Development of draft protocol for testing of structural components and systems for use in schemes under ‘Housing for all’ project of the Government of India

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System vs. Component Level Testing

- System level testing means that the testing is done for the complete assembly or the product like customer at the top level looking for the harmony among different components.
- Component level testing (or Unit testing) is focused on the functionality of a particular part without considering much on how it works with others.

**System**
- Masonry Structure
- RC Structure
- Steel Structure
- Timber Structure
- Precast concrete Structure

**Component**
- Slab
- Wall Panel
- Beam
- Column
- Beam-column connection
For Systems & Components:
Test standards for performance of different construction practices e.g. masonry walls, Precast slabs and beams, RC Beam-columns etc.

- Subjected to in-plane and out-of-plane bending
- Cyclic loading
- Wind Loading

Types of component include-
Cast-in-situ component
Precast or Prefabricated component
Cast-in-situ vs. Precast

• Precast concrete structures are able to resist to earthquake loading as reliably as analogous cast-in-place ones.
• Energy dissipation in prefabricated columns occurs within a volume of material which is equal to that top and bottom edge sections of cast-in-place columns designed to withstand the same base shear force.

Ferrara et al. 2004
Precast beam-column connection

- Precast concrete structures are traditionally designed as moment resisting frames with plastic hinges occurring at the column base, and beams hinged to the columns.
- Replacement with Precast system gives the advantage of designing continuous beams with a reduced beam depth, or with an increase of either span length or carried load.
Precast beam-column connection

Experimental Set Up for Joint Testing

Cyclic Loading Protocol

Instrumentation Set-Up

_EUCENTER Report, 2016_
Precast beam-column connection

Pseudo dynamic Testing

Input motion, scaled to PGA of 1 g.

Modified Response Spectra by EC8 soil Factor B

(Negro et al. 2013)
- The presence of two stiff precast wall units in prototype 1 was quite effective in limiting the maximum inter-storey drift ratios for both the serviceability and ultimate limit states. 
  
  \( T = 0.3 \text{ Sec} \)

- The seismic response of prototype 2 was highly influenced by the effects of higher modes.
  - This results into large force demands in the connections in the nonlinear regime.
  - The 1% drift limitation was exceeded, precast system with hinged beam-to-column joints was characterized by excessive deformability.
  - No significant damage in its structural members.

\( T = 1.09 \text{ Sec} \)

(Negro et al. 2013)
After the seismic test results of prototype 3, the concept of emulative beam–column joints at the top floor only was not much effective.

- The effect of higher modes is also significant.
  
  \[T=1.08\text{ Sec}\]

Finally, when activated at all the floors, the proposed connection system is quite effective as a means of implementing dry precast (quasi) emulative moment-resisting frames.

- Dense flexural cracking at the base of the ground floor columns, but again without considerable damage.
  
  \[T=0.66\text{ Sec}\]

(Negro et al. 2013)
Behavior of connection

Category 1: connections is that between adjacent floor or roof elements.  
Category 2: connections between floor or roof panels and supporting beams.  
Category 3: connections between columns and beams.  
Category 4: connections used to join columns and foundations  
Category 5: connections between wall (or cladding panels) and slab elements.

(Bournas et al. 2013)
Precast beam-column connection

Pinned Joint Connection:
• It is able to transfer shear and axial forces both for the gravity and seismic forces and possible uplifting forces due to overturning.
• By definition, they cannot transfer moment and torsion, although in reality they do transfer a small amount of bending moment.
• The horizontal connection between the beam and the column was established by means of two vertical steel dowels which were protruding from the column into special beam sleeves.

(a) Seating of a secondary beam on the column capital.
(b) A central beam–column joint.
(c) Detail of a pinned beam–column joint connection.
(d) Special dowels with increased diameter at the critical section.

(Bournas et al. 2013)
The second beam–column connection type, which emulates fixed beam–column joints. 

In order to provide continuity to the longitudinal reinforcement crossing the joint, an innovative ductile connection system, embedded in the precast elements, was activated. 

This connection system comprises four steel rebars slightly enlarged at their ends, two thick steel plates and a bolt that connects the two steel plates.

(a) Connector used to realize dry emulative beam–column joints. 
(b) Test set-up adopted to assess the tensile capacity of the connection system. 
(c) Typical load versus displacement curve of the bare connection system. 
(d) Ductile rupture of the longitudinal rebars. 

(Bournas et al. 2013)
Precast beam-column connection

B. Hinged beam–column joints

- To fulfill the demand of large forces in the connections, if designer does not include shear walls in these flexible systems, the large magnification of storey forces (determining the capacity design of connections) should be considered.

- The beam–column joint slip was reduced dramatically in the case of moment resisting joints, that is 3.5 times lower than its counterpart with hinged beam-to-columns joints.

- The participation of the beams in the frame behavior of prototype 4 was higher, however; the emulative beam–column joint response in prototype 4 was quite different from a rigid joint. The execution of this mechanical connection has no quality control or certification for the time being. This resulted into a semi-rigid beam–column joint with asymmetric (in the two directions of loading) and unequal (between beams and columns) rotations.

(Bournas et al. 2013)
Precast beam-column connection

- 3 storey prototype building structure
- **Instrumentation and setup:**
  - LVDT, Strain Gauge, Hydraulic jack, Reaction frame

Complete Building System  Scaled Beam-Column Joint

(Vidjepriya et al.)
Precast beam-column connection

Experimental setup and models

- 3 experimental models
  - Monolithic (cast-in-situ) (ML)
  - Precast members with single stiffener (PC-SS)
  - Precast members with double stiffener (PC-DS)

Reverse cyclic displacement controlled loading

(Vidjeapriya et al.)
Precast beam-column connection

Sample Results

Vidjeapriya et al.
**Precast beam-column connection**

**Performance Evaluation (Cast-in-situ vs. Precast)**

- Column damage is minimal in pre cast systems
- Double stiffener pre cast system emulates performance of cast in situ monolithic section considering strength and damping
- PC-DS has better ductility than that of Specimen PC-SS and ML specimen

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Cracks in ML joint

Cracks in PC joint

(Vidjeapriya et al.)
A precast wall panel system can be comprised of:
- Flat or curved panels (solid, hollow-core, or insulated)
- Window or mullion panels
- Ribbed panels
- Double-tee
Precast Diaphragm wall panel

Horizontal load deformation Scenarios:

Wall and Horizontal Loading

Excessive gap opening between panels

Shear slip

Typical Wall Deformation:
- Due to Shear
- Due to Flexure

Undesirable deformations along horizontal joints

EUCENTER Report, 2016
Cantilever walls resist the overturning moment resulting from the lateral forces by bending.

Coupled walls resist the overturning moment not only by bending of the individual walls but also through an axial force couple.

Rocking walls resist overturning moment at the base of the walls through the couple arising from the eccentricity between the acting gravity load and the reaction at the wall-foundation interface.
• 3 storey Precast box structure.
• Symmetric Structure to avoid the twist.
• **Instrumentation:** LVDT, Strain Gauge, Potentiometer, Accelerometer.
• **Shake Table Movement:** White Noise of different intensity.

*Lee et al. 1996*
Results:

• Model was taken in Non-linear range during the 0.8g with rocking motion.
• Cracks appeared in Horizontal joints in 0.12g and were propagated in the horizontal direction.
• In 1.4g, the joint box was crushed in Horizontal joints without any crack in wall panels and vertical joints.

Lee et al. 1996
Precast Diaphragm wall panel

In-plane loading setups

- Instrumentation:
  - Hydraulic Jack
  - LVDT
  - Strain gauges
  - Load cell
  - Shear actuator

Side Elevation

Free End

Fixed End

Teflon Sheet

4'-0\frac{1}{4}"

Feedback LVDT 1

Shear Actuator

Fixed Support

Movable Support

Feedback LVDT 2

Tension/Compression Actuator 1

Tension/Compression Actuator 2

Monitor 1

Monitor 2

Monitor 3
The test thus provides an estimate of average connector yield, peak strength, and the deformation capacity.

Monotonic shear protocol consists of three cycles to 0.01 inch

Instrumentation
- Hydraulic Jack
- LVDT
- Strain gauges
- Load cell
Precast Diaphragm wall panel

In plane loading protocols

- **Force controlled**
  - Monotonic In-plane Shear
  - Cyclic In-plane Shear
  - Monotonic In-plane Tension
  - Cyclic In-plane Tension and Compression
  - Monotonic In-plane Shear with Proportional Tension

- **Displacement controlled**
  - Monotonic and Cyclic Shear Deformation with a Target Axial Load of 0 kips;
  - Cyclic Shear Deformation with a Target Axial Load of 10 kips
Precast Diaphragm wall panel

- performance Categorization as per ASCE/SEI 41-06 Seismic Rehabilitation
- Each connection classification as deformation-controlled (ductile) or force controlled (non-ductile)
- Assessment with Back-bone curves
The purpose of the test-
The system can handle above and beyond the typical design loads we work with, while offering advantages over other systems – advantages such as lighter weight and insulation.
Precast Beams

Dead load test on Pre-stressed Precast Beams for different magnitude of static loads

load testing of new precast concrete floor plank system
Precast Beams

- Static Deflections were measured and dead load on the component is simulated.
  - Deflection is measured immediately after loading.
  - Deflection is measured 136 hours after loading.
  - Crack propagation is monitored for different dead loads

deflection at mid-span of plank

Cracking at mid-span

Precast.org
Precast slabs are cast in a factory environment and include the following options:

- Hollow core
- Double Tee (TT)
- Solid
- Biaxial void slabs
Depending on the position of slab following slab panels are considered for testing.

(Fleischman et al.)
Precast Slab

Loading protocols

- Instrumentation
  - Shear actuator
  - LVDT
  - Strain gauges

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Load History</th>
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<tbody>
<tr>
<td>Simple Panel-Panel Connection Tests</td>
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<tr>
<td>High Shear Region</td>
<td>Monotonic</td>
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<tr>
<td>High Shear and Tension</td>
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<tr>
<td>High Shear Region</td>
<td>Cyclic</td>
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<tr>
<td>High Shear and Tension</td>
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<tr>
<td>Diaphragm Panel-Panel Connection Tests</td>
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<tr>
<td>High Flexure Region</td>
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<td>High shear and Flexure</td>
<td>Cyclic</td>
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<tr>
<td>Multiple Connection Panel-Panel Tests</td>
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<tr>
<td>High Shear, Tension, &amp; Flexure Region 1</td>
<td>From Analysis</td>
</tr>
<tr>
<td>High Shear, Tension, &amp; Flexure Region 2</td>
<td>From Analysis</td>
</tr>
<tr>
<td>High Shear, Tension, &amp; Flexure Region 3</td>
<td>From Analysis</td>
</tr>
</tbody>
</table>

(Fleischman et al.)

A. Diaphragm panel-panel connection
B. Diaphragm - wall or intermediate support
C. Scaled diaphragm panel-panel connection
Since their constituent materials have limited strengths, the joints have limited force carrying capacity.

Repairing damaged joints is difficult, and so damage must be avoided.

Thus, beam-column joints must be designed to resist earthquake effects.
Reinforced Concrete Beam-Column Joint

Casting specimen

Casting specimen details
The displacement at the ends of the beams was increased by steps from 0.25 % up to a drift of 1.0 % per drift amplitude, then two cycles for each drift amplitude greater than 1 %.

A total of twelve displacement cycles were applied up to 5 % drift cycle.

**Instrumentation**
- Hydraulic Jack
- LVDT
- Laser Sensor
- Strain gauges
- Load cell
Reinforced Concrete Beam-Column Joint

- Performance of specimen

Crack propagation

Recorded Strain
Steel Beam-Column Joint

✅ Steel beam-column joints are vulnerable to brittle fracture during seismic events
✅ There are higher chances of formation of plastic hinges near the beam-column joint during nonlinear response of structure
✅ Thus, beam-column joints must be designed to resist earthquake effects.
Steel Beam-Column Joint

Possible Test Setups

Displacement applied to beam tip

Displacement applied to column tip

LVDT

plastic hinge length

continuity plates

column flange

beam top flange

strain gage locations (same locations on bottom flange)
Steel Beam-Column Joint

Sample Test Setup

- Instrumentation
  - Hydraulic Jack
  - LVDT
  - Strain gauges
  - Load cell
Steel Beam-Column Joint

Loading Protocol

<table>
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<tr>
<th>Load Step #</th>
<th>peak deformation $\theta$</th>
<th>number of cycles, $n$</th>
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<tbody>
<tr>
<td>1</td>
<td>0.00375</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>0.0075</td>
<td>6</td>
</tr>
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<td>0.02</td>
<td>2</td>
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<tr>
<td>7</td>
<td>0.03</td>
<td>2</td>
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</tbody>
</table>

Continue with increments in $\theta$ of 0.01, and perform two cycles at each step

Initial Stage

Deformed Stage
Realistic earthquake type loading for prototypical structural systems
Equations of motions are solved on-line for displacements to be applied in real time while updating the system parameters from on-line measurements of forces and displacements.

Effect of inertia force is accounted for in approximate sense and strain rate effects are not considered as test is carried out at slow rate.

Pseudo Dynamic (PsD) Test
IITK Pseudo Dynamics Testing Facility

- Synthesis of numerical modeling and experimental testing.
- Require adequate simulation of boundary conditions at the interface.

Hybrid PsD using Substructures
IITK Shake Table Testing Facility

**Uni -Axial Shake Table**

- **For small scale dynamic model testing i.e. component testing**

**Characteristics:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
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<td>1.2 m x 1.8 m</td>
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<tr>
<td>Weight of Table</td>
<td>8 kN</td>
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<tr>
<td>Maximum Payload</td>
<td>40 kN</td>
</tr>
<tr>
<td>Maximum Displacement</td>
<td>75 mm</td>
</tr>
<tr>
<td>Maximum Velocity</td>
<td>1.5 m/s</td>
</tr>
<tr>
<td>Maximum Acceleration</td>
<td>5 g</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>upto 50 Hz</td>
</tr>
</tbody>
</table>
IITK Cyclic Testing Facility

Reaction Frame

For Wall Testing or Frame Testing (Small Scale)

ISMB600 sections for all members
Height: 4.2 m,
Lateral load: 4000 kN and Overturning moment capacity: 6000 kNm
IITK Wind Tunnel Facility

Tall Chimney

Tall Building

Civil Engineering Application of Wind Tunnel
• “SAC - Nonlinear Structural Dynamics And Control Research” by SACJ Venture
• Northeast Precast company blogs- By Peter Gorgas (Precast.org)
Thank You