglu, 2011)

- 11 short wall specimens
- Aspect ratios: 1, 1/2, 1/3
- Width = 1.5 m
- Thickness = 120 mm
- Web reinforcement ratios: ρ_{web} = 0.34% or 0.68%
- Boundary reinforcement: 4-ϕ16 or 2-ϕ8
- P_{axial} = 0%, 5%, 10%$A_g f_c$
- f_c = 20 MPa – 35 Mpa
- f_y = 520 MPa

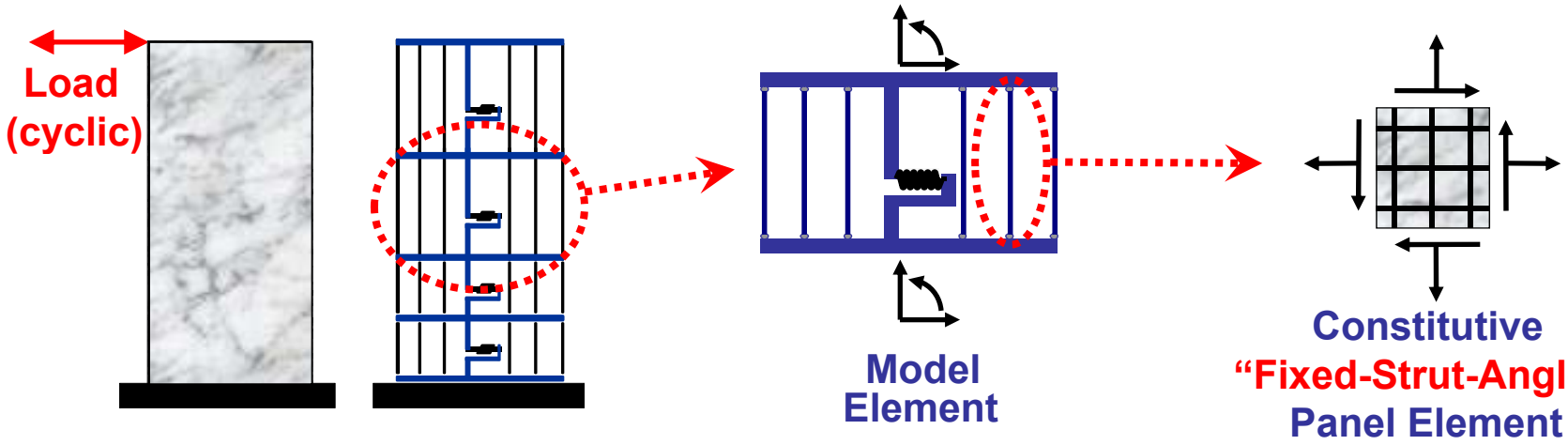
Different Failure Modes Observed



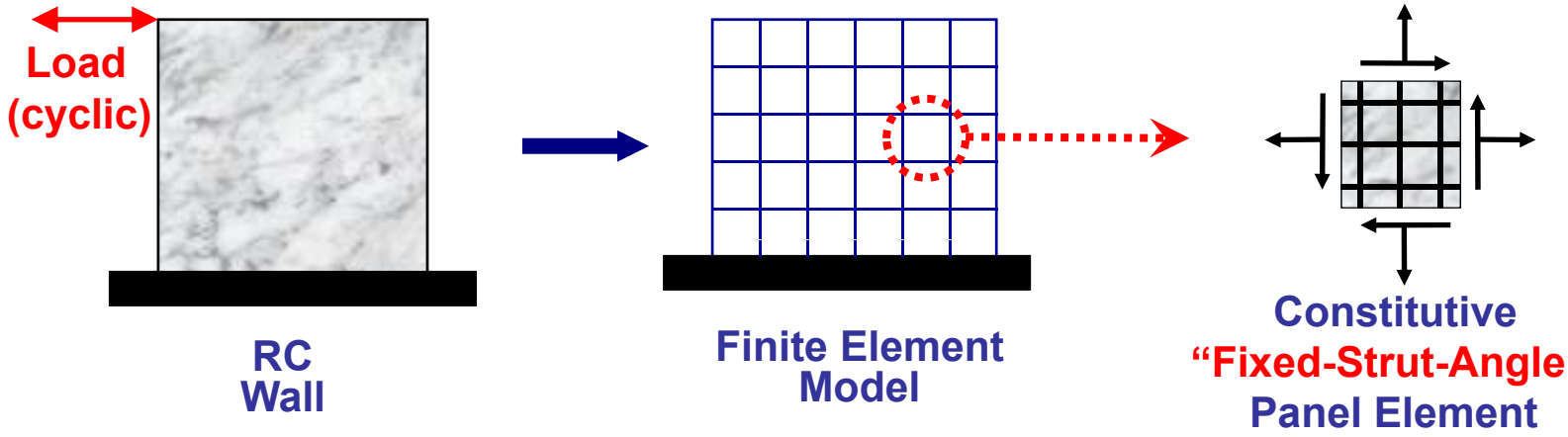
Instrumentation

- **Detailed measurement of flexural and shear deformations, and average transverse normal strain (ε_x) distribution**

Overview of Shear Modeling Approaches



- developed a "modified" fiber modeling approach for shear-flexure interaction



- ongoing efforts on a simplified finite element modeling approach for predominant shear (diagonal tension/compression or sliding)

Results and Ongoing Efforts

- **Flexural response modeling for slender walls**
  - accurate response predictions overall
  - compressive strain predictions improved via SFI
  - bar buckling and low-cycle fatigue effects can be adopted
- **Bond slip response modeling for lap-spliced columns**
  - accurate predictions for columns with deformed bars
  - reasonable predictions for columns with plain bars
  - need better constitutive models for 180^{o} hooks
- **Shear and shear-flexure interaction response modeling**
  - fixed-crack-angle constitutive panel element developed
  - accurate response predictions for M/Vl ratios > 0.7
  - test results will help improve predictions for shorter walls
  - a simple finite element modeling approach underway
- **Implementation into computational platforms**
  - OpenSees (in progress)

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