SEISMIC PERFORMANCE OF CORNER NON-DUCTILE BEAM COLUMN JOINTS IN GRAVITY LOAD DESIGNED REINFORCED CONCRETE BUILDINGS

WAEL HASSAN

Advised By

Prof. J ACK MOEHLE
Outline

- Part 1: Background & Review of Available Relevant Literature
  1- Background, past Earthquake Joint Failures
  2- Tests on Non-Ductile Exterior Joints
  3- Tests on Non-Ductile Corner Simulated Joints
  4- Tests on Non-Ductile Corner Joints
  5- General Experimental Conclusions
  6- Joint Shear Strength Degradation Trends

- Part 2: Full Scale Corner Joint Tentative Test
  1- Suggested Test Parameters
  2- Suggested Test Matrix & Specimen Design
  3- Test Setup
  4- Work Schedule
PART 1

REVIEW OF AVAILABLE LITERATURE
**BACKGROUND**

PAST EARTHQUAKE Corner & Exterior BEAM COLUMN JOINT FAILURES

Severe Joint Damage
BACKGROUND

PAST EARTHQUAKE Corner & Exterior BEAM COLUMN JOINT FAILURES

Partial Building Collapse
BACKGROUND

PAST EARTHQUAKE Corner & Exterior BEAM COLUMN JOINT FAILURES

Complete Building Collapse
TEST ON EXTERIOR BEAM COLUMN JOINTS

1- Hanson & Conner 1965 (PCA, Illinois)

TEST PARAMETERS

- Axial Load Level 0.54 $f_c' A_g$ to 0.86 $f_c' A_g$. Constant Axial Load
- Joint Concrete Strength (matching either column or beam strength).
- Isolated Joint versus Joint with transverse stubs both sides.
1- Hanson & Conner 1965 (PCA, Illinois)

**TEST RESULTS**

- Isolated Exterior Joint, with joint $f_c' = Beam f_c'$:
  Totally inadequate & Brittle, causing joint failure at $\gamma = 11.3$, without beam yielding.

- Exterior Joint with transverse stub & joint $f_c' = column f_c'$:
  Performed very satisfactorily, ductility index $\mu = 17$, joint failure at $\gamma = 11.3$ after beam yielding. No need for joint hoops (sic).
TESTS ON EXTERIOR BEAM COLUMN JOINT

2- Uzumeri 1977 (U of Toronto)

TEST PARAMETERS

- Axial Load Level constant $0.51 f'_c A_g$. Constant Axial Load
- Loading History
- Isolated Joint versus Joint with transverse stub on one side (simulated corner joint).
TESTS ON EXTERIOR BEAM COLUMN JOINT

2- Uzumeri 1977 (U of Toronto)

TEST RESULTS

-Axial Load is Helpful in Early Loading Stages & Detrimental at Later Stages.

-Loading History doesn’t Affect the Response

-Simulated corner joint showed similar performance to isolated one
TESTS ON EXTERIOR BEAM COLUMN JOINT

3- Beres et al 1990 (Cornell University)

TEST PARAMETERS

- Axial Load Level 0.11 $f_c' A_g$ vs 0.39 $f_c' A_g$ Constant Axial Load.
- Column to Beam Flexural Capacities
- Isolated Joint versus Joint with transverse stubs on both side (Prestressed stubs)

Realistic Pre 1971 Construction with all deficiencies
TEST RESULTS

- Failure mode generally is joint shear failure accompanied or followed by upper column splice failure. Joint shear strength ranges from $\gamma = 5.3 - \gamma = 8.3$

- Higher Axial Load: Increase joint strength by 20%, more gradual strength degradation, but sudden failure at the end.

- Transverse stubs: Nothing to the strength at high axial load- 25% joint strength gain at low axial load & generally less severe cracking & more gradual degradation.
TESTS ON EXTERIOR BEAM COLUMN JOINT

4- Clyde et al 2000 (U of Utah)

TEST PARAMETER

- Axial Load Level $0.10 f'_c A_g$ vs $0.25 f'_c A_g$
- Randomly varied Axial Load.
TESTS ON EXTERIOR BEAM COLUMN JOINT

4- Clyde et al 2000 (U of Utah)

TEST RESULTS

-Failure mode generally is joint shear failure after initial beam yielding. Joint shear strength coeff. ranges from $\gamma=11.5$ – $\gamma=14$

-Higher Axial Load: Slight increased joint strength by 8%, tendency to more brittle failure, reduced the deformational capacity by 40% & energy dissipation by 20%

-Residual Axial Capacity: 18% drop in axial capacity at joint shear failure
TESTS ON EXTERIOR BEAM COLUMN JOINT

5- Pantelides et al 2002 (U of Utah)

TEST PARAMETERS

- Axial Load Level $0.10 f_c'A_g$ vs $0.25 f_c'A_g$

- Bottom Beam Rft Anchorage Detail
TESTS ON EXTERIOR BEAM COLUMN JOINT

5- Pantelides et al 2002 (U of Utah)

TEST RESULTS (Bond Slip Failure Specimens)

- Failure modes: Bond slip in short embedded length bottom bars with Loss of lateral load Capacity

- Joint shear strength coefficient $\gamma = 5.2 - 7$

- Higher Axial Load: Increase joint strength by 35%, tendency to more brittle failure, 25% reduction in displacement ductility & 32% reduction in energy dissipation
TESTS ON EXTERIOR BEAM COLUMN JOINT

5- Pantelides et al 2002 (U of Utah)

**TEST RESULTS (Joint Shear Failure Specimens)**

- Failure modes: Joint Shear Failure with Loss of Gravity Load Capacity, more brittle (35% less ductility) than bond slip failure

- Joint shear strength coefficient $\gamma = 10.3 - \gamma = 11.8$ (77% higher than bond slip joints)

- Higher Axial Load: Increase joint strength by 15%, tendency to more brittle failure, 5% reduction in displacement ductility & 15% reduction in energy dissipation
TESTS ON EXTERIOR BEAM COLUMN JOINT

6- Pampanin et al 2002 (Italy)

TEST SPECIMENS

- Deficient 1960 Joints:
  1- Plain (Smooth) Rebars
  2- Beam Rebars Anchorage Deficient (Unhooked)
  3- Absence of Capacity Design
  4- Low Characteristic Strength of Materials

Axial Load

Low level 0.10 $f'_c A_g$
Varied with lateral load bilinear

Test Parameter

Effect of Beam Flexural Strength
TESTS ON EXTERIOR BEAM COLUMN JOINT

6- Pampanin et al 2002 (Italy)

TEST RESULTS

- Failure modes: Brittle hybrid failure mechanism: sudden and severe joint shear damage after the first diagonal crack combined with slip failure of beam rebars. (Joint Wedge)

- Final Failure: By loss of Axial load capacity

- Joint shear strength coefficient $\gamma = 4.3$ (Diagonal Strut not developed), Displacement Ductility $\mu = 2.67$

- Similar Performance to Bent out Beam Rebars Joints
TESTS ON SIMULATED CORNER BEAM COLUMN JOINT

1- Hanson & Conner 1972 (PCA, Illinois)

TEST SPECIMEN

- One preloaded Transverse Stub until cracking
- Preloading removed before test

Axial Load

High Ratio 0.86 $f'_c A_g$ Constant Load

Test Parameter

Effect of Transverse Stub Confinement on Joint Strength
TESTS ON SIMULATED CORNER BEAM COLUMN JOINTS

1- Hanson & Conner 1972 (PCA, Illinois)

TEST RESULTS

- Failure mode: Joint Shear Failure After Beam Yielding. Adequate response up to $\mu=2.67$
  Followed by severe cracking

- Joint shear strength coefficient $\gamma=12$, Displacement Ductility $\mu=4$

- Very Slight Strength gain over the isolated joint,
- Some improvement in ductility
TESTS ON SIMULATED CORNER BEAM COLUMN JOINT

2- Uzumeri 1977 (U of Toronto)

TEST SPECIMEN

-One preloaded Transverse Stub until cracking
-Preloading persists during test

Axial Load
High Ratio $0.51 f'_{cA_g}$ Constant Load

Test Parameter
Effect of Transverse Stub Confinement on Joint Strength
TEST RESULTS

- Failure mode: Joint Shear Failure. Beam & Column Intact
- Joint shear strength coefficient $\gamma = 11.2$, Displacement Ductility $\mu = 3$
- Generally behaved similar to isolated exterior joint.
- No additional confinement effect strength gain due to transverse stubs.
- Slight increase in ductility (15%)
- Stub slightly increased the anchorage capacity of beam reinforcement
TESTS ON CORNER BEAM COLUMN JOINT

1- Preistley 1994 (UCSD)

TEST SPECIMENS
- One Unreinforced Corner Joint
- One reinforced Corner Joint
- No Slab
- Unrealistic Boundary Conditions

Axial Load
Axial Load Ratio 0.15 \( f'_c \cdot A_g \) Varied with Lateral (Dynamic Analysis)

Test Parameter
Evaluate Unreinforced Joint Shear Strength

Load History
Uniaxial Loading followed By diagonal Biaxial
TESTS ON CORNER BEAM COLUMN JOINTS

1- Preistley 1994 (UCSD)

TEST RESULTS (Unreinforced Joint)

- Failure mode: Joint Shear Failure After Beam Yielding
- Final Failure: Loss of Gravity Load Capacity
- Generally Very Poor Performance
- Joint shear strength coefficient:
  \( \gamma = 5.61 \) for Uniaxial Loading,
  \( \gamma = 8.11 \) Diagonal Loading.
- Displacement Ductility Factor \( \mu = 2.39 \)
GENERAL EXPERIMENTAL CONCLUSIONS

EFFECT OF AXIAL LOAD

On Strength

- Opinion 1: Slightly increases Joint shear strength (8%-20%)
- Opinion 2: No Effect at All
- Opinion 3: Helpful in early stages of loading, Detrimental in inelastic stages

On Ductility

- More pronounced effect than on strength
- More tendency to brittle failure with higher axial load
- 15% -32% Reduction in Drift and Displacements Ductility
- 20% drop in Energy Dissipation

Mitigation of Collapse Risk in Older Concrete Buildings

Grand Challenge Research

Pacific Earthquake Engineering Research Center & Network for Earthquake Engineering Simulation
GENERAL EXPERIMENTAL CONCLUSIONS

EFFECT OF SLAB PRESENCE

Non-Ductile Joints
No Data Available

Ductile Exterior Joints
- Increasing Beam Plastic Capacity, Imposes Higher Demand on Joint
- Reduces Spandrels Confining Effect on Joint due to Imposed Torsional Stresses, more rapid Joint Strength Deterioration
GENERAL EXPERIMENTAL CONCLUSIONS

EFFECT OF LOADING HISTORY

1- No Effect on Joint Shear Strength (Uni. vs Diagonal)

2- More Pronounced Deterioration in Stiffness with Biaxial Loading

3- Quasi-Static is more Conservative than Dynamic Loading (Apparent Strength Increase with Rapid Dynamic)
GENERAL EXPERIMENTAL CONCLUSIONS

EFFECT OF TRANSVERSE SPANDREL CONFINEMENT

1- **Opinion 1:** Tremendous Strength Improvement (Questionable Result)

2- **Opinion 2:** No or Very Slight Strength Improvement

3- Slight Increase in Beam Rebar Anchorage Capacity

4- Decrease Severity of Cracking & Strength Degradation

5- Minor Ductility Improvement (15%)
GENERAL EXPERIMENTAL CONCLUSIONS

EFFECT OF BEAM REBAR ANCHORAGE DETAIL IN JOINT

1- Detail 1: Bent-Out Rebars: Entirely inadequate, very low Joint Shear Strength, Can’t Develop Diagonal Strut, $\gamma < 4$

2- Detail 2: Bent-In Rebars : Better Performance, still inadequate, $\gamma$ up to 11-12

3- Detail 3: Short Bottom Rebar Embedded : Certain Bond Slip Failure, $\gamma=5 -7$, Little More Ductile

4- Detail 4: Smooth Unhooked Rebars: Similar Performance to Detail 1, No Strut Developed, $\gamma=4.2$
JOINT SHEAR STRENGTH DEGRADATION TRENDS

NON-DUCTILE ISOLATED EXTERIOR JOINTS

Suggested $\gamma = 11.25$
Suggested $\mu = 2.7$
JOINT SHEAR STRENGTH DEGRADATION TRENDS

NON-DUCTILE EXTERIOR JOINT with TWO SPANDRELS

Joint Shear Stress-Displacement Ductility Relationship (Exterior Joints with 2 Stubs)
JOINT SHEAR STRENGTH DEGRADATION TRENDS

CORNER NON-DUCTILE JOINTS

Suggested $\gamma = 11.50$

Suggested $\mu = 3.5$
PART 2

TENTATIVE FULL SCALE CORNER BEAM COLUMN JOINT TEST
Drawbacks & Unanswered Questions in Previous Tests

1- Definite Result about the Effect of High Axial load

2- Distinction of Joint Strength for Different Failure Scenarios,

3- Reliable Shear Strength Degradation Models for Non-ductile Joints

4- Corner Joint Shear Strength Coeff. $\gamma$, and Corresponding $\mu$

5- Non-ductile Joint Shear Strength, for varying Joint Aspect Ratio

6- Effect of Beam to Column Width Ratio, (Joint Masking Area)

7- Effect of Slab Presence for non-ductile joints

8- Realistic Representation of Biaxial Loading

9- Assessment of Joint capability to support Gravity Axial Load after severe inelastic loading
Mitigation of Collapse Risk in Older Concrete Buildings

Grand Challenge Research
Pacific Earthquake Engineering Research Center & Network for Earthquake Engineering Simulation

SUGGESTED TEST PARAMETERS

1- Axial Load Level, $0.15 \, f'c'Ag$ vs $0.30 \, f'c'Ag$

2- Failure Mechanism, Joint Shear failure vs Joint Shear Failure after Beam Yielding

3- Beam to Column Flexural Strength $\sum M_c / \sum M_b$, Strong Column Weak Beam vs Strong Beam Weak Column Conditions.

4- Joint Shear Strength, through Joint Aspect Ratio, $1$ vs $1.67$

5- Beam to Column Width Ratio, (Joint Masking Area), $0.9$ vs $0.55$

6- Effect of Slab Presence
Mitigation of Collapse Risk in Older Concrete Buildings

Grand Challenge Research

Pacific Earthquake Engineering Research Center & Network for Earthquake Engineering Simulation

SUGGESTED TEST MATRIX

Axial Load 0.15 fc'Ag

Beam Yields First

Joint Failure

Axial Load 0.30 fc'Ag

Beam Yields First

Joint Failure

Axial Load .15 fc'Ag
Join Aspect Ratio 2

Joint Failure

Beam Yields First

Weak Column Strong Beam

Axial Load 0.15 fc'Ag

Smaller Beam to Column Width Ratio

No Slab Specimen

J1

J2

J3

J4

J5

J6

J7

J8

J9

J10

The George E. Brown, Jr. Network for Earthquake Engineering Simulation
Mitigation of Collapse Risk in Older Concrete Buildings

**Grand Challenge Research**
Pacific Earthquake Engineering Research Center & Network for Earthquake Engineering Simulation

**SUGGESTED SPECIMENS**

Specimen 1: Low Axial Load, Aspect Ratio 1, Beam Yield → Joint Failure
Specimen 2: High Axial Load, Aspect Ratio 1, Beam Yield → Joint Failure
Specimen 3: Low Axial Load, Aspect Ratio 1, Joint Failure
Specimen 4: High Axial Load, Aspect Ratio 1, Joint Failure
Specimen 5: Low Axial Load, Aspect Ratio 2, Beam Yield → Joint Failure
Specimen 6: Low Axial Load, Aspect Ratio 2, Joint Failure
Specimen 7: High Axial Load, Aspect Ratio 2, Joint Failure
Specimen 8: Low Axial Load, Aspect Ratio 1, Lower Beam Rft, Beam Yield → Joint Failure
Specimen 9: Low Axial Load, Aspect Ratio 1, Weak Column Strong Beam, Beam Yield → Joint Failure
Specimen 10: Low Axial Load, Aspect Ratio 1, Smaller Beam to Column Width Ratio, Joint Failure
Specimen 11: Low Axial Load, Aspect Ratio 1, No Slab, Beam Yield → Joint Failure
Mitigation of Collapse Risk in Older Concrete Buildings

Grand Challenge Research

Pacific Earthquake Engineering Research Center & Network for Earthquake Engineering Simulation

**SPECIMEN DESIGN**

**Column Section**

- **Specimen 1**
  - Beam Section: 16''x18''
  - Slab: All Specimens: thickness=6''
  - Column Section: 18''
  - Column: #3@varies

- **Specimen 2**
  - Beam Section: 10''x18''
  - Slab: Except Sp. 6: No Slab
  - Column Section: 18''
  - Column: #3@varies

- **Specimen 3**
  - Beam Section: 16''x18''
  - Slab: All Specimens: thickness=6''
  - Column Section: 18''
  - Column: #3@varies

- **Specimen 4**
  - Beam Section: 16''x18''
  - Slab: All Specimens: thickness=6''
  - Column Section: 18''
  - Column: #3@varies

- **Specimen 5**
  - Beam Section: 10''x18''
  - Slab: Except Sp. 6: No Slab
  - Column Section: 18''
  - Column: #3@varies

- **Specimen 6**
  - Beam Section: 10''x18''
  - Slab: Except Sp. 6: No Slab
  - Column Section: 18''
  - Column: #3@varies

- **Specimen 7**
  - Beam Section: 16''x18''
  - Slab: All Specimens: thickness=6''
  - Column Section: 18''
  - Column: #3@varies
Mitigation of Collapse Risk in Older Concrete Buildings

Grand Challenge Research

Pacific Earthquake Engineering Research Center & Network for Earthquake Engineering Simulation

Axial Load -- Varied with lateral load through Dynamic Analysis Obtained Relation (Overturning Moment) --

Two 1000 Kips Actuators

Lateral Load -- Two 120 Kips Actuators

Realistic Biaxial Loading

Test Setup

East
Test Attachments

3D Universal Joint

800 Kips Compression, 350 Kips Tension Capacities
Work Schedule

Tentative First Test
End of Oct 2008

| Weeks | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Experimental Tasks                           |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 1. Specimen                                  |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Construction                                 |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Final Decision on Design & Parameters        |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Prepare Detailing & Constr. Drawings         |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Procurement of Materials & Labor             |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Contractor Arrangement                        |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Internal Instrumentation                      |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Building 9 Steel Cages                       |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Building 3 Formworks                         |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Casting, 3 Specimens at a time               |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Curing of Specimens                           |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Drilling Installing, Fixtures for Test Items |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Fabricate or Arrange Strong, Axial, Beams, Fab. Braces for Column |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Fabricate Top & Bottom Collars               |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Arrange External Instrumentations with Lab, Personnel |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Plan Procedures, Load Sequence, Special Test Instructions with Lab |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Secure Video Filming, Photography Positions   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Inventory Check for Needed Access, Supplies for Positioning |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Prepare Test Area, Clear Obstacles, Secure Specimen Transp. |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 3. Test                                      |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Specimen 1 Placement & Test                 |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Specimen 4-6 Placement & Test               |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Specimen 7-9 Placement & Test               |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
Thank You