Advanced Guidelines for Stability Design of Slender Reinforced Concrete Bridge Columns

Michael H. Scott (PI), Oregon State University

and

Mark D. Denavit (Co-PI), University of Tennessee, Knoxville

PEER Annual Meeting

August 25, 2023

Oregon State University

The University of Tennessee Knoxville

Project Overview

- Develop guidelines for the efficient design of RC bridge columns
  - Approximate method (moment magnification)
  - Refined method (second-order analysis)
- AASHTO method adopted from building codes (e.g., ACI 318)
  - Some analogies carry over from buildings to bridges
  - Engineers make conservative assumptions to fill in gaps
- Primarily analysis-based project to achieve the objective
  - Period of Performance: June 1, 2021 - November 30, 2023
  - PEER-Bridge TO4

PEER

Caltrans®

Project Overview

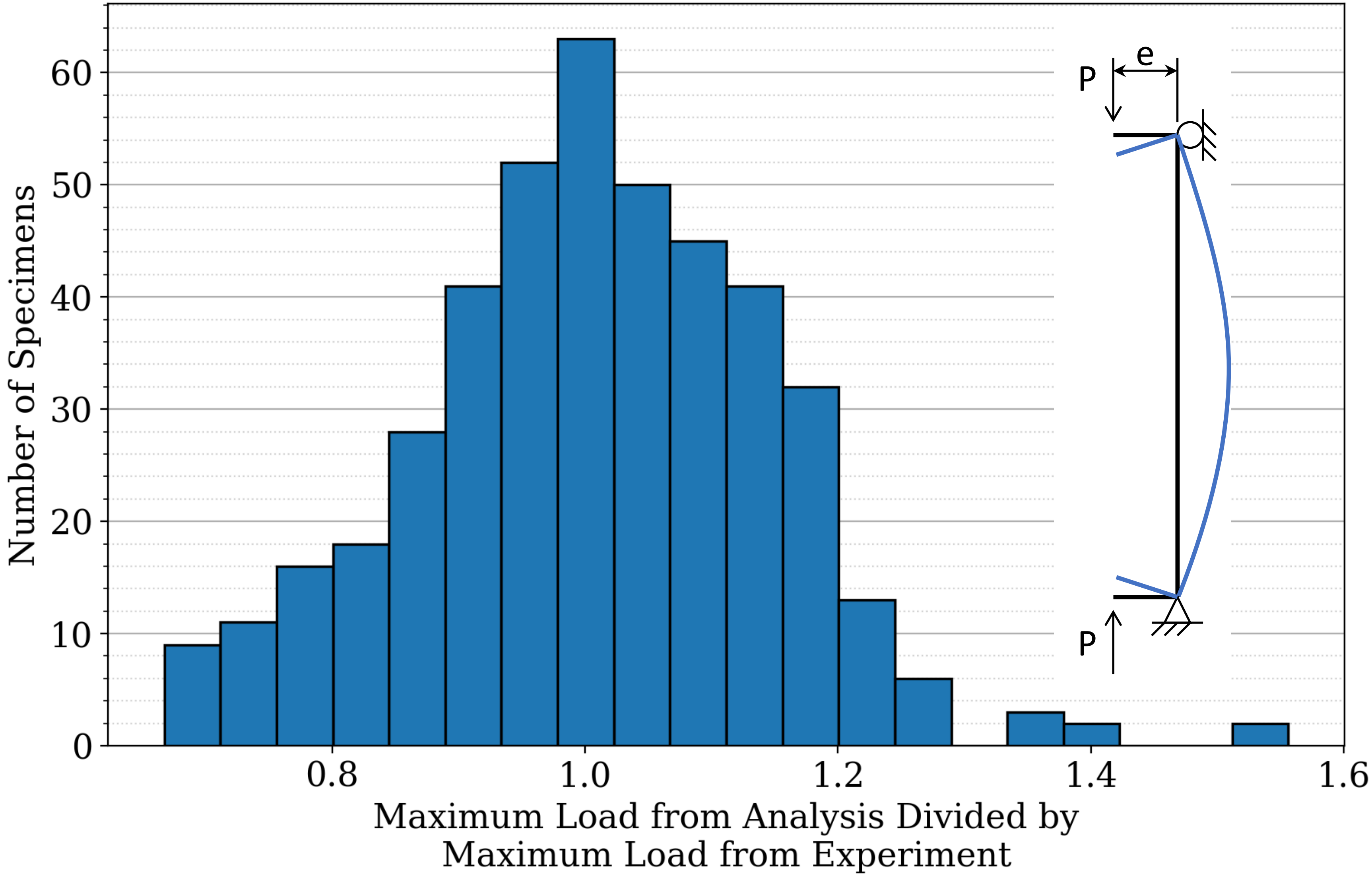
- Task 1: Literature review (behavior, analysis, and design)
- Task 2: Model selection and identification of parameter ranges
- Task 3: Develop and validate refined second-order analysis method
- Task 4: Evaluate current methods
- Task 5: Develop and verify modifications to design guidance
    - 5A - Establish member effective stiffness (EI)
    - 5B - Establish effective length factor (K)
    - 5C - Validate AASHTO slenderness ratio limits
    - 5D - Establish bridge responses as a function of KL/r
    - 5E – Bridge modeling guidelines for second-order analysis
- Task 6: Develop final recommendations and validate CSiBridge

Develop and Validate Second-Order Analysis

- Second-order inelastic analysis as a "best guess" of true behavior against which current and trial design methods can be benchmarked.
- OpenSees with mostly "off-the-shelf" components
- Short-term loading
    - Concrete stress-strain relationship based on Mander et al. 1988
    - Elastic perfectly plastic steel stress-strain relationship
- Long-term loading
    - TDConcrete models in OpenSees (Knaack, Tosic, Kurama – Notre Dame)
- Single column models and simplified whole bridge models

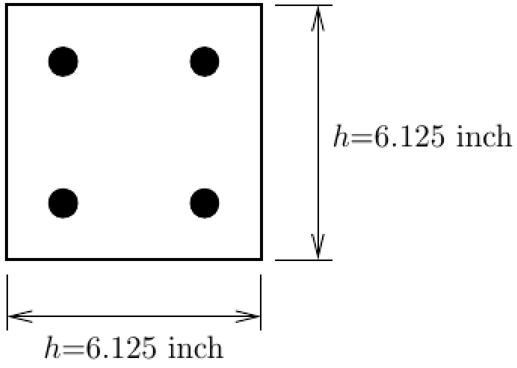
Validation Results (Short-Term)

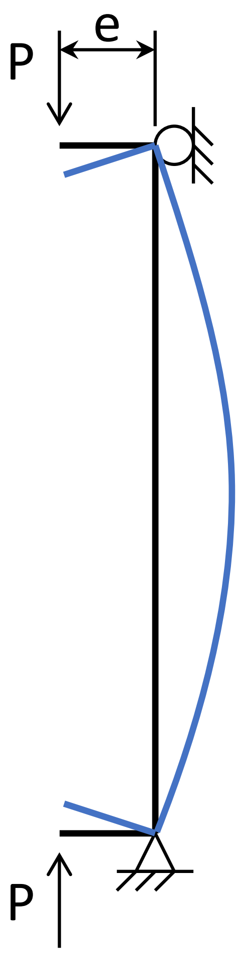
- Database of 432 short-term loaded proportionally loaded rectangular RC beam-columns
- Strength ratio
  - Mean = 1.004
  - St. Dev. = 0.141

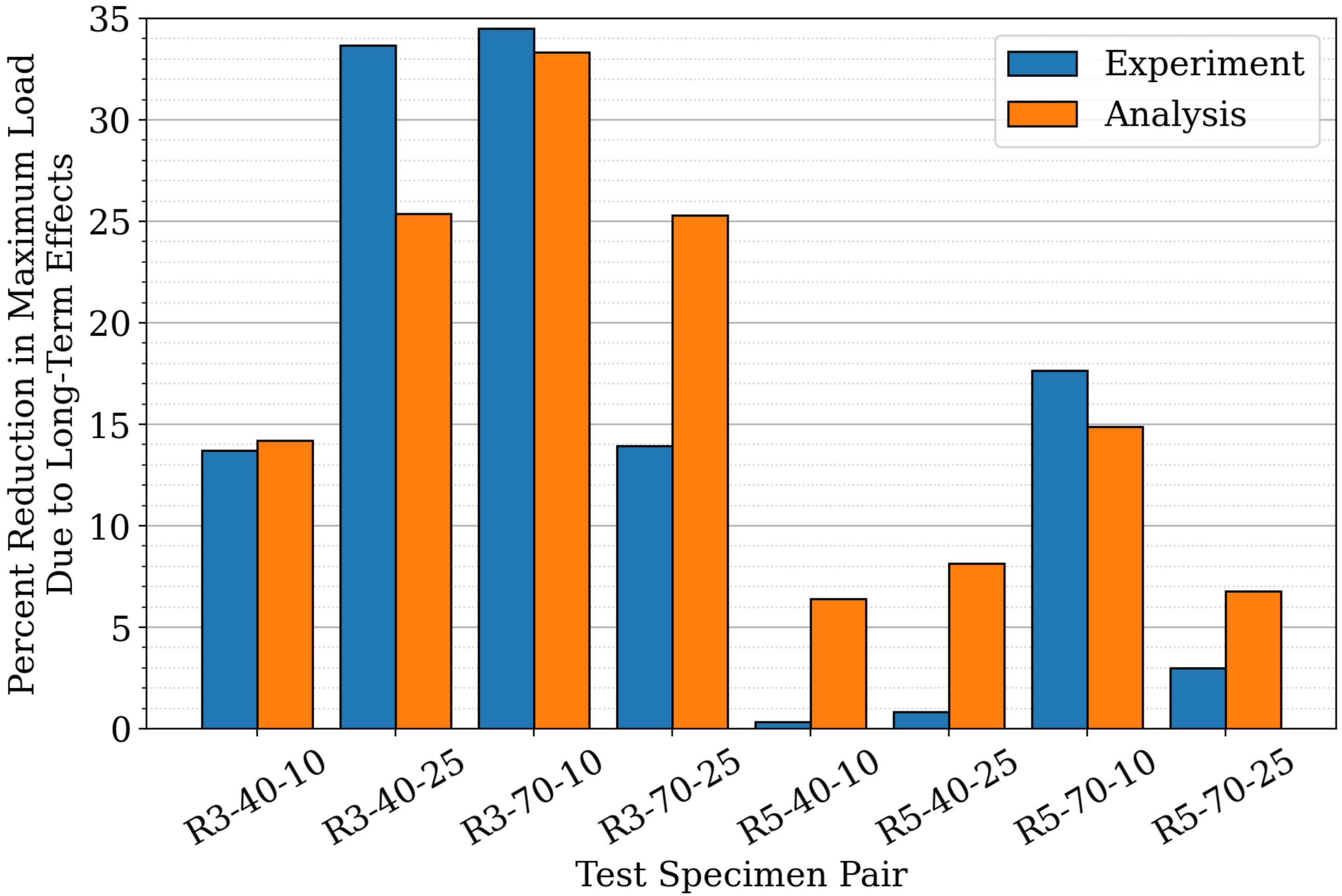


Validation Results (Long-Term)

- Jenkins and Frosch (2015) tested pairs of specimens.
- Difference (i.e., reduction) in strength due to long-term effects captured well by the analysis model.

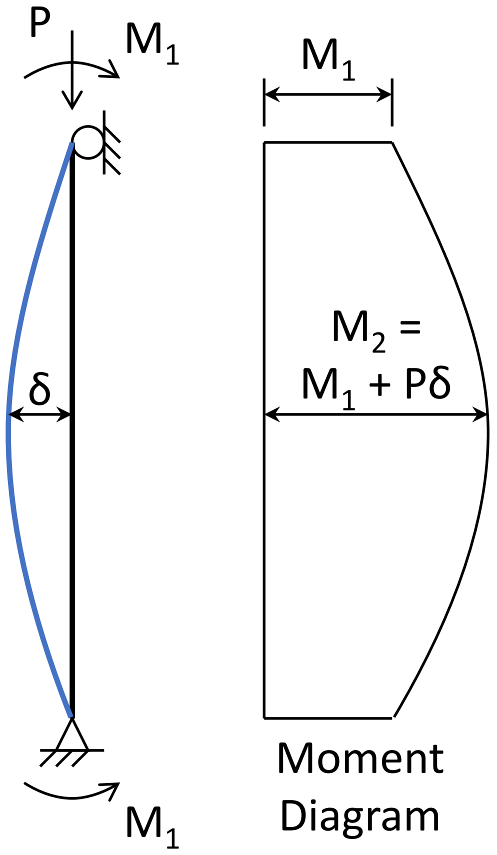


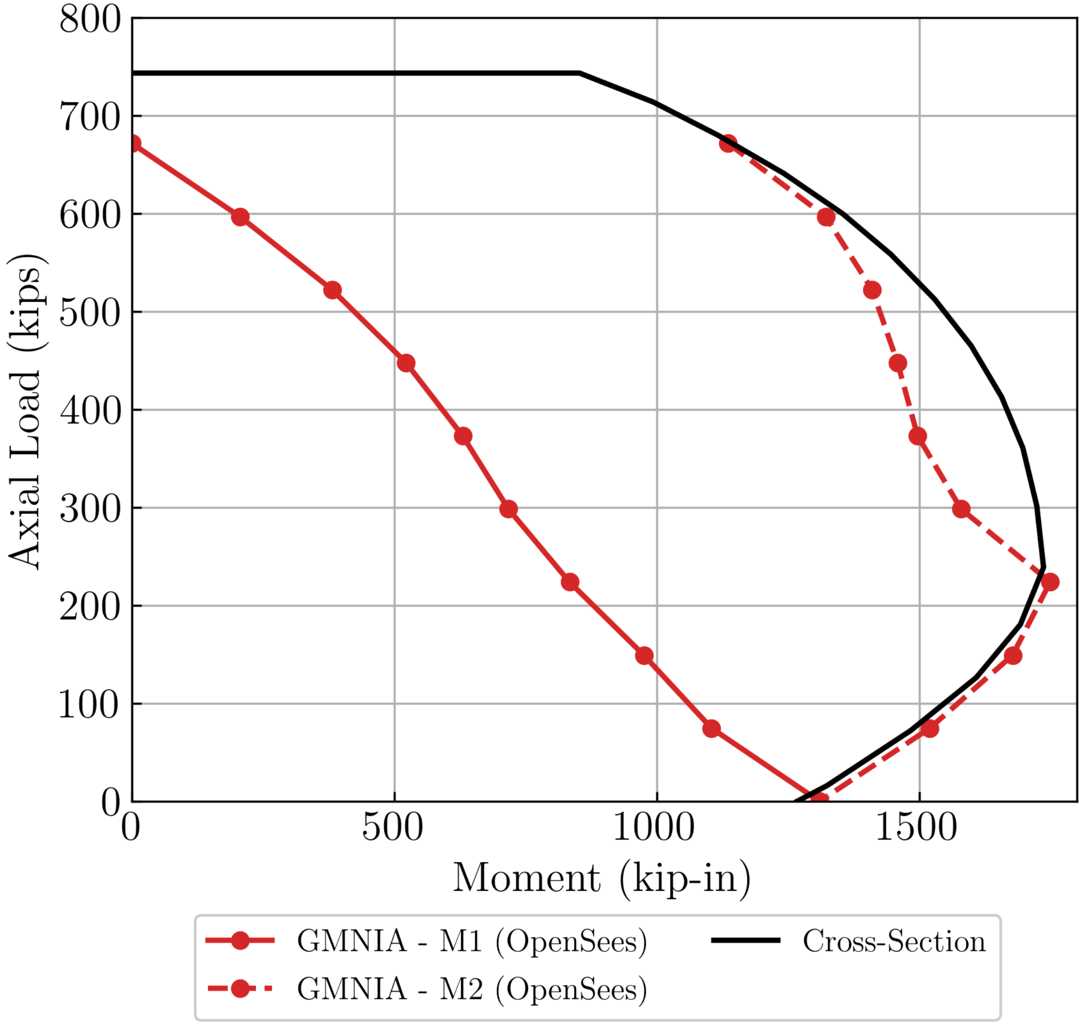




Design Method Evaluation

- Run second-order inelastic analyses in OpenSees to determine the applied loads that cause failure.
- First analysis with axial load only then several analysis with constant axial plus bending moment.

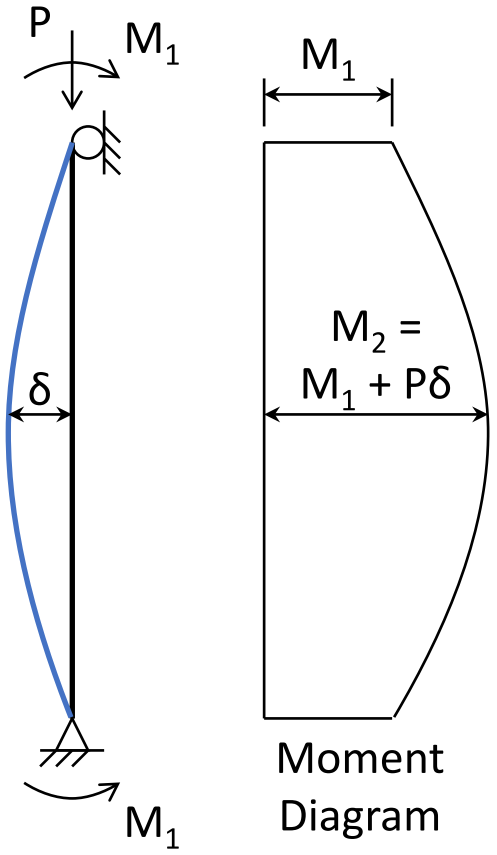


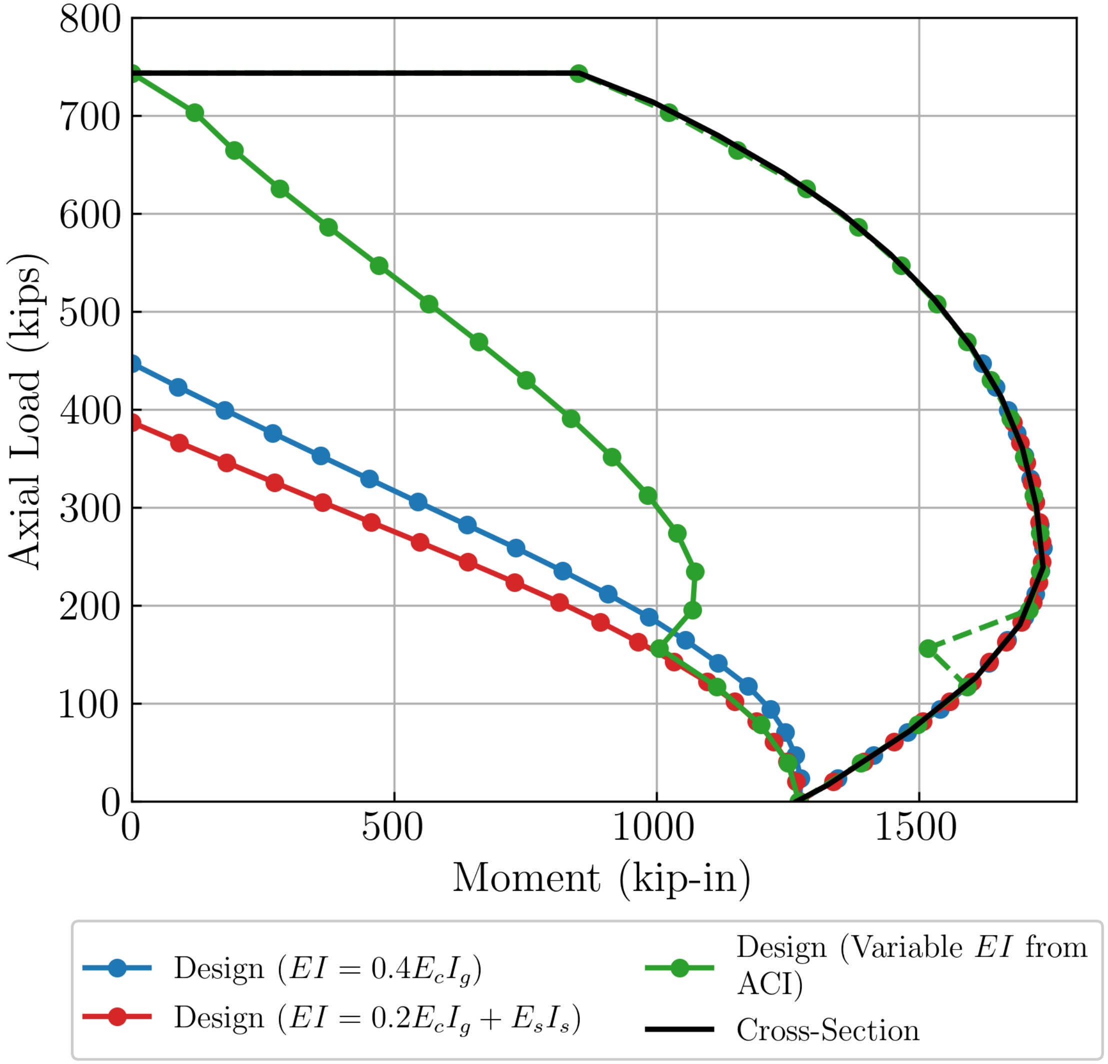


GMNIA = Geometrically and materially nonlinear analysis with imperfections included

Design Method Evaluation

- Run design calculations (moment magnifier) to determine maximum permitted applied loads.
- Different maximum permitted applied load for different options in design (e.g., *EI*).





Design Method Evaluation

Region of conservative error when using either constant EI

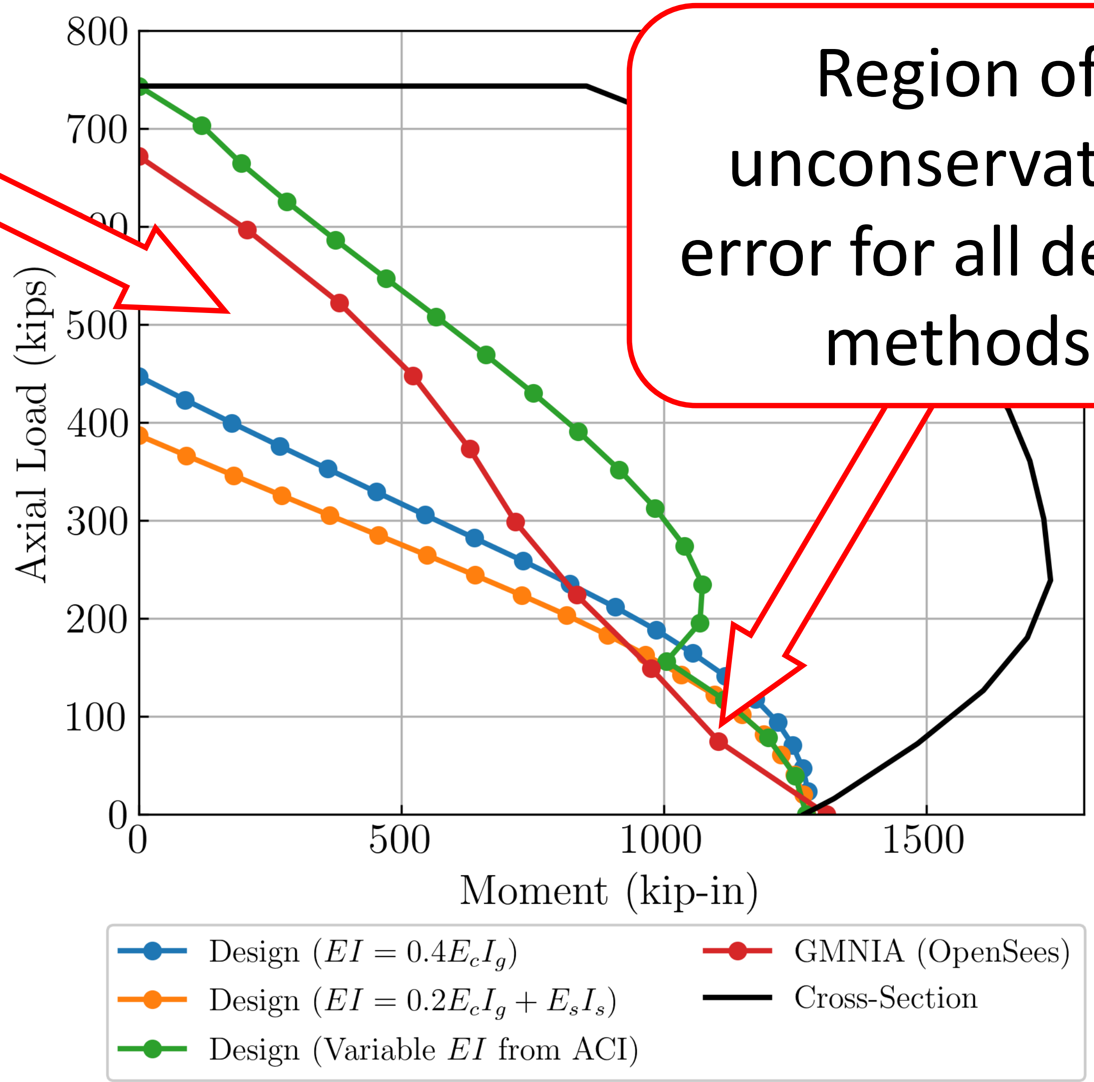
Compare the

- applied loa[...] determine[...] elastic analysis

and the

- maximum permitted applied loads per the design method

to identify regions of conservative and unconservative error.

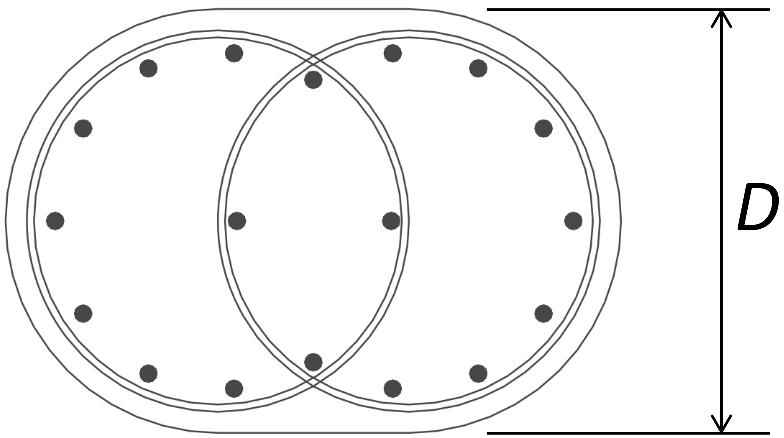


Region of unconservative error for all design methods

GMNIA = Geometrically and materially nonlinear analysis with imperfections included

Parameter Set

- Automate these procedures to enable a broad evaluation
- Circular and obround (*x*- and *y*-axis bending) cross-sections
- Different diameters (D = 16, 48, and 72 in.) but always 2 in. cover
- Different steel ratios (A_s/A_g = 1, 2, 3, and 4%)
- Different columns lengths (L/D = 5, 10, 15, 20, 25, 30, 35, and 40)
- Sway and non-sway with different boundary conditions (11 cases)
- Always f'_c = 4 ksi and f_y = 60 ksi
- 3,168 single column cases



Evaluation Results

- Maximum and minimum errors using the AASHTO moment magnifier approach with $EI = 0.4E_cI_g$

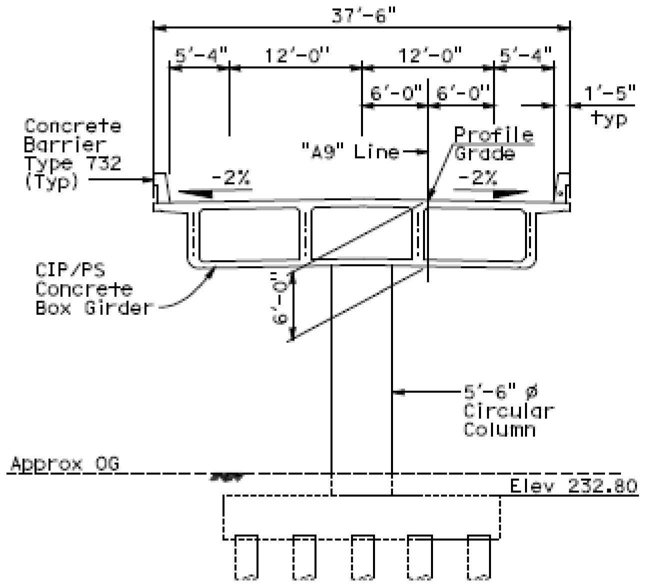
$\rho = A_s/A_g$	Error	Slenderness (KL/r)					
		≤ 22	22-50	50-75	75-100	100-125	≥ 125
0.01	Min	-3.7%	-8.7%	-15.9%	-23.7%	-25.4%	-28.4%
	Max	29.5%	28.5%	32.8%	59.4%	63.5%	65.3%
0.02	Min	-1.5%	-4.2%	-9.0%	-14.8%	-16.4%	-18.1%
	Max	28.3%	27.4%	27.1%	53.7%	58.1%	59.9%
0.03	Min	-1.1%	-3.0%	-6.5%	-11.0%	-13.7%	-15.7%
	Max	27.4%	26.5%	24.2%	50.1%	54.5%	56.2%
0.04	Min	0.3%	-2.0%	-4.8%	-9.3%	-10.8%	-12.9%
	Max	26.6%	25.8%	21.5%	46.2%	50.6%	52.2%

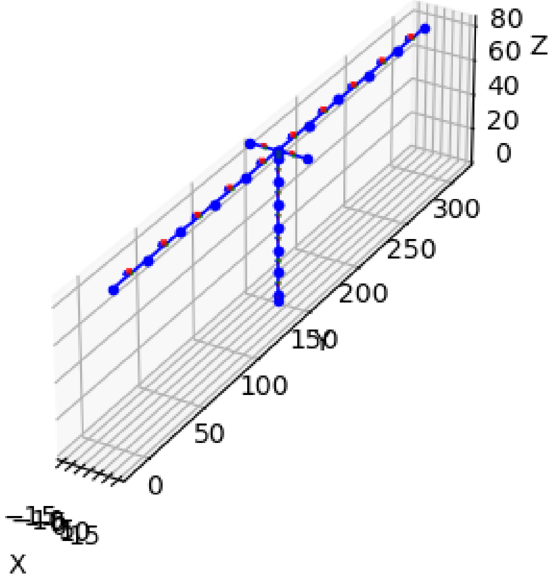
Effective Length Factor

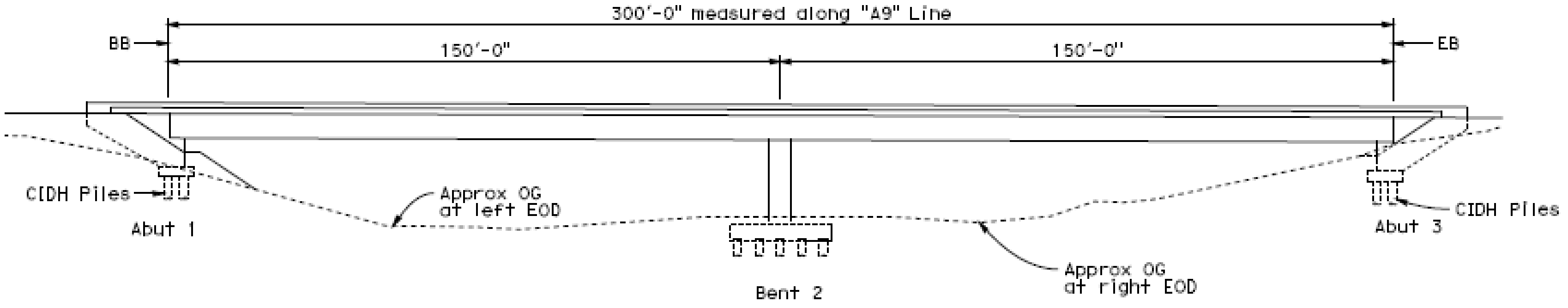
Preliminary OpenSees analyses of bridges helped identify where typical Caltrans practice for determining effective length factors is conservative.

Base assumptions:

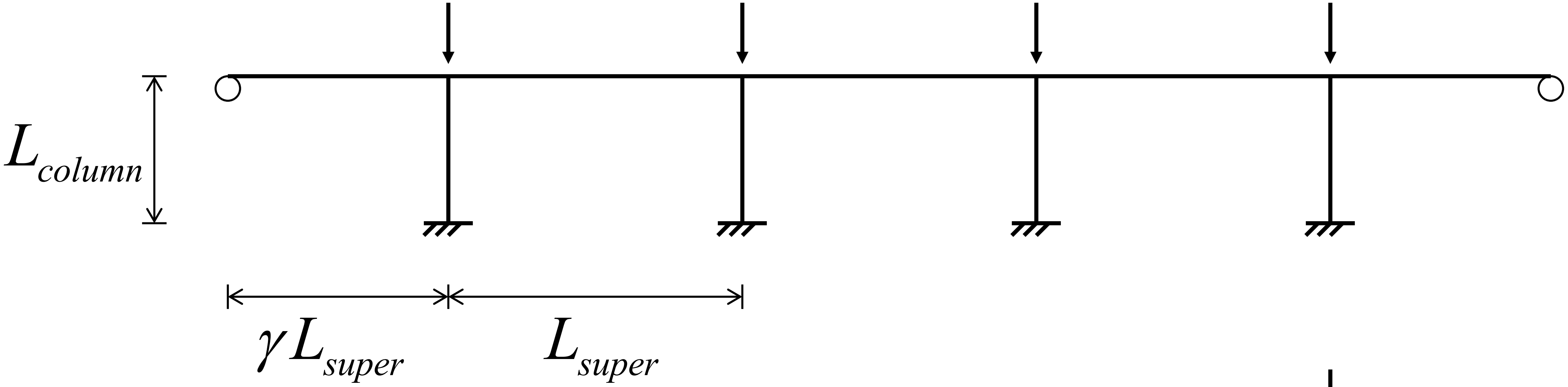
- Consider superstructure stiffness
- Neglect lateral restraint of abutments





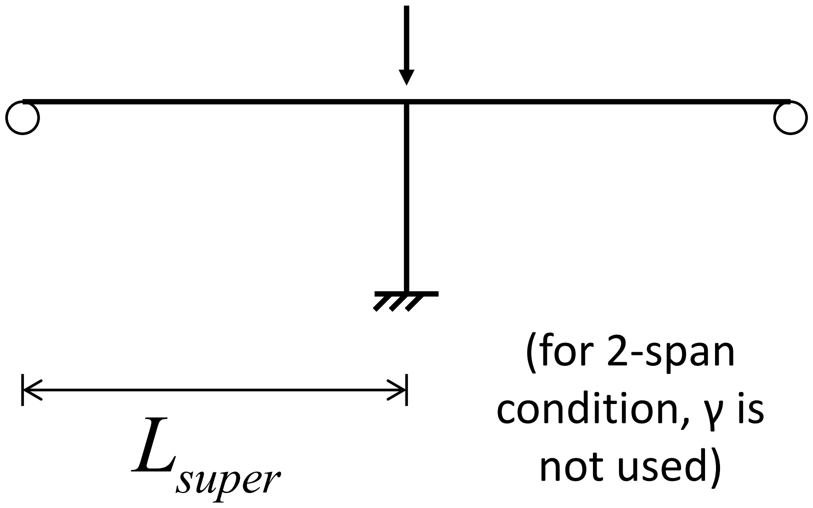


Idealized Bridge



Key parameter related to effective length factor for out-of-plane buckling:

$$g = \frac{\left(GJ/L\right)_{super}}{\left(EI/L\right)_{column}}$$



(for 2-span condition, γ is not used)

Effective Length Factor From Solution of Governing Differential Equation (Three Span Bridge)

$$v_1'''' + k^2 v_1'' = 0 \qquad v_2'''' + k^2 v_2'' = 0 \qquad k^2 = \frac{P}{EI}$$

Fixed base
(no rotation
or translation)

$$v_i\left(0\right) = 0$$
$$v_i'\left(0\right) = 0$$

Translation
at top free

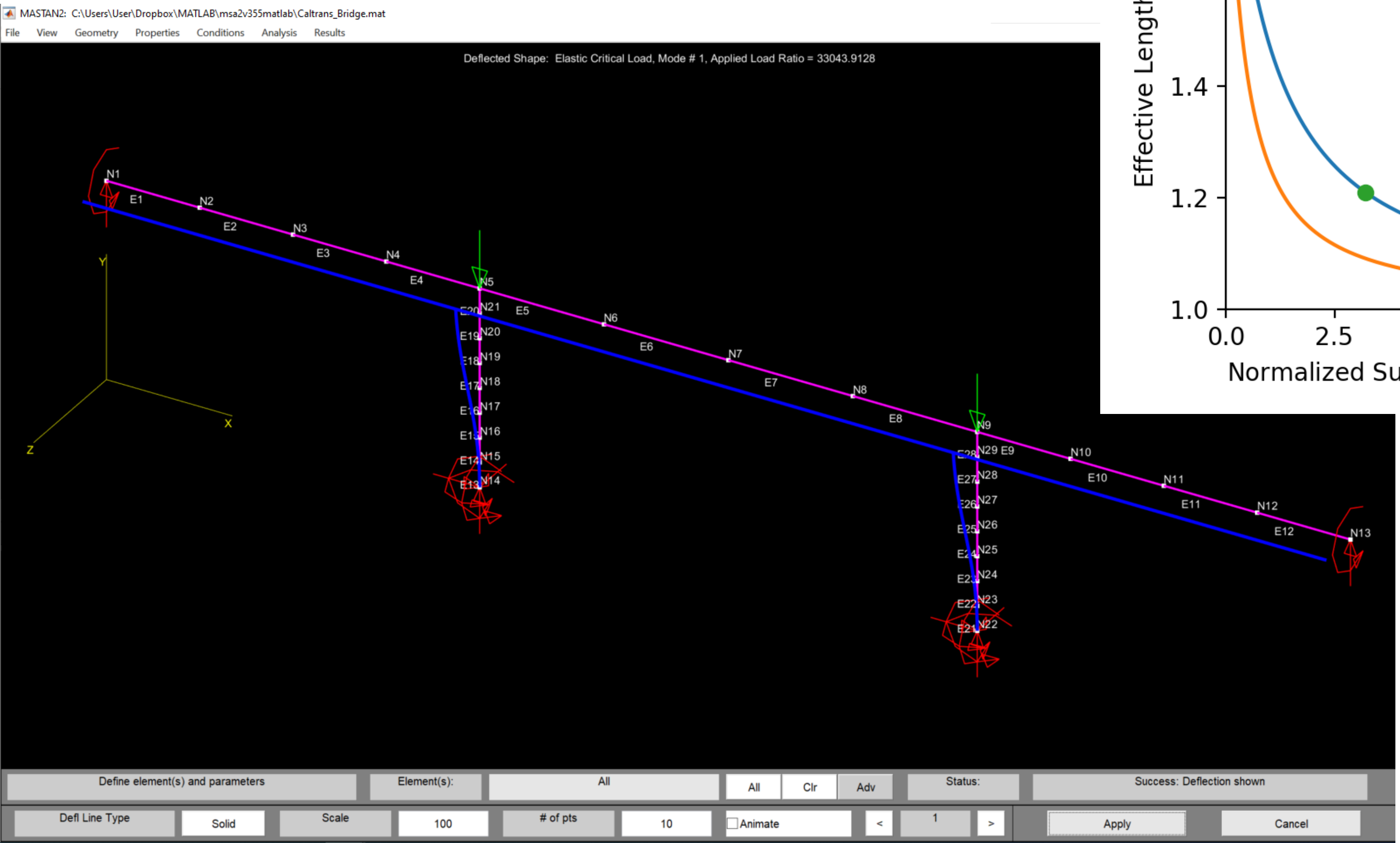
$$v_i'''\left(L_{column}\right) + k^2 v_i'\left(L_{column}\right) = 0$$

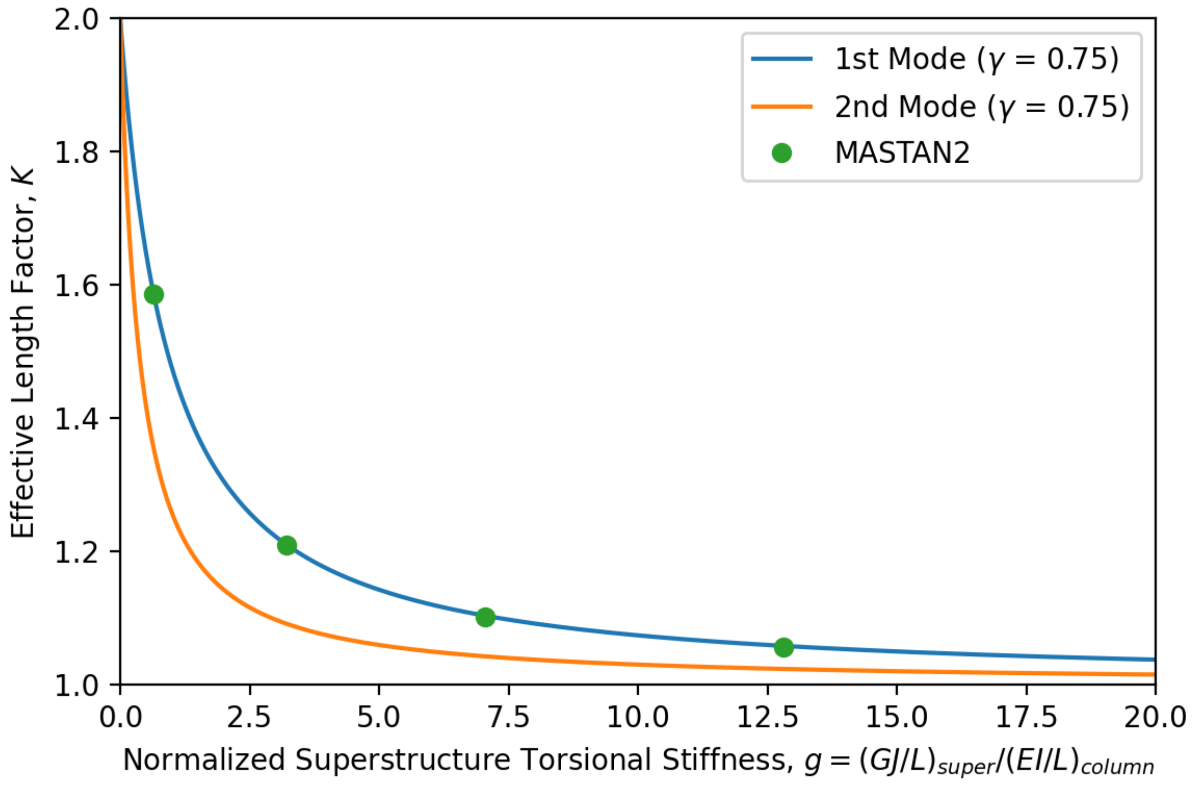
Rotation at top
restrained by
torsional stiffness
of superstructure

$$v_1''\left(L_{column}\right) + \frac{g}{\gamma L_{column}} v_1'\left(L_{column}\right) + \frac{g}{L_{column}}\left[v_1'\left(L_{column}\right) - v_2'\left(L_{column}\right)\right] = 0$$

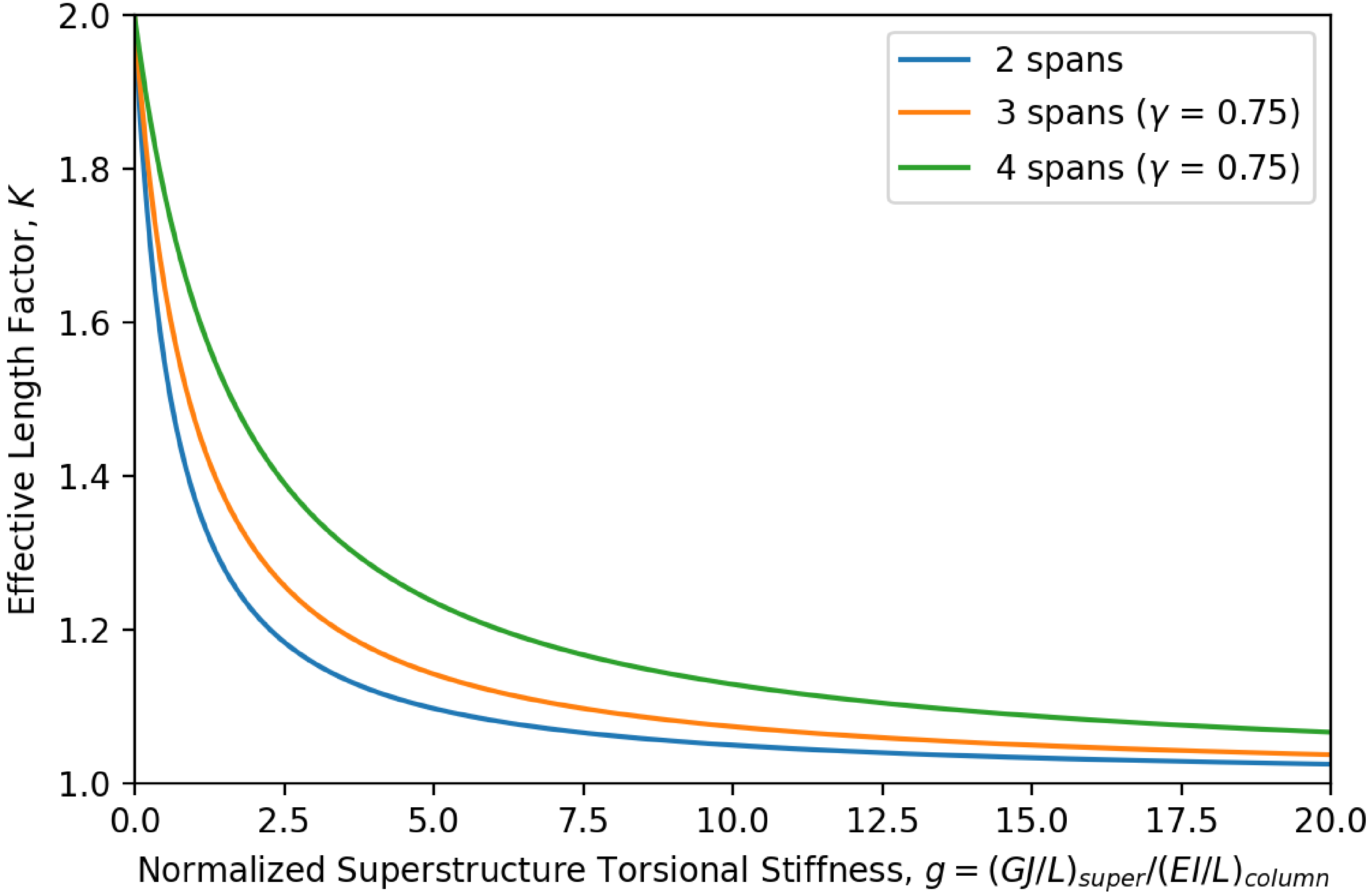
$$v_2''\left(L_{column}\right) + \frac{g}{\gamma L_{column}} v_2'\left(L_{column}\right) + \frac{g}{L_{column}}\left[v_2'\left(L_{column}\right) - v_1'\left(L_{column}\right)\right] = 0$$

MASTAN2 Verification





Comparison of Spans



Ongoing Work

- Further development and finalization of design recommendations
  - Effective flexural rigidity, *EI*
    - Variable with *P* and *M*
    - Long-term effects
  - Tools for practical implementation of recommended effective length factor
  - Validate AASHTO slenderness ratio limits
    - At what value of *KL*/*r* is consideration of second-order effects necessary?
    - At what value of *KL*/*r* is a refined analysis necessary?
  - Heuristics (rules-of-thumb) for preliminary design
  - Recommendations for refined analysis
- Validate recommendations with CSiBridge

Outcomes

- Thorough evaluation of current design method for slender RC bridge columns.
- Identification and quantification of errors due to simplifications in the design method.
- Rigorously justified and practical recommendations to reduce error in design.

Engineers able to make more confident, accurate decisions when designing slender RC columns.

Thank you!

Image from
Sharon Yen, Caltrans