IMPROVED LATERAL LOAD DISTRIBUTION FOR SLAB AND T-BEAM REINFORCED CONCRETE BRIDGES

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SPR-4120 (BO: Jeremy Hunter 2017-2019)
SPR-4444 (BO: Jennifer Hart 2019-2021)

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Topics of the presentation

- Justification
- Hypothesis
- Research Objectives
- Methodology
- Results
- Summary

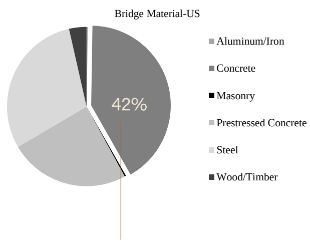
Justification

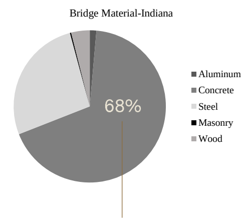
AASHTO-LRFD Specifies Simplified Analysis for Bridge Evaluation

- United States Bridge Population
- Load Rating Procedure

Justification

U.S. Bridge Population





- About 250,000 RC bridges
- Popular in 1950s-1970s
- 32,000 replaced RC bridges

- 3000 slabs and 700 T-beams
- 50% aged more than 50 years
- 21% structurally deficient
- 26% reconstructed
- 200 bridges posted/closed

Standard Load Evaluation Procedure

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[Federal Highway Administration, 2019]

Justification

Load Rating Procedure

Standard routine for load-carrying assessment

- Check for new code specifications
- Check for current/future demand
- Check for permit vehicles

capacity vs. demand → Rating Factor (RF) →

- ≥ 1 safe
- < 1 weight posting
- < 0.3 closure

$$RF = \frac{R_n - DL}{LL\ (1 + IM)}$$

Importance of Demand Estimate

R_n	nominal capacity
DL, LL	load effects
IM	impact factor

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[AASHTO LRFD, 2017]

Hypothesis

Current Demand Estimate Provisions Overestimate the Load Share of Interior Bridge Sections

- Background
- AASHTO LRFD Provisions

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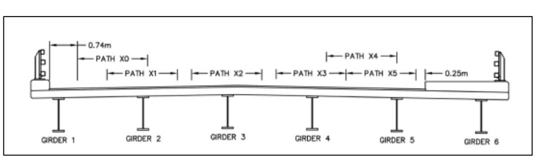
Hypothesis

Based on available literature AASHTO underestimates the RF

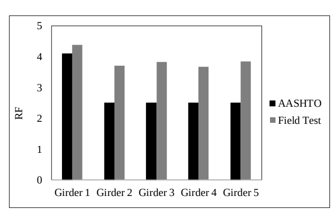
[Power Mill Bridge-Massachusetts]

[Data Acquisition System]

- Three-span girder bridge
- Measured strain values
- Applied standard truck
- Compared with AASHTO results



[Bridge Cross-Section]



[Sanayie et al., 2015]

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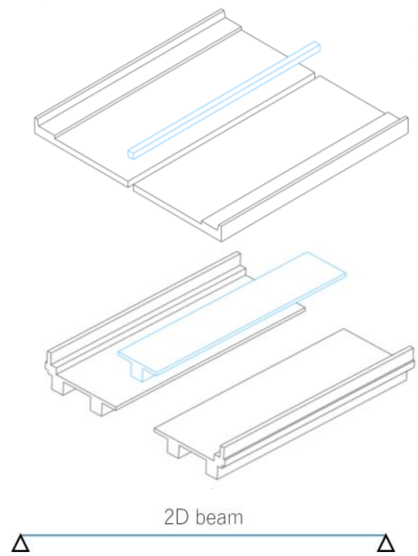
Hypothesis

AASHTO Specifications

- Simplified representation of superstructure
- Member-by-member assessment
- Two-dimensional analysis
- Distribution factor for lateral load effect

× Whole system behavior
× Actual lateral load distribution
× Effect of non-structural components

Edge-elements: barriers: railings/parapets/curbs; end-diaphragms



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[Cai and Shahawy 2003; Catbas et al. 2003; Hasancebi and Dumlupinar 2013]

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Hypothesis

Distribution Factor Background

Empirical Formulations
- 1930s
  - Introduction of DF concept
  - Based on experimental/field test data

Standard (S/D) Formulations
- up to 1994
  - Related to bridge type
  - Single-span non-skewed bridges
  - Under/overestimating

LRFD Formulations
- 1998-present
  - Included more geometrical properties
  - Improved accuracy
  - Increased range of applicability

Neglected Effect of Secondary Elements

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Original Contribution

Revise Distribution Factor Formulation Considering Effect of Secondary Elements

- Research Objectives

Original Contribution

Research Objectives

- Improve accuracy of demand estimation for slab and T-beam bridges
- Revise current distribution factor formulations
- Include effect of secondary components

$$RF = \frac{R_n - DL}{LL\,(1 + IM)}$$

LL → $Live\ Load * DF$

DF → load share to strips/girders

$$DF = c + \left(\frac{S}{a_1}\right)^{b_1} \left(\frac{S}{a_2 L}\right)^{b_2} \left(\frac{K_g}{a_3 t_s}\right)^{b_3} \rightarrow girder$$

$$DF = \frac{1}{a + b\sqrt{LW}} \rightarrow slab$$

S	girder spacing
L	span length
K_g	girder stiffness
t_s	slab thickness
W	bridge width

[AASHTO LRFD, 2017]

Methodology

Finite Element Methods Could Be Used for A Thorough Investigation of Lateral Load Distribution

- Exploratory Case Study: Indiana Bridge Sample
- Parametric Study
- Statistical Analysis

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Methodology

Indiana Bridge Case Study

- RF assessment for a sample of slab and T-beam bridges

- Construction Year
- Span length
- Roadway width
- Deck skew

- Application of Conventional Load Rating (CLR) procedure ⟶ LRFD
- Performing Finite Element (FE) analysis ⟶ ABAQUS
- Comparison of CLR and FE results

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[National Bridge Inventory, 2013]

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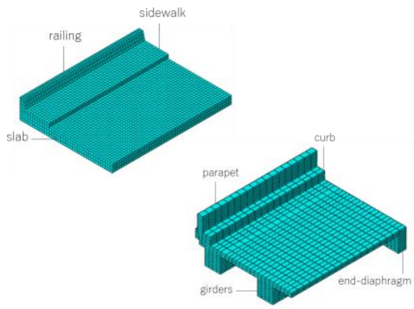
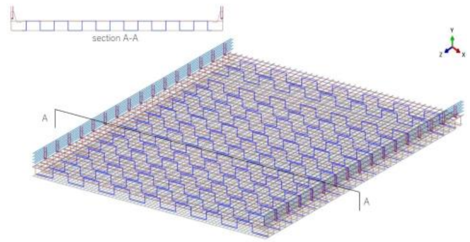
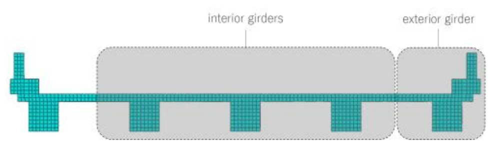
Methodology

Modeling Assumptions

- Linear elastic analysis
- Material properties based on drawings
- 3D solid elements for concrete
- Truss elements for reinforcement
- Bridge partitioning





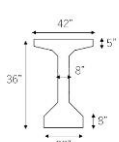


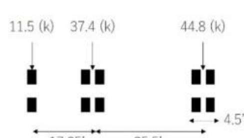
Methodology

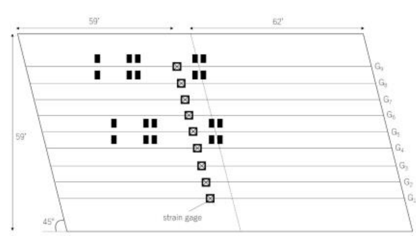
Model Validation

- Slab on concrete girder bridge
- Elastic Modulus: 4031 ksi
- Strain values measured
- Span length: 125 ft.
- Deck skew: 45°
- Prestressed AASHTO V Type beams
- Two FDOT trucks applied

[St. Lucie County Bridge - Florida]



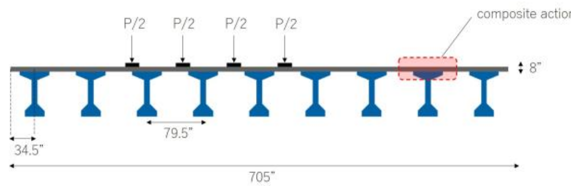




[Cai et al., 2002]

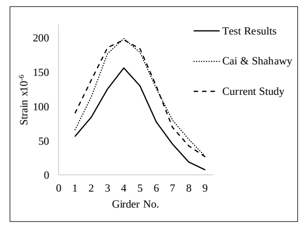
Methodology

Model Validation



Strain values comparison

- Comparable magnitude
- Similar pattern for strain distribution
- Greater strain values for girders under applied loading
- Similar results to Cai study's



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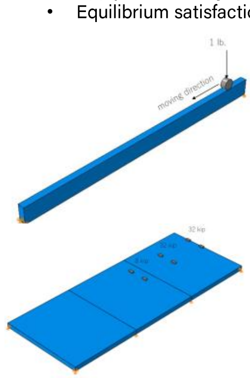
[Cai & Shahawy, 2004]

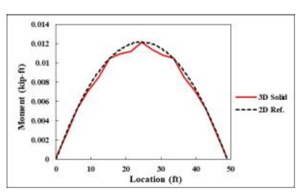
Methodology

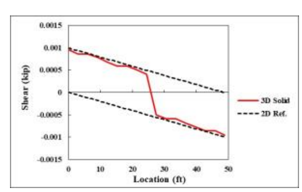
Model Verification

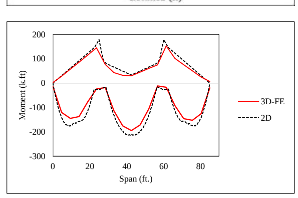
Moving Load Application

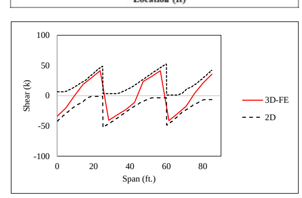
- Apply 1 lb. moving load → step-by-step
- Equilibrium satisfaction











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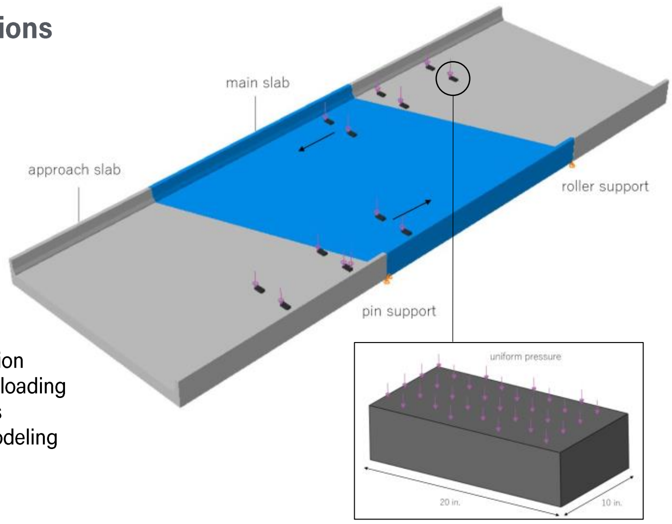
Methodology

Modeling Assumptions



- Standard HL-93 application
- Single and multiple lane loading
- Different lateral positions
- Rigid patch for wheel modeling

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Methodology

Obtaining FE Results

ABAQUS
FE analysis results in form of normal and shear stresses

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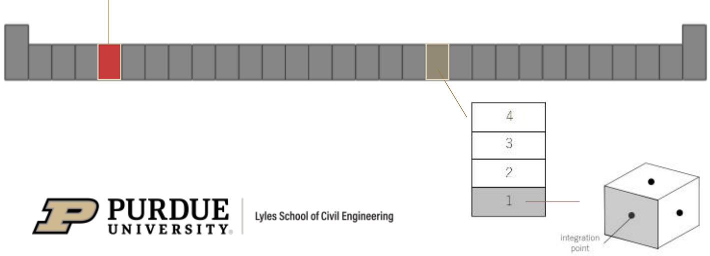
PYTHON
moment and shear envelopes for each individual strip/girder

↓

MATLAB
maximum of shear/moment response for critical strip/girder

Max. M
Max. V → critical strip



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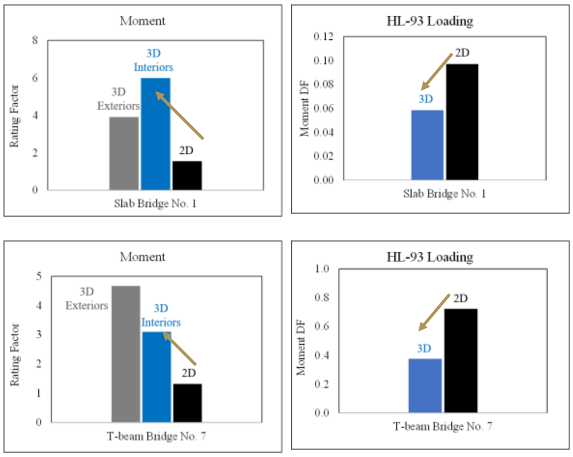
Methodology

Case Study Results

Slab

T-beam



$$RF = \frac{R_n - DL}{LL\ (1 + IM)}$$

- Same pattern for shear
- Similar results for all samples

Methodology

Findings Summary

- Bridge system behavior was reflected in superstructure 3D models
- Rating factors of studied sample increased with 3D finite element analysis
- CLR could overestimate bending moment and shear forces of bridge components
- Presence of non-structural elements has substantial effect on load distribution over bridge deck
- Edge-stiffening effect is neglected in current distribution factor provisions
- Demand estimates could be improved with revised DF formulations

Performing Parametric Study to Include Effect of Edge Elements

Methodology

Parametric Study

- Statistical distribution of bridge features → NBI dataset
  - Counties in Indiana
  - 1900-2016
  - Bridge dimensions
- → Bridge drawings
  - Material properties
  - Edge members dimensions

↓

- ✓ Reference models
- ✓ Range of variables

- 3D modeling of bridge samples → ABAQUS
- Comparison of FE and code-specified demand results → Potential modifications

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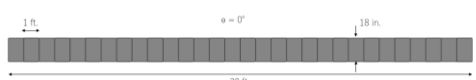
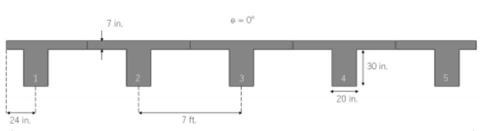
Methodology

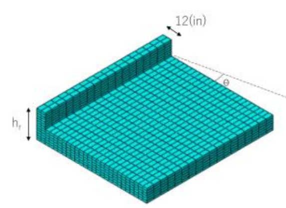
Parametric Study

- Reference Models

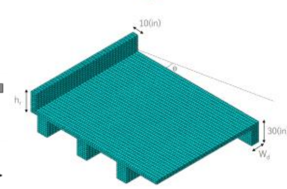




- Range of Variables



$h_r = 0" - 50"$
$\theta = 0° - 40°$



$h_r = 0" - 45"$
$\theta = 0° - 45°$
$w_d = 0" - 15"$

- Combined effect of variables
- Single and multiple span bridges

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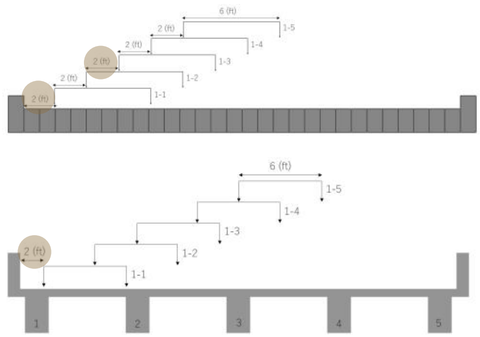
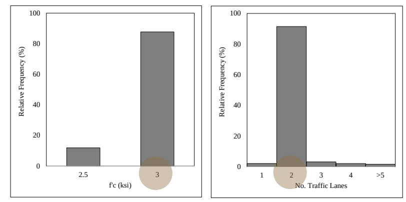
Methodology

Modeling Assumptions





- Elastic modulus of 3438 (ksi)
- Solid 3x3x6 in. elements
- Single and multiple traffic lanes
- Moment and shear responses
- Interior and exterior sections

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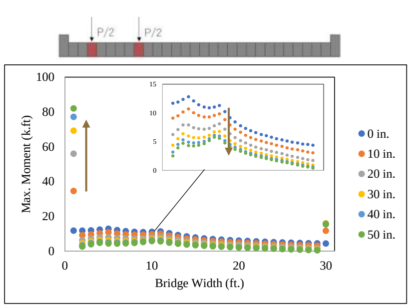
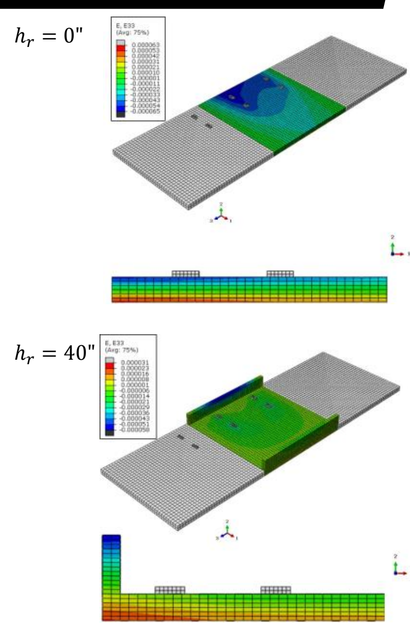
Methodology

Results

- Railing Effect





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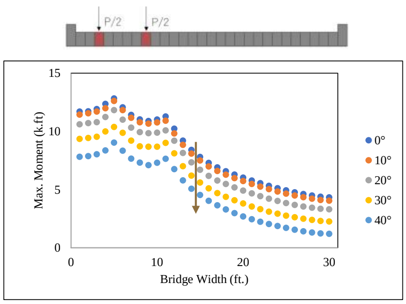
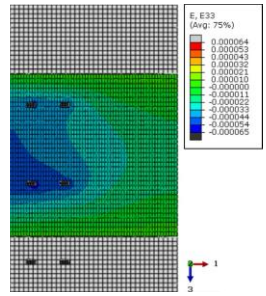
Methodology

Results

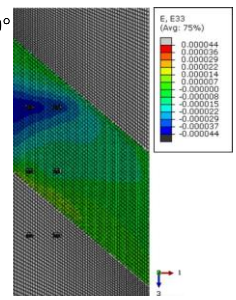
- Skew Effect



$\theta = 0°$



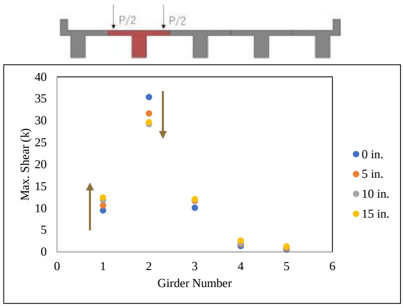
$\theta = 40°$

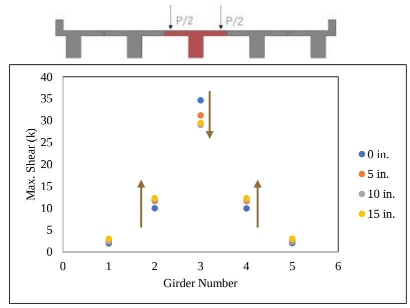


Methodology

Results

- End-diaphragm Effect





Methodology

Findings Summary

- Edge elements significantly influenced the demand distribution over bridge deck
- Railing produced the most drastic change in moment and shear demands
- Revised live load distribution factors could incorporate effect of secondary elements
- Modification factors could adjust current DFs for this purpose

Conducting Statistical Analysis to Propose Modification Factors

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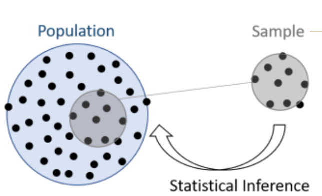
Methodology

Statistical Analysis

- Applied statistical methods to collect, organize, and analyze sample set of data
- Utilized quantified models and representations to characterize given set of data
- Proposed conclusions appliable to whole data population



Dependent variable (Y): demand ratio

$$Ratio = \frac{Max.Demand\ in\ models}{Demand\ in\ ref.model}$$

Independent variable (X): parameters

$rail\ height\ (h_r)$
$skew\ angle\ (\theta)$
$diaphragm\ width\ (w_d)$

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Methodology

Regression Analysis

- Determines numerical relationship between variables that are correlated
- Mathematical formulation that relates the dependent variable (Y) to independent variable (X)
- Used Nlogit-4 data analysis software
- Based on non-linear multivariate regression model

$Y = f(X) + \varepsilon$ ⟶ $f(X) = ?$

$$f(x) = a_1[f'(h_r)] + a_2[f''(\theta)] + a_3[f'''(w_d)] + c$$

- Linear
- Polynomial
- Logarithmic
- Power trendline
- etc.

$f(x)$	regression function
ε	errors
a_i	slope
c	intercept

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Methodology

Statistics

- Correlation coefficient ⟶ statistical relationship between two sets of variables
- Student t-test ⟶ statistical significance of independent variables
- Residuals sum of squares ⟶ performance indicator of regression model
- Coefficient of determination ⟶ measure of goodness of fit

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Methodology

Regression Models

- Determine dependency function between variables
- Select statistically significant independent variables
- Try different trendline formats for each variable set
- Minimize the errors
- Maximize the goodness of fit

$$y_i = f(x_i) + \varepsilon_i$$

$$f(x) = a_1[f'(h_r)] + a_2[f''(\theta)] + a_3[f'''(w_d)] + c$$

$$MF(h_r, \theta, w_d) * DF$$

proposed modification factor — current distribution factor

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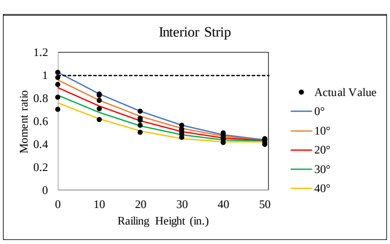
Methodology

Regression Model Estimation



- Variables
  - Dependent variable → *moment ratio*
  - Independent variables: h_r, θ, $h_r.\theta$ (product variable)
- Regression coefficients

$$MF = 1 - 0.02h_r + 0.0002h_r^2 - 0.3tg\theta + 0.006h_r tg\theta$$

- Model Performance: $RSS = 0.04$, $R^2 = 0.98$

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Results

Research Implementation

- Proposed Modifications
- Verification of Proposed Correction Factors

Results

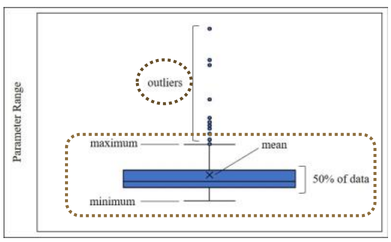
Proposed Modification Factors

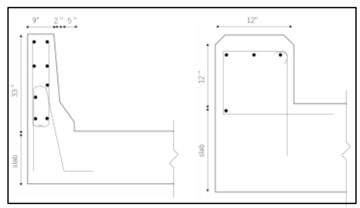
Bridge	Loading	Section	Effect	Railing MF	Diaphragm MF
Slab	Single-Lane	Interior Strip	Moment	$1 - h_r(0.02 + 0.006tg\theta) + 0.0002h_r^2$	NA
			Shear	$1 - 0.004h_r$	
		Exterior Strip	Moment	$1.2 + h_r(0.2 - 0.02tg\theta) - 0.002h_r^2$	
			Shear	$1.4 + h_r(0.07 - 0.03tg\theta)$	
	Multiple-Lane	Interior Strip	Moment	$1 - h_r(0.01 + 0.008tg\theta)$	
			Shear	$1 - 0.003h_r$	
		Exterior Strip	Moment	$1.2 + h_r(0.2 - 0.04tg\theta) - 0.002h_r^2$	
			Shear	$1.6 + h_r(0.09 - 0.04tg\theta)$	
T-beam	Single-Lane	Interior Girder	Moment	$1 - 0.004h_r$	$1 - 0.004w_d$
			Shear	NA	$1 - w_d(0.03 - 0.006tg\theta) + 0.001{w_d}^2$
		Exterior Girder	Moment	$1 + 0.007h_r$	$1 - 0.002w_d$
			Shear	$1 + h_r(0.003 - 0.003tg\theta)$	NA
	Multiple-Lane	Interior Girder	Moment	$1 - 0.001h_r$	$1 - 0.003w_d$
			Shear	NA	$1 - 0.009w_d tg\theta$
		Exterior Girder	Moment	$1 + 0.008h_r$	NA
			Shear	$1 + h_r(0.004 - 0.004tg\theta)$	NA

Results

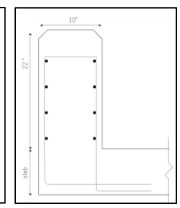
Modification Factors Verification

- Select random bridges from NBI dataset →
  - ✓ Ten each bridge type
  - ✓ Different geometries than reference bridge
- Estimate effect of secondary elements on response of bridges →
  - ✓ Railing (standard drawings)
  - ✓ Skew (bridge plans)
  - ✓ End-diaphragm (bridge plans)





Slab
[E706-BRSF]



T-beam
[E706-BRPP]

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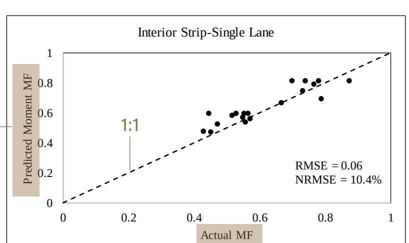
Results

Modification Factors Verification

- Perform FE analysis on 3D models of selected bridges
- Investigate performance of proposed formulations →
  - ✓ FE results vs. MF values
  - ✓ Error analysis → RMSE, NRMSE

from proposed formulations



from 3D models

Samples	RMSE	NRMSE (avg.)
slab	0.06-0.48	10.57%
T-beam	0.03-0.11	7.11%

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Summary

Research Findings

- Conclusions
- Future Work

Summary

Conclusions

- Bridge 3D models enabled inclusion of non-structural elements in FE analysis
- Non-structural elements such as railings, curbs, and end-diaphragms changed lateral distribution of load
- The findings of this study will improve the accuracy of RF evaluation

Recommendations

- Modification factors were proposed to update current DFs in both bridge types
- This might prevent posting/closure of critical bridges conservatively identified as structurally deficient

Summary

Suggested Future Work

- Perform parametric study to consider different edge geometries
- Investigate potential rehabilitation technique of adding rails in critical bridges
- Extend findings of the study to other similar bridge systems

THANK YOU FOR YOUR ATTENTION!

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