Assessing Seismic Safety of Concrete Moment Frames with High Strength Reinforcing Steel

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Sponsors:
The Charles Pankow Foundation
The Concrete Reinforcing Steel Institute
The ACI Foundation’s Concrete Research Council

with contributions by:
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1. Evaluate relative fracture risk and collapse safety of structural systems (higher grades vs. Grade 60)
2. Evaluate HS bar material (e.g., T/Y) and design criteria (s/db) for seismic design
3. Relate deformation demands in RC buildings to subassembly loading protocols

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<td>Potentially larger bar slenderness (s/db)</td>
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Tie spacing & buckling (Gr 80 #8) (Slavin & Ghannoum, 2016)
System Assessment Framework

RC System Analysis

- Cyclic hinge model ($f_y$, T/Y & s/db)
- Joint panels & gravity system
- IDA (44 FEMA P695 + 44 spectrally equivalent long-duration motions)

MCE Performance & Collapse assessment

Beam-Column RC member

- Fiber element model
- Translate drift history to rebar strain history

Reinforcement Fracture

- Fatigue-fracture model
- Estimate fracture potential based on cyclic strain demands

Non-simulated fracture mode

Ground acceleration

Time

Deformation history

Chord rotation (rad)

Time (sec)

Strain history

Nominal steel strain over 8-in gage

Time (sec)

Fracture index

Time (sec)
Bar Fracture Model

Bar Fracture Index – a metric as a function of rebar cumulative plastic strain

- Base model: Manson-Coffin
- Involved variables: $f_y$, $T/Y$, $s/d_b$, $\varepsilon_f$
- Calibrate $a_f$ and $C_f$ to 45 monotonic tension tests + 206 low-cycle fatigue tests (courtesy by Prof. Ghannoum)

$$FI = f\left(\varepsilon_{p,i}\right) = \sum_{i=1}^{N}\left(\frac{\varepsilon_{p,i}}{C_f}\right)^{1/a_f}$$

Material Constant

$$\alpha_f = 0.729 - 0.075 \cdot \left(\frac{f_y}{60\,ksi}\right) + 0.038 \cdot (s/d_b) - 0.217 \cdot (T/Y)$$

Prediction Equation

$$C_f = 0.5^{a_f} \cdot \left(\varepsilon_f - \frac{f_y}{E_s}\right)$$

Bar Fatigue-Fracture Fragility

P (fracture | FI)
median FI = 1.0
dispersion = 0.5
Validation of Bar Fracture Model

1. Simulated history is comparable to recorded strains
2. **Average FI ~ 1.0** at reported fracture point
FEMA P695 archetype frame
SDC D_{max} (S_{M1}=0.9g) Gr. 60, s/d_k = 3.5-4

Expand Designs:
- 3 grades (Gr. 60, 80, and 100)
- 3 tie spacings (4d_{b}, 5d_{b}, and 6d_{b})
- 3 T/Y ratios (e.g., 1.1, 1.2, and 1.3 for Gr. 100 bars)

Periods:
- T_{code} = 3.4 sec
- T_{60} = 2.7 sec, T_{80} = 3.0 sec (0.8k_o), T_{100} = 3.2 sec (0.7k_o)

Nonlinear Dynamic Analysis Evaluations:
1. FEMA P695 – Standardized Collapse Safety (SDC D_{max})
2. Hazard Consistent IDA

- Site: San Francisco (Site Class D, S_{MCE}=0.34g)
- SDR_{max} increases as grade increases
  - Gr 60: 0.025
  - Gr 80: 0.027 (+8%)
  - Gr 100 0.028 (+12%)
Translate Drift Demands in Frame to Fracture Index

1. Frame NLRHA

2. Random Drift History

3. Beam/Column Fiber Analyses

4. Rebar Strain History

5. Rain Flow Fatigue Counting

6. Fracture Index
Non-Simulated Fracture Collapse Modes

- $F_{I_{\text{max}}}$: the fracture index of the worst beam/column
- Evaluated up to the highest intensity before collapse ($SDR_{\text{max}} > 0.1$)
- Providing statistics about fracture at $MCE_R$ intensity levels
- Map non-simulated fracture failure modes (FEMA P695)

**Maximum Fracture Index in Columns**

**IDA curves (Simulated and Non-Simu. Failure Modes)**

- $MCE_R = 0.34g$
- Median $F_{I} \sim 0.3$
- $P(\text{fracture}) \sim 1\%$

- Collapse due to premature fracture
- Collapse without rebar fracture
- Collapse due to premature fracture

Non-fracture collapse
Collapse w/ fracture
Collapse Probability
\( P(\text{frac.}) = \int f_{\text{demand}}(x) \times F_{\text{capacity}}(x) \, dx \)

**Observed Trends**
- Hardening ratio ↓ \(\rightarrow\) fracture probability ↑
- Tie spacing ↑ \(\rightarrow\) fracture probability ↑

**Suggested Limits:**
- Median \(T/Y\) >= 1.2
- Tie spacing \(s/db\) <= 5
Total Collapse Probability

- Comparable collapse safety ($T/Y \geq 1.2 \ s/db \leq 5$)
- $T/Y \downarrow \rightarrow \text{collapse probability} \uparrow$
- $s/db \uparrow \rightarrow \text{collapse probability} \uparrow$

Gr 60 $T/Y = 1.3 \ s/db = 6$

Gr 80 $s/db = 5 \ T/Y = 1.3$

Gr 80 $s/db = 5 \ T/Y = 1.4$

Gr 100 $T/Y = 1.2 \ s/db = 4$

Gr 100 $T/Y = 1.2 \ s/db = 5$

Gr 100 $s/db = 6 \ T/Y = 1.2$

Benchmark: 7.1%

$T/Y \downarrow \rightarrow P(\text{col.}) \uparrow$

$s/db \uparrow \rightarrow P(\text{col.}) \uparrow$

Collapse probability under MCE$_R$
### 20-story vs. 4-story

**20-story (27 archetypes)**

- **Period**: 2.6 ~ 3.2 sec
- **Drift Demand (MCE)**: 2.5% ~ 2.8%
- **Fracture Probability (MCE)**: 1.4% ~ 3.0%
- **Collapse Probability (MCE)**: 7.1% ~ 11.6%
- **Fracture-Induced Collapse Probability (MCE)**: 0.4% ~ 2.0%

**4-story (13 archetypes)**

- **Period**: 1.2 ~ 1.5 sec
- **Drift Demand (MCE)**: 3.0% ~ 3.2%
- **Fracture Probability (MCE)**: 5.8% ~ 8.3%
- **Collapse Probability (MCE)**: 5.3% ~ 10.6%
- **Fracture-Induced Collapse Probability (MCE)**: 1.0% ~ 3.0%

- **Shorter period** → more reversal cycles
- **Higher fracture risk in short-period frames**
- **Higher fracture-induced collapse risk in short-period frames**
• 4-story frame case: Gr 100 bars with T/Y = 1.2, s/d_b = 5.

• Lab tested curves have a good coverage on the demand curve for both the beam and column.

• The demand is slightly over the tested envelope when SDR>3%.
Conclusive Remarks

1. Under $MCE_R$, high-strength reinforcement (HSR) frames:
   - higher drift demands
   - higher collapse probability
   - still acceptable

2. Bar fracture potential is generally small (<10% under $MCE_R$), but sensitive to
   - strain demands (larger drifts; lower $T/Y$ ratios)
   - bar buckling ($s/d_b$)
   - fatigue fracture resistance

3. Suggestions on material and design criteria for HSR frames
   - Median $T/Y \geq 1.2$
   - $s/d_b \leq 5$

4. Low-rise frames can be more vulnerable (period matters)

Ongoing studies

1. *Relate cyclic deformation demands in buildings to subassembly loading protocols
2. Additional archetypes: shear walls, bridge columns, …
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Thank you! Questions & Comments~

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