Accounting for Earthquake Duration in Performance-Based Evaluation and Design of Bridges

PEER Transportation Systems Research Program

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Background and Motivation

- Previous research (Stanford, U.Colorado, U.Washington) has quantified the influence of earthquake duration on building collapse safety.
- Shake-table experiments (Mohammed and Sanders, 2016) indicated that the reinforcing bars under long-duration motions were subjected to a large number of high-strain cycles, which led to significant effects of cyclic fatigue on the collapse resistance of the bridge column.
- Current seismic design standards do not explicitly consider the effect of earthquake duration.

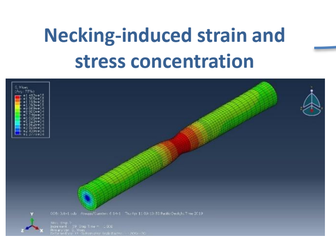
Objectives

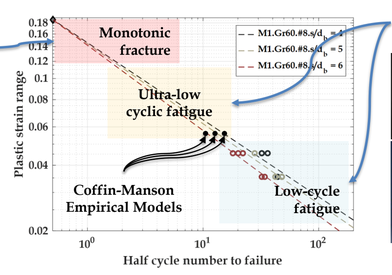
- Develop a fatigue-fracture material model of reinforcing steel accounting for local buckling effects and cumulative damage under long-duration loadings.
- Quantify the duration effects on archetype bridge systems and develop improved design details to mitigate the effect of duration on reinforced concrete bridge piers.
- Leverage research on cyclic deterioration to help qualify the use of high-strength reinforcement in seismic design and construction of bridges.

Fatigue and Fracture of Reinforcement

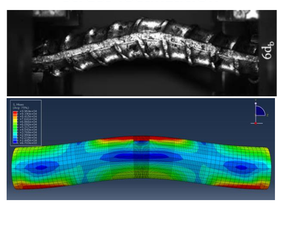
- Rebar failure occurs due to micro void-growth and coalescence under large plastic strain cycles as well as crack striation mechanism under small strain cycles.
- Necking-induced strain concentration and buckling induce strain localization.
- Empirical models have significant limitations especially under random earthquake loads.

Necking-induced strain and stress concentration





Buckling-induced strain and stress localization



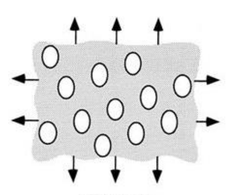
Proposed Reinforcement Ductile Fracture Model

The proposed reinforcement ductile fracture model quantifies the cumulative damage through a Fracture Index (FI) which is defined as a function of local strain-stress responses and calibrated material coefficients, C, λ_0 and β_0.

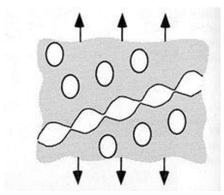
Cyclic deterioration coefficient; Symmetric coefficient; Local stress Triaxiality

$$FI = Ce^{\int_{T<0}^{\lambda} \left(\beta e^{A^+ T} - e^{-A^- T}\right) d\varepsilon_p}$$

Fracture Index; Void-growth coefficient; Local plastic strain increment

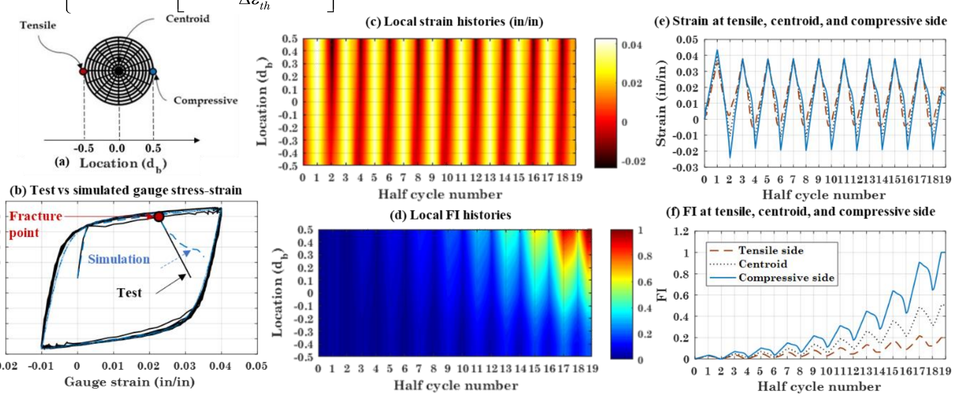


Void growth (captured by *C*)



Cyclic deterioration effects by void coalescence, shrinkage and crack striation (captured by *λ and β*)

$$where,\ \begin{cases} \beta = 1.0 + (\beta_0 - 1.0)\left[\dfrac{\min(\Delta\varepsilon_{\max}, \Delta\varepsilon_{th})}{\Delta\varepsilon_{th}}\right]^{\gamma} \\ \lambda = \lambda_0\left[\dfrac{\min(\Delta\varepsilon_{\max}, \Delta\varepsilon_{th})}{\Delta\varepsilon_{th}}\right]^{\gamma} \end{cases}$$



Closed-form solutions of local strain demands after bar necking and buckling are developed separately as functions of bar gauge strain demands.

$$\varepsilon_{local} = \begin{cases} \varepsilon_{gauge}, & \varepsilon_{gauge} \le \varepsilon_{su} \\ \varepsilon_{su} + k_1\left(\varepsilon_{gauge} - \varepsilon_{su}\right)\left(\dfrac{L_{gauge}}{8\ in.}\right), & \varepsilon_{gauge} > \varepsilon_{su} \end{cases}, \quad k_1 = \frac{\varepsilon_{f,local} - \varepsilon_{su}}{\varepsilon_{f,gauge} - \varepsilon_{su}}$$

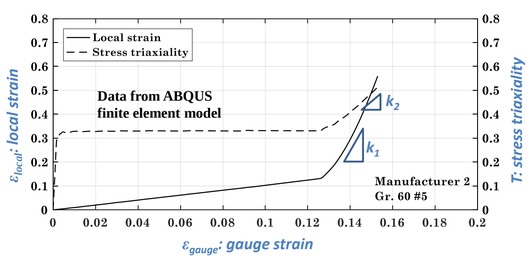
$$T = \begin{cases} 0.33, & \varepsilon_{gauge} \le \varepsilon_{su} \\ 0.33 + k_2\left(\varepsilon_{gauge} - \varepsilon_{su}\right)\left(\dfrac{L_{gauge}}{8\ in.}\right), & \varepsilon_{gauge} > \varepsilon_{su} \end{cases}, \quad k_2 = \frac{T_f - 0.33}{\varepsilon_{f,gauge} - \varepsilon_{su}}$$

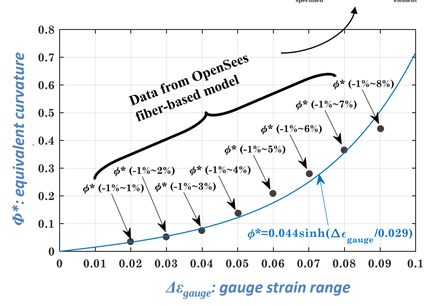
Necking coefficients

Buckling coefficients

$$\varepsilon_{local} = \varepsilon_{gauge} + b_1 \sinh\left(\frac{\Delta\varepsilon_{gauge}}{b_2}\right)\left(\frac{d_b}{2}\right)$$

Φ^*: equivalent curvature





Validation with Shake-Table Test *(University of Nevada, Reno)*

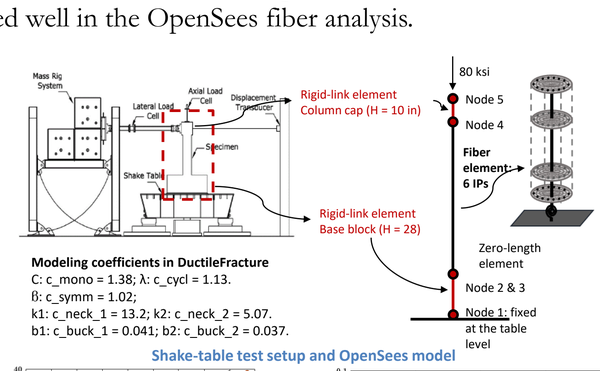
A new uniaxial material, DuctileFracture, is developed and implanted in OpenSees to explicitly simulate bar fracture in nonlinear dynamic analysis of reinforced concrete members

Material Tag; Steel constitutive material Tag; Void-growth coefficient: C; Cyclic deterioration coefficient: λ; Symmetric coefficient: β

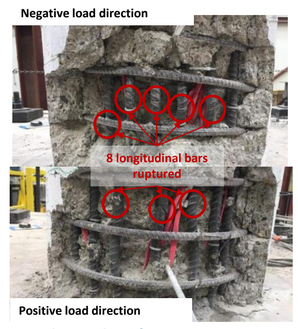
```
uniaxialMaterial DuctileFracture $matTag $refTag -c_mono $c_mono -c_cycl $c_cycl -c_symm $c_symm <-E_s $E_s> <-esu $esu
–k1 $k1 -k2 $k2> <-db $db –b1 $b1 –b2 $b2> <-c_dete $c_dete>
```

Necking model: k1 and k2; Buckling model: b1 and b2; Strength degradation ratio (optional)

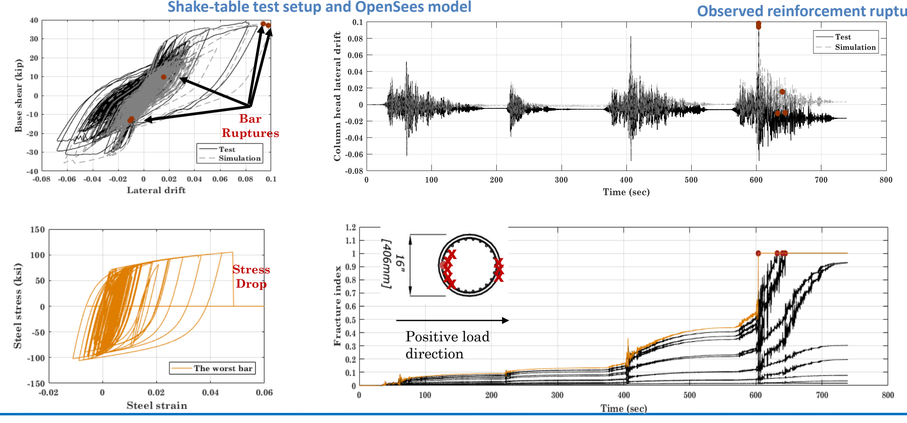
The successive reinforcement ruptures observed in shake-table tests (Alian and Moustafa, 2019) are captured well in the OpenSees fiber analysis.



Shake-table test setup and OpenSees model

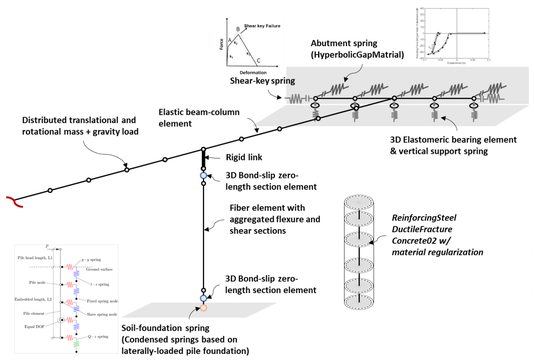


Observed reinforcement ruptures

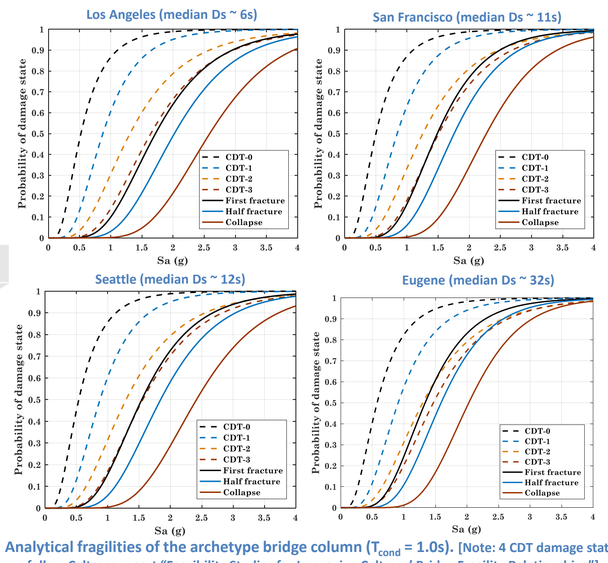


Long-Duration Effects on Bridge Column Performance

Damage and collapse fragilities are evaluated for a 2-span single-column bent bridge for 4 sites with varying earthquake intensity and ground motion duration targets



OpenSees model of the archetype bridge system (T_{cond} = 1.0s)

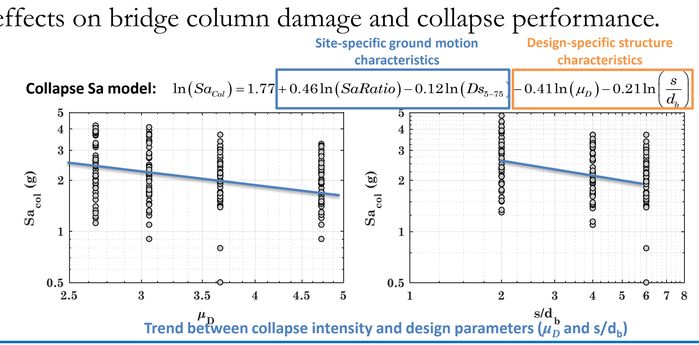


Analytical fragilities of the archetype bridge column (T_{cond} = 1.0s). [Note: 4 CDT damage states follow Caltrans report "Feasibility Studies for Improving Caltrans' Bridge Fragility Relationships"]

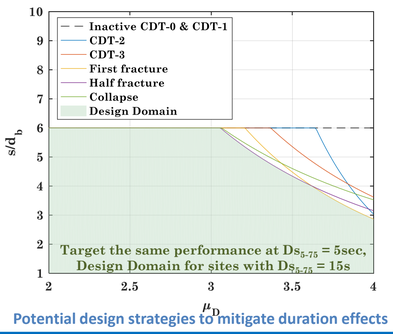
Alternative design strategies are explored (with different displacement ductility demand factors and confinement tie spacing ratios) to investigate their effectiveness for mitigating earthquake duration effects on bridge column damage and collapse performance.

Site-specific ground motion characteristics; Design-specific structure characteristics

Collapse Sa model: $\ln(Sa_{Col}) = 1.77 + 0.46\ln(SaRatio) - 0.12\ln(Ds_{5-75}) - 0.41\ln(\mu_D) - 0.21\ln\left(\frac{s}{d_b}\right)$



Trend between collapse intensity and design parameters (μ_D and s/d_b)



Potential design strategies to mitigate duration effects

Summary

- A fatigue-fracture model was proposed and validated to simulate rebar fracture under random earthquake loading
- The influence of ground motion duration on rebar fracture and bridge collapse risk is evaluated
- Strategies to mitigate the duration effect are proposed, including (1) closer reinforcing bar tie spacing, and (2) increased strength to reduce displacement ductility demands.

Acknowledgement

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