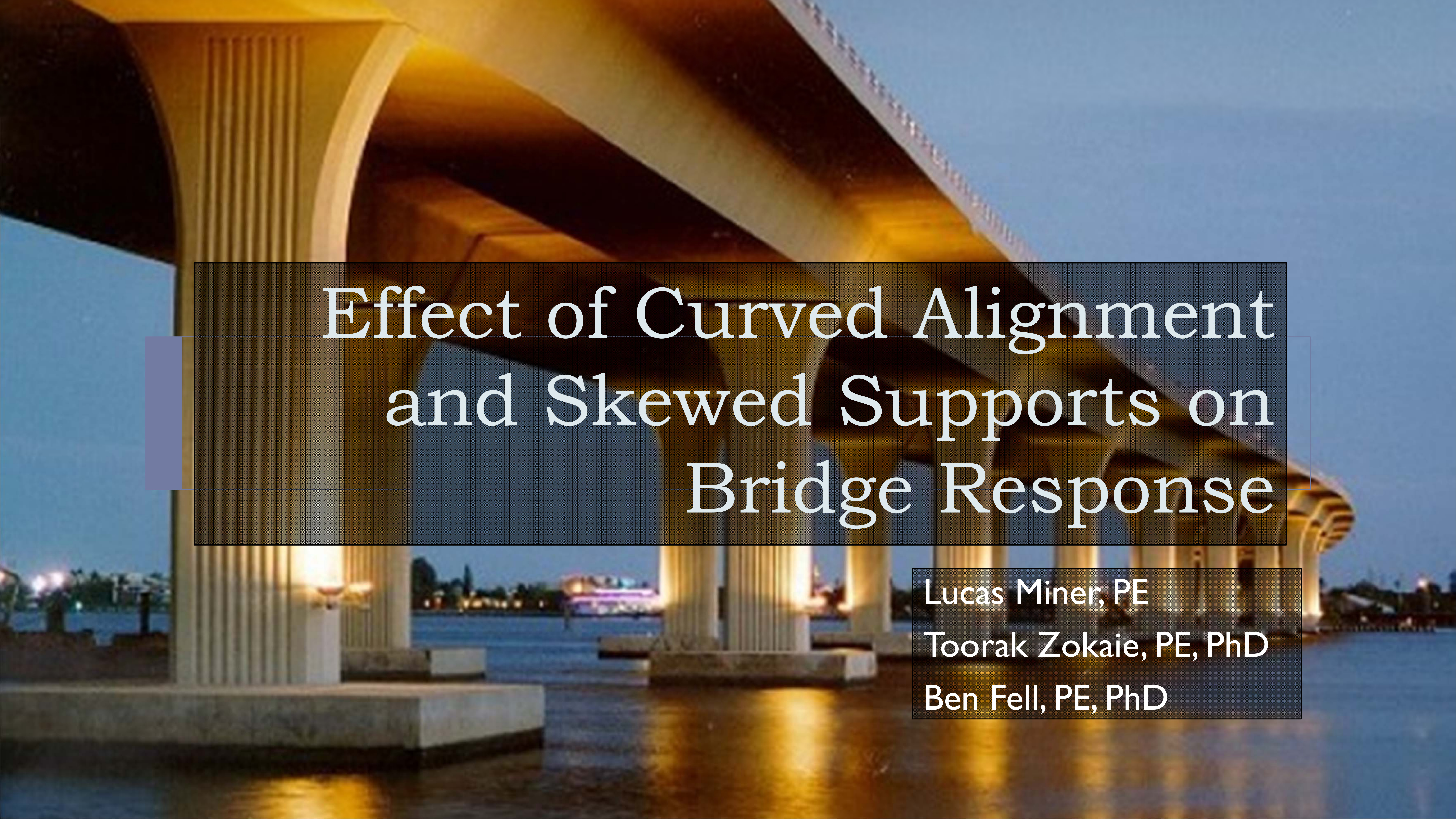


Effect of Curved Alignment and Skewed Supports on Bridge Response

Lucas Miner, PE
Toorak Zokaie, PE, PhD
Ben Fell, PE, PhD

Outline

- Motivation
- Code Procedure
- Study Results
- Conclusions
- Questions

Curve Effect and Skew Effect

The support forces at the end of skewed and curved bridges vary along the bridge width.

Curve Effect – Effect of curving a bridge horizontally on the bridge reactions (support forces)

Skew Effect – Effect of skewing a bridge on the bridge reactions

Issues Caused

Effects cannot be accurately predicted in 2D models

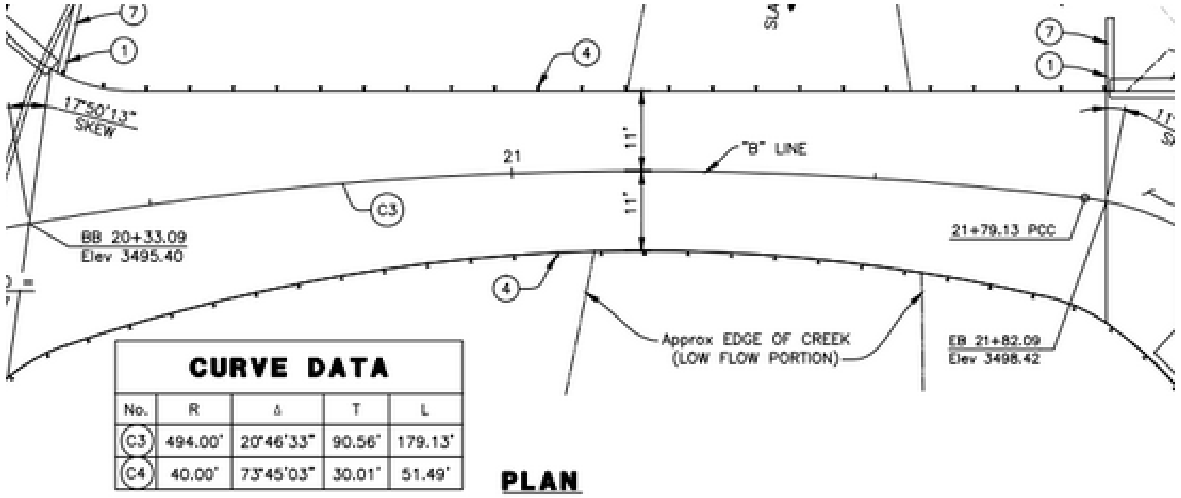
Girders can be under-designed for shear

Bearings receive overload or uplift

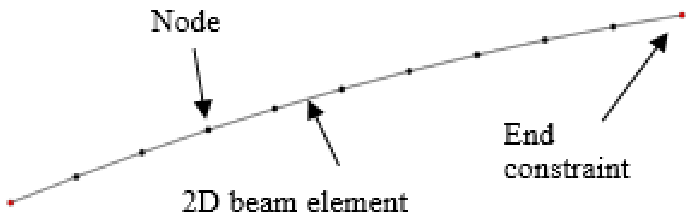
Additional moments on substructure

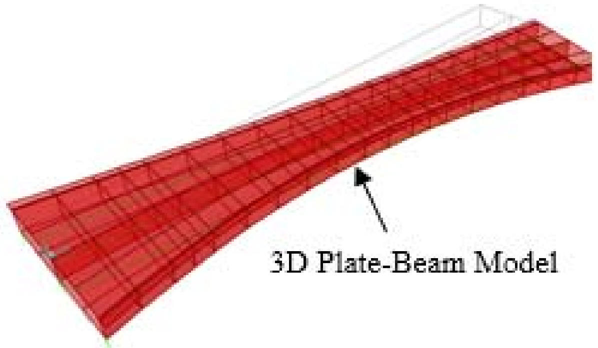
Code Procedures

- AASHTO LRFD 6th
  - 2D analysis limits for curved bridges
  - Skew shear correction factors for Live Load only



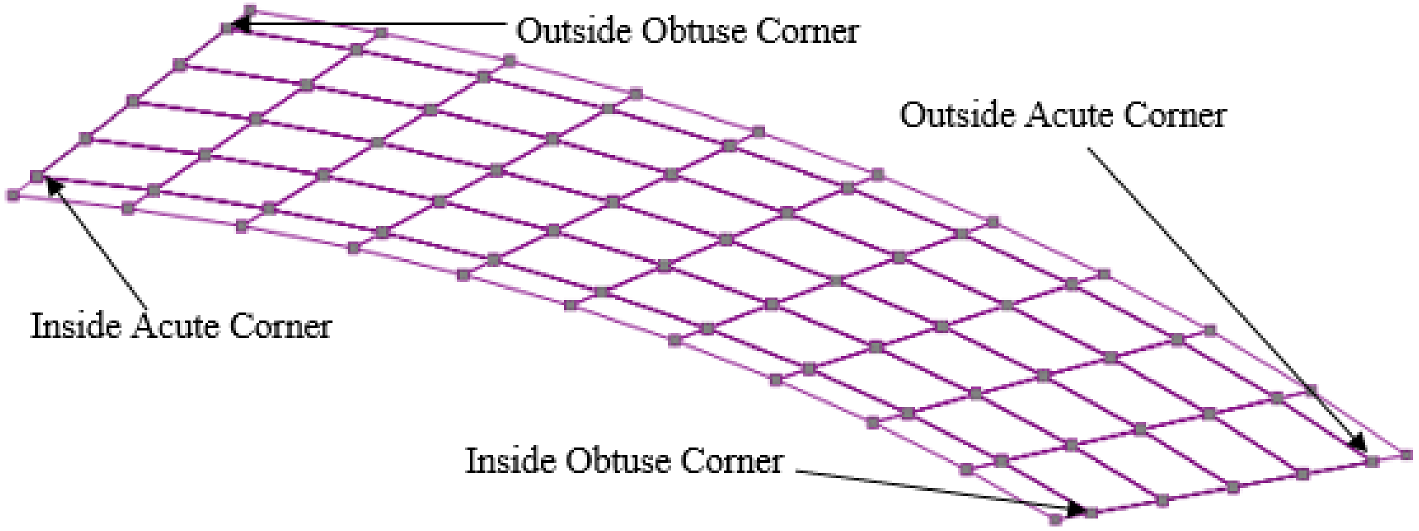
- Caltrans Amendments to AASHTO
  - Skew shear factors changed for some bridge types and applications.
  - Skew shear factors applied to all loads for T-beam and box-girder bridges





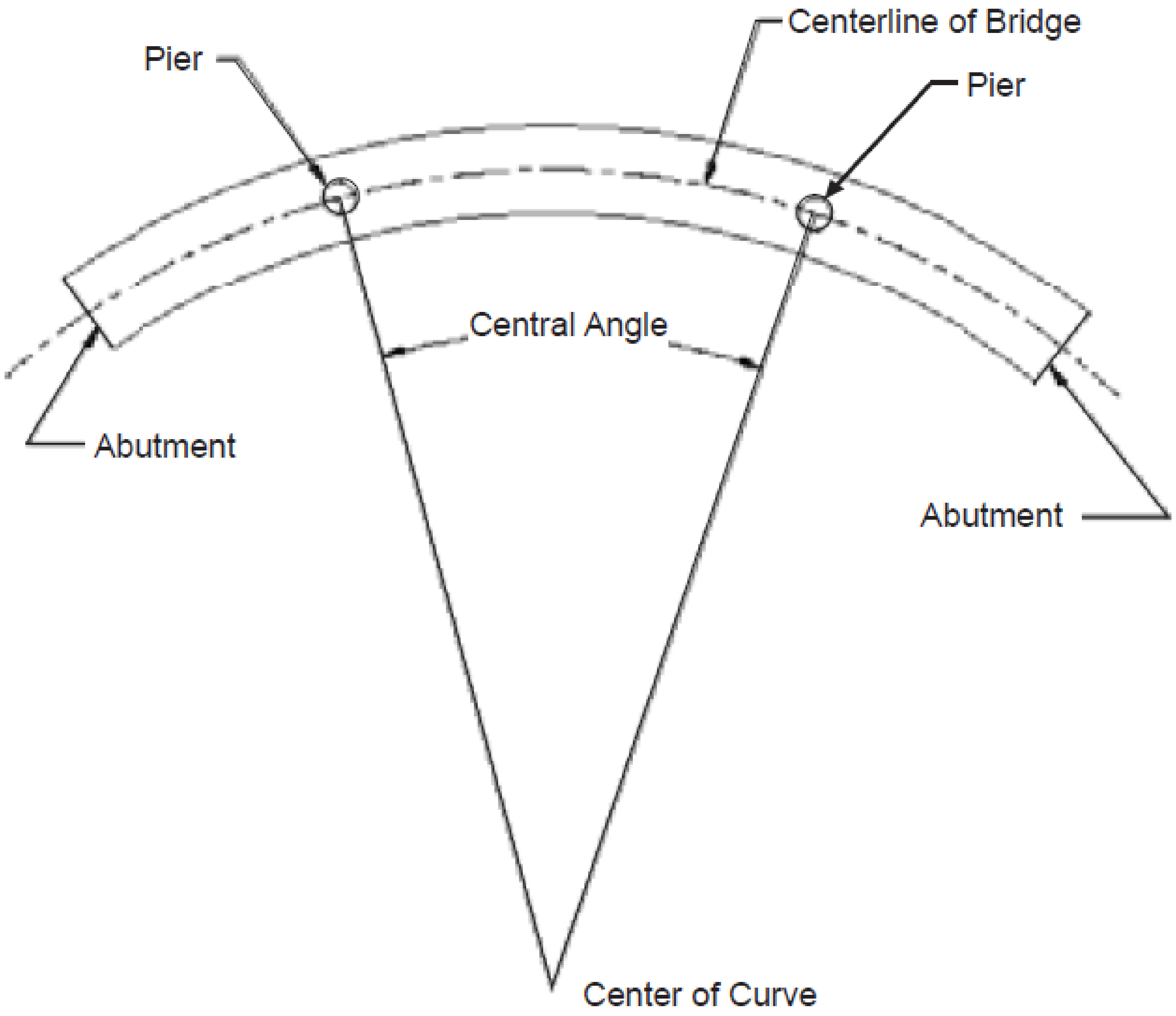
Code Procedures

- No clear guidance concerning Skew and Curve Effects on:
  - How to account for torsion in reaction response (Rigid Beam Analogy?)
  - Distributing reaction forces to substructure (non-monolithic)
  - Bearing design
  - Varying post-tensioning
  - Uplift in acute corners



Code Procedures: Curve Limits

- Ignore curve for central angles < 12 degrees (L/R=0.2)
- Model as curved spine model for central angles between 12 and 34 (L/R=0.6)
- Full 3D analysis for central angles > 34



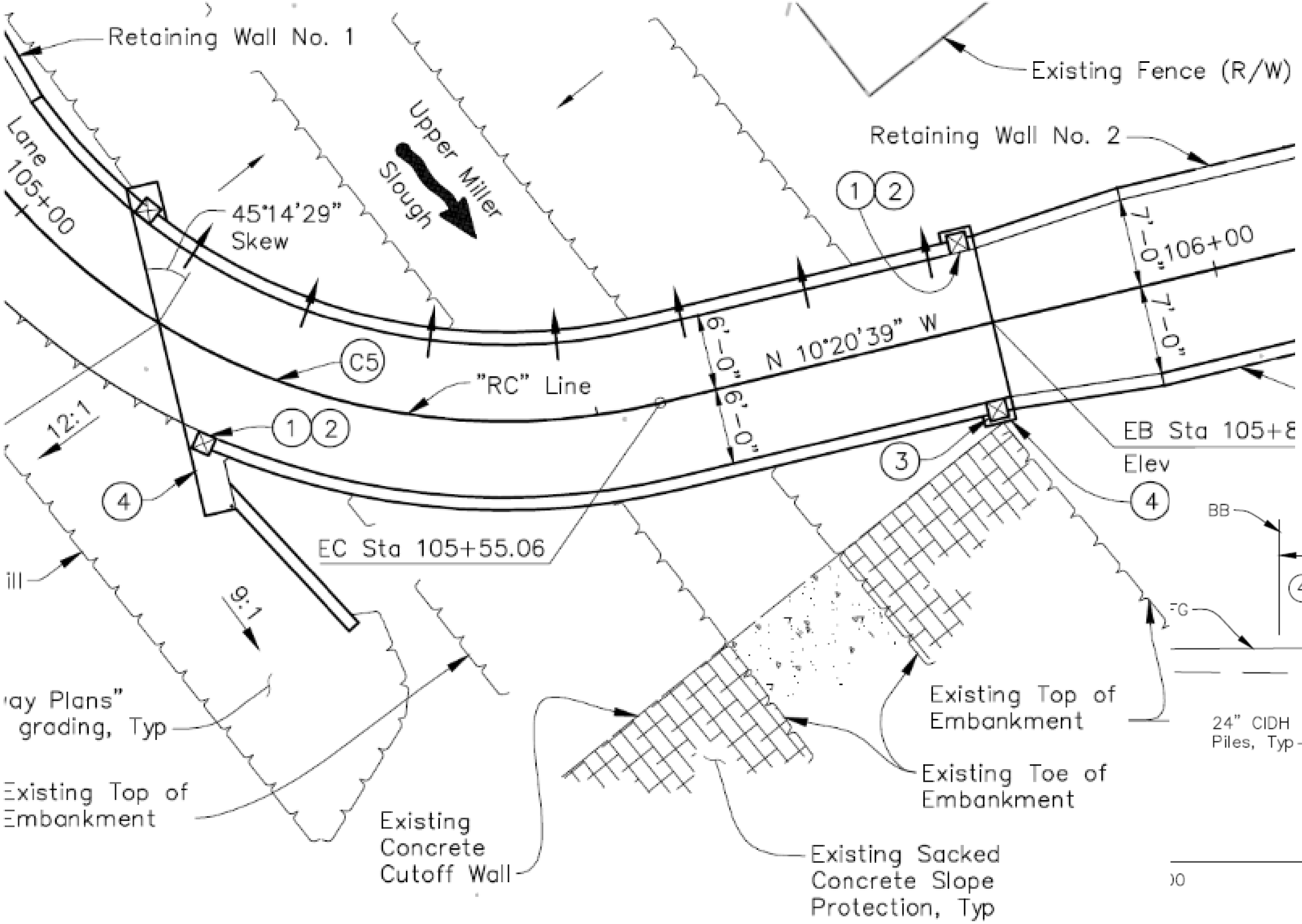
Code Procedures: Skew

- Dead Loads
  - No skew correction in AASHTO LRFD 6th
  - Caltrans Amendment provides a correction factor for exterior girders for Box Girder Bridges

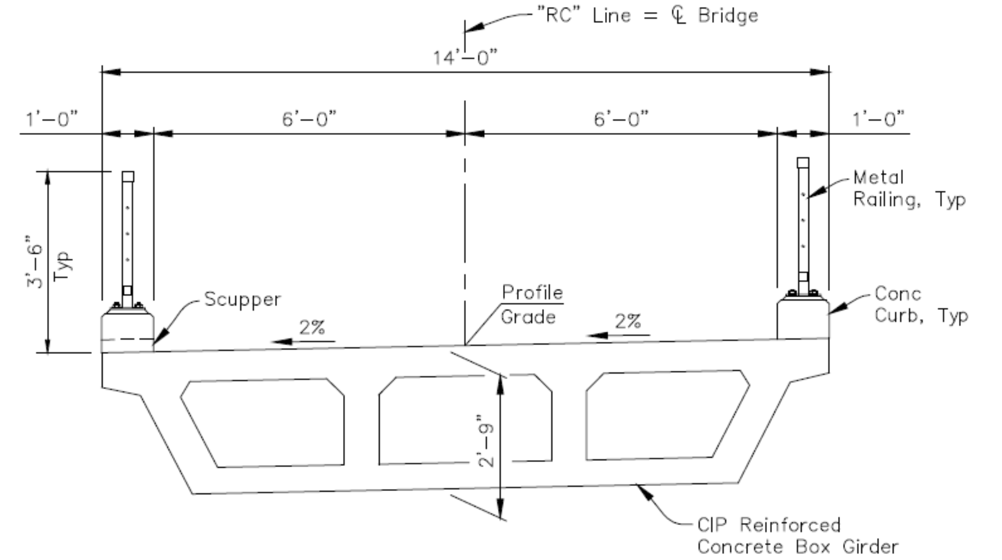
$$Correction\ Factor = 1.0 + \frac{\theta}{50}$$

  - This factor is only dependent on skew angle, θ, and yielded non-conservative results for most models in this study.

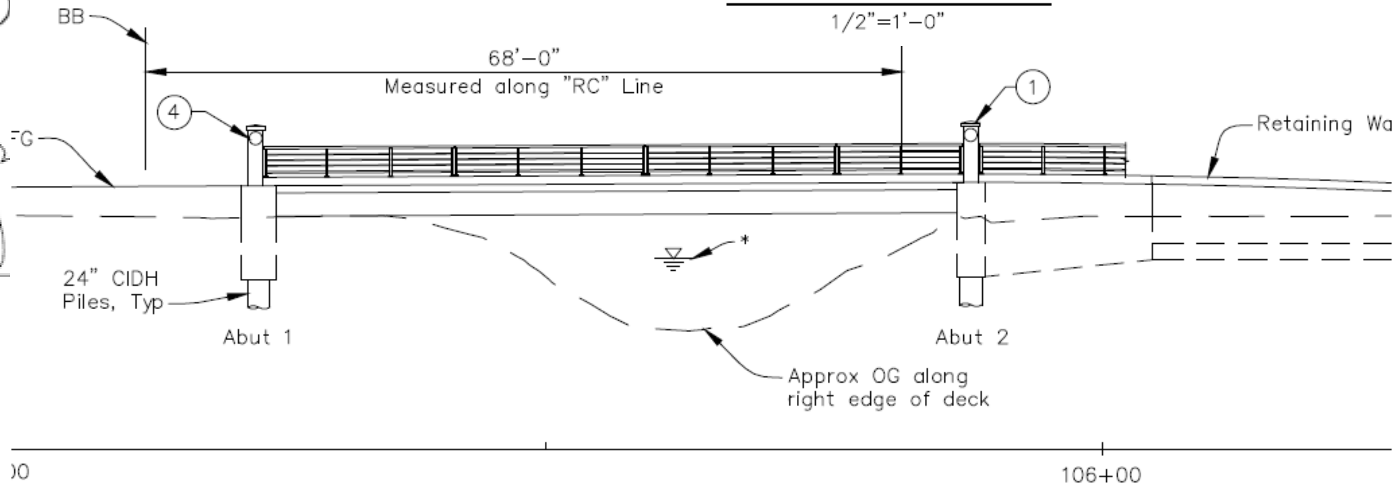
Example: West Llagas Pedestrian Bridge (Gilroy, CA)



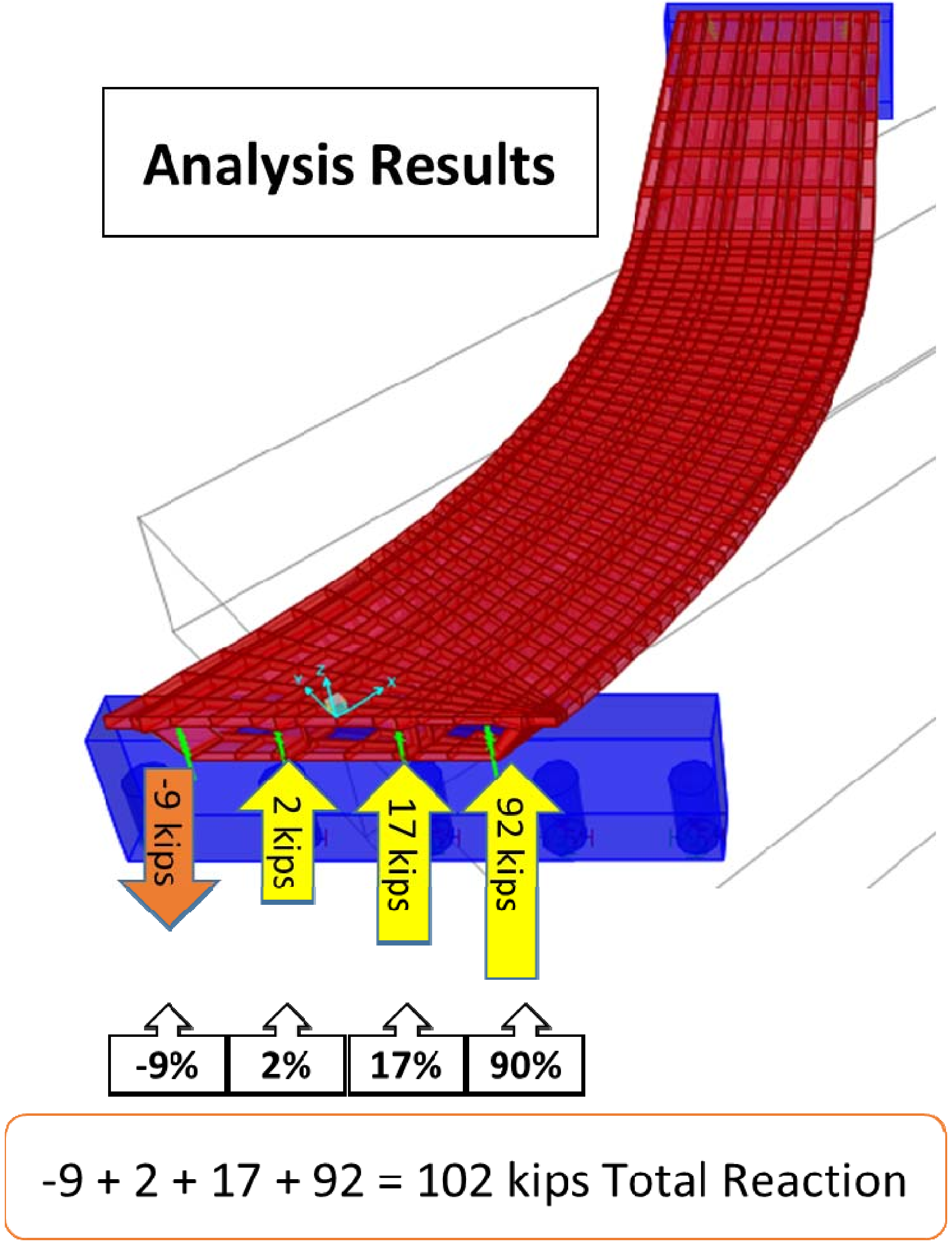
PLAN
1"=10'

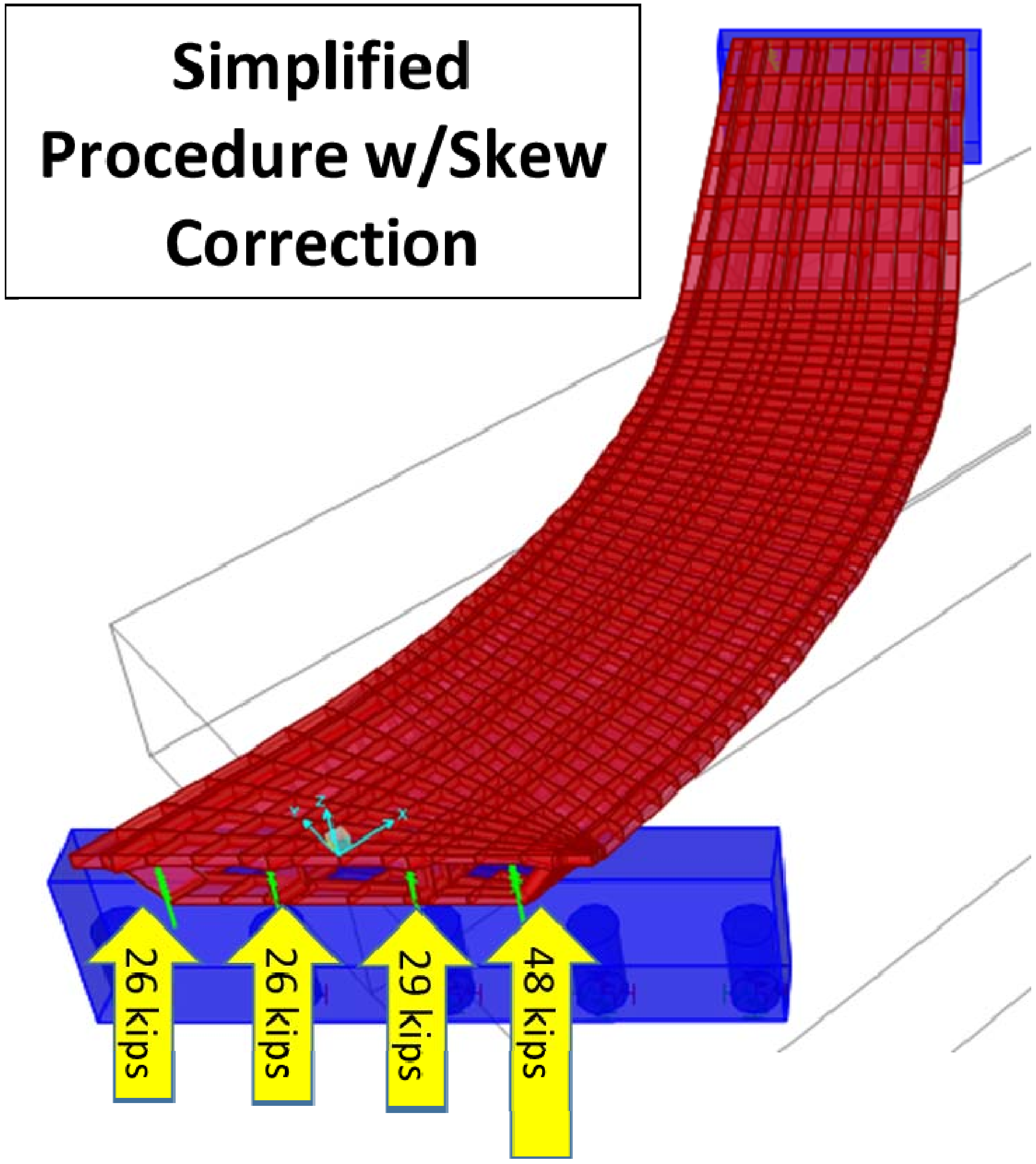


TYPICAL SECTION
1/2"=1'-0"

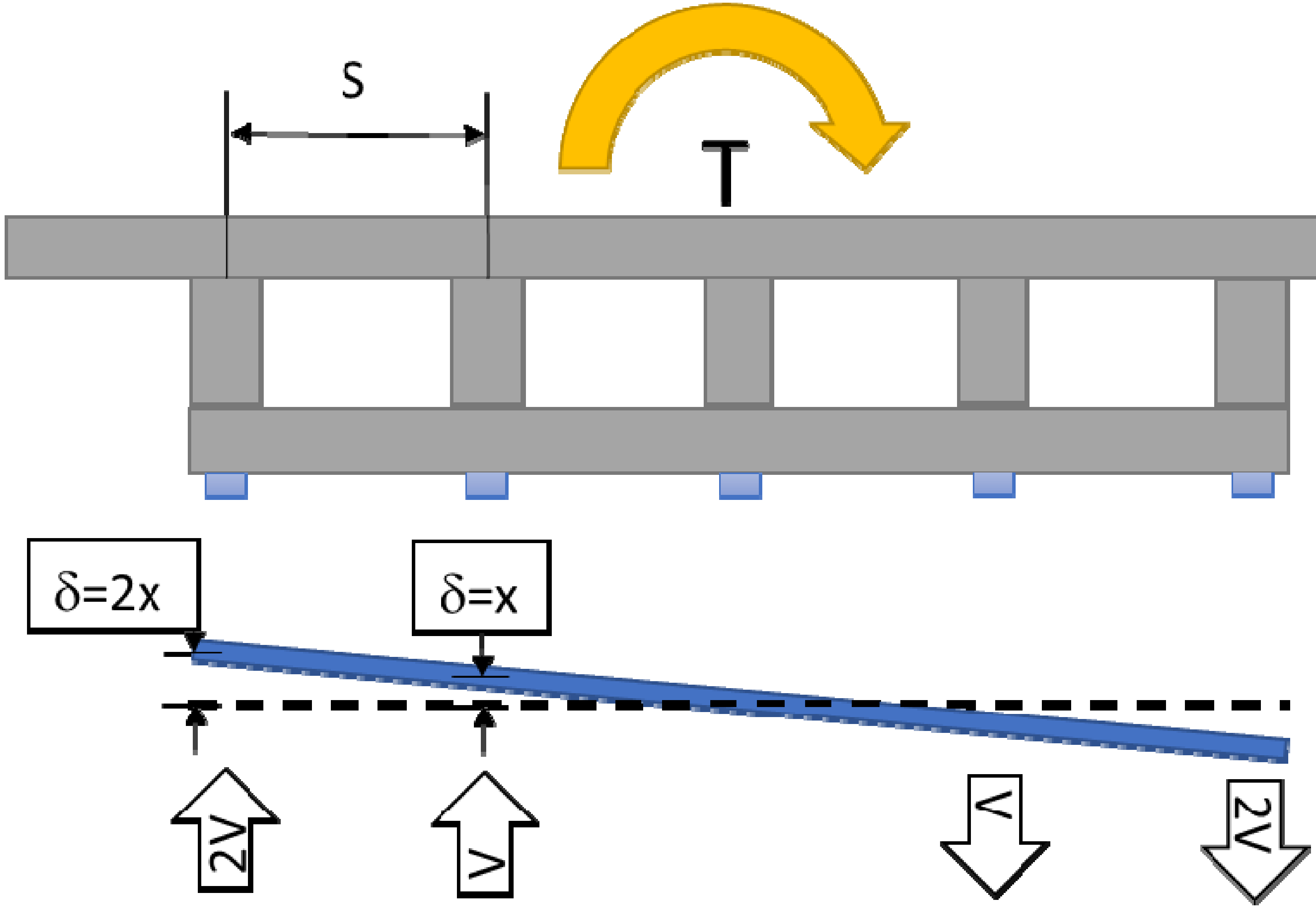


DEVELOPED ELEVATION
1"=10'


Analysis Results
-9 kips
2 kips
17 kips
92 kips
-9%
2%
17%
90%
-9 + 2 + 17 + 92 = 102 kips Total Reaction

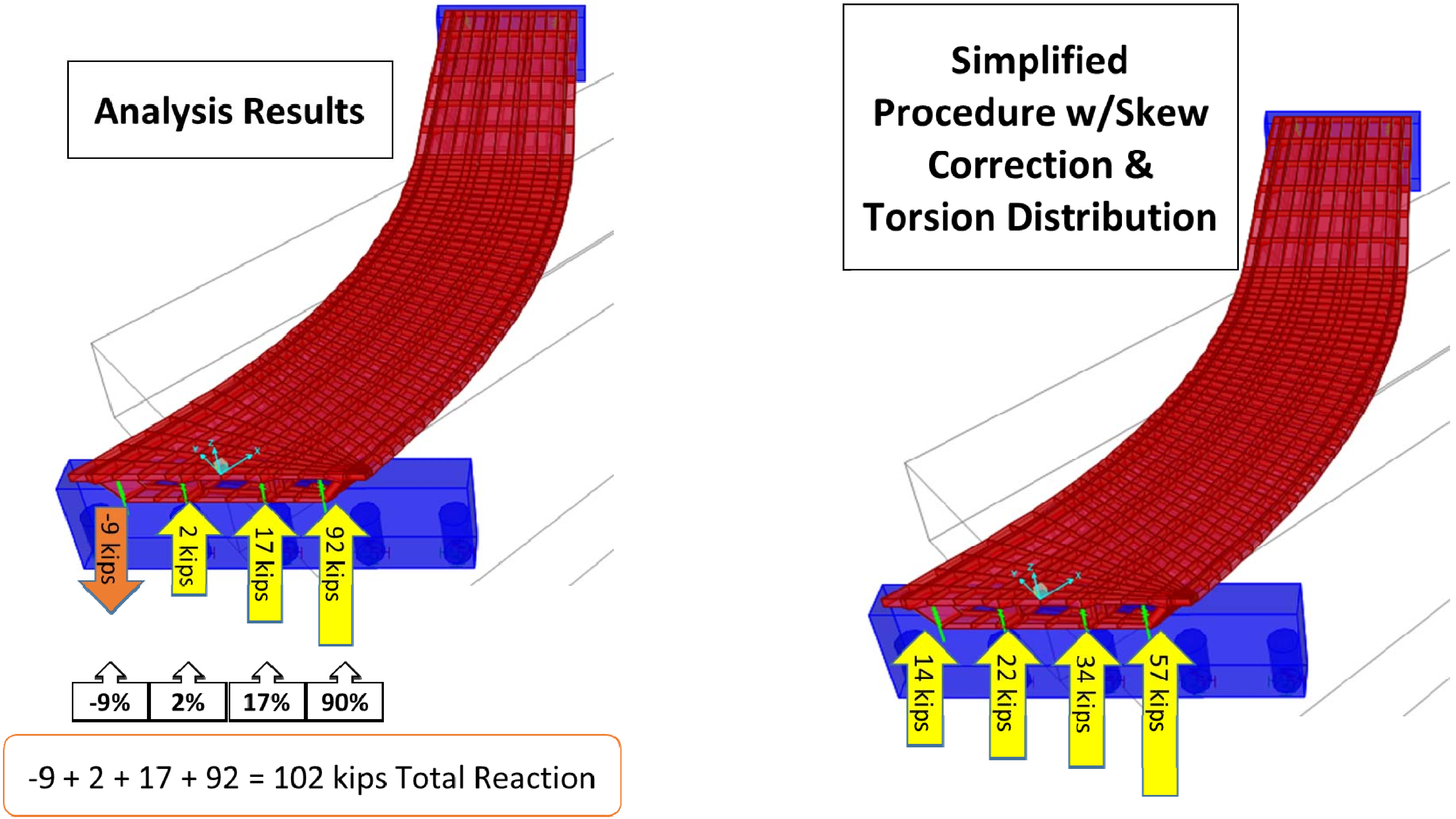

Simplified Procedure w/Skew Correction
26 kips
26 kips
29 kips
48 kips

Reaction Distribution for Torsion: Rigid Beam Analogy



Sum moments about center girder:

$$V = \frac{T}{10 * S}$$

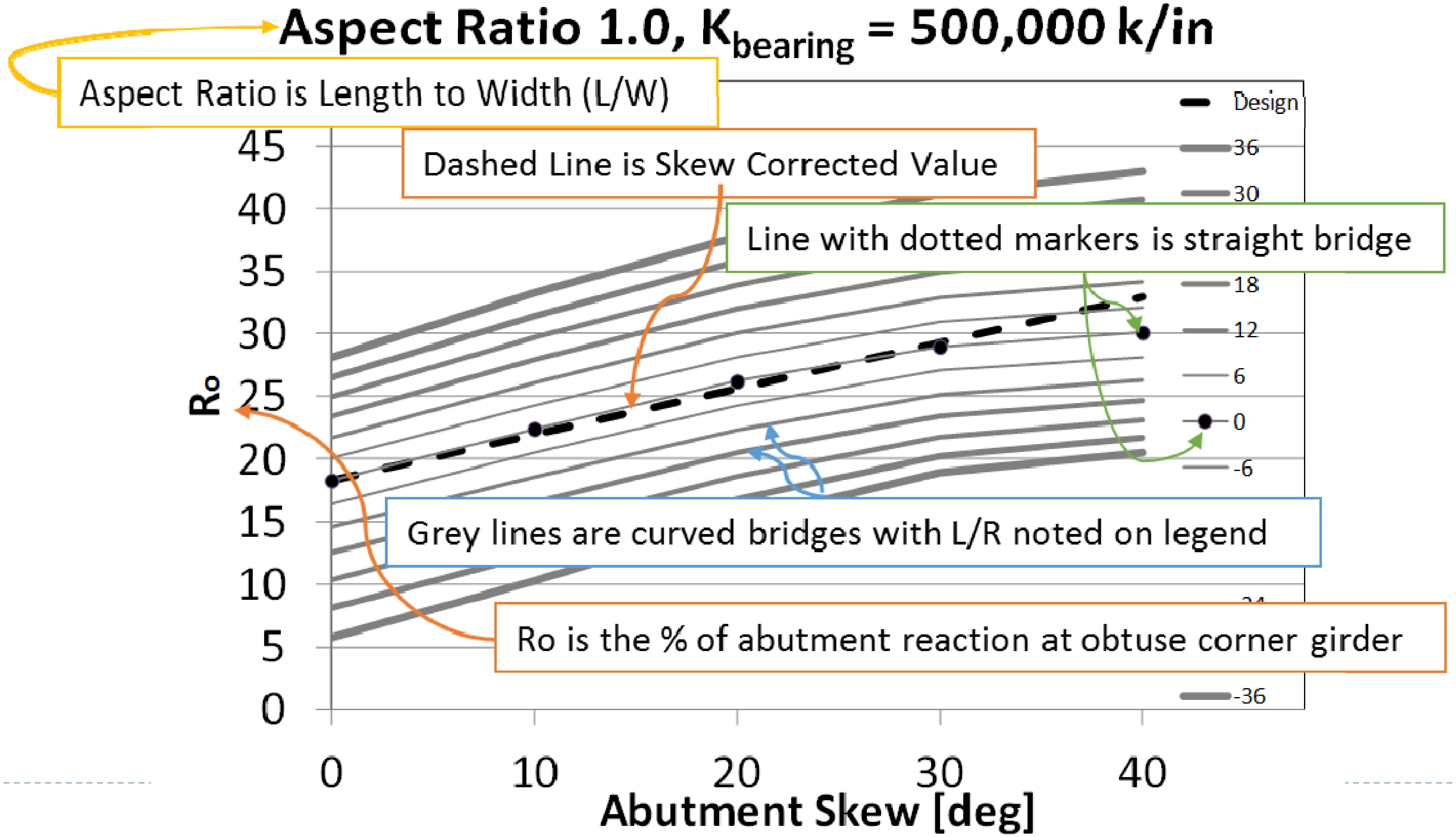


Analysis Results
-9 kips
2 kips
17 kips
92 kips
-9%
2%
17%
90%
-9 + 2 + 17 + 92 = 102 kips Total Reaction
Simplified Procedure w/Skew Correction & Torsion Distribution
14 kips
22 kips
34 kips
57 kips

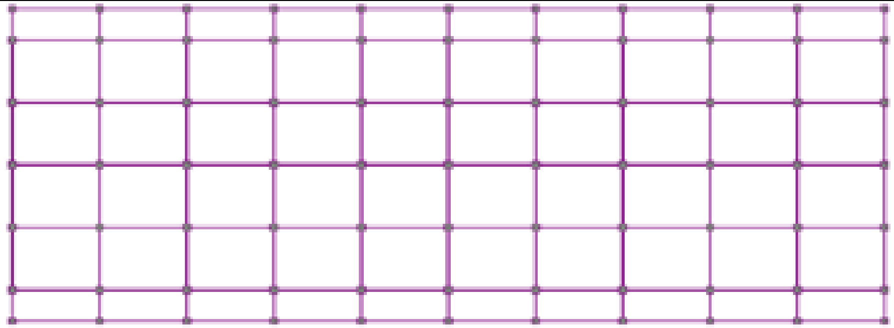
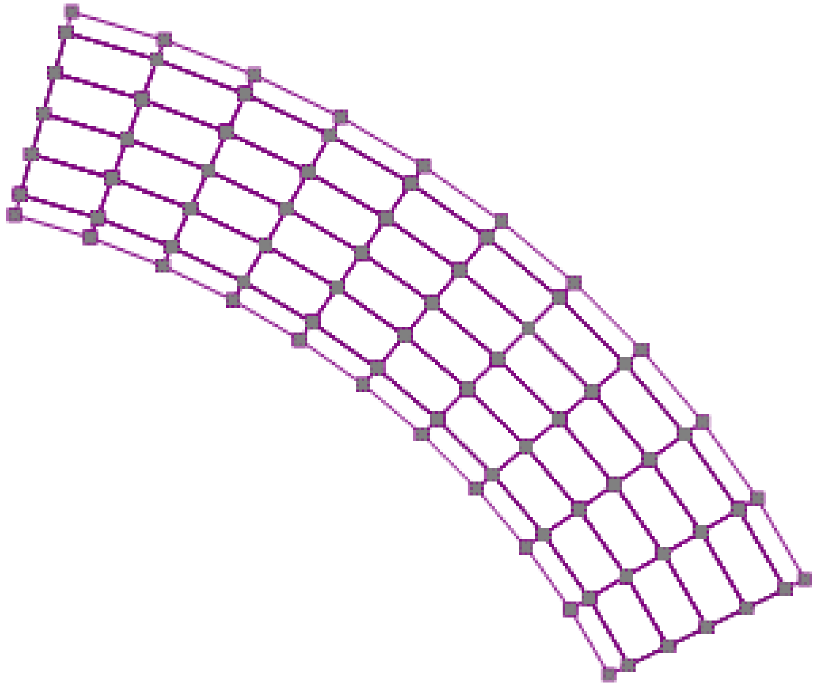
Analysis Study

- Scope
  - Over 800 4-Cell Box-Girder Bridges
  - Single-span
  - Bridge models were varied between 0 and 60 degree skew angle and -48 to 48 degree central angle
  - Varied bearing stiffness

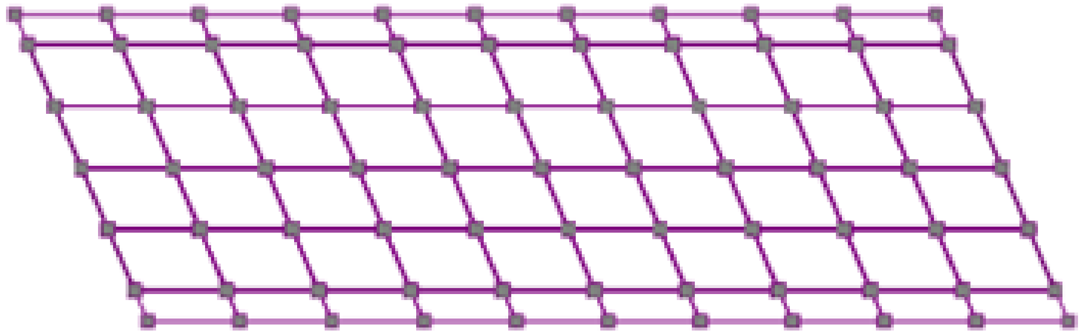
Features of Characteristic Plot



Sample of Bridge Models

Bridge Model – Plan View	*Description*
	Aspect Ratio = 4.0 Central Angle = 0° Skew Angle = 0°
	Aspect Ratio = 4.0 Central Angle = -48° Skew Angle = 0°

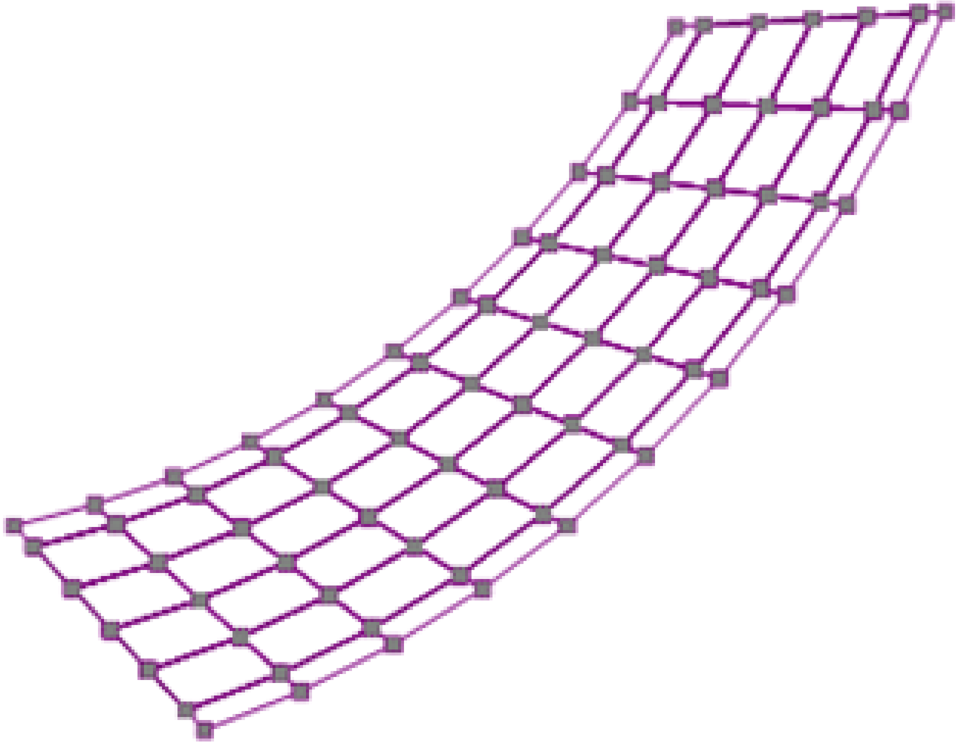
Sample of Bridge Models



Aspect Ratio = 4.0

Central Angle = 0°

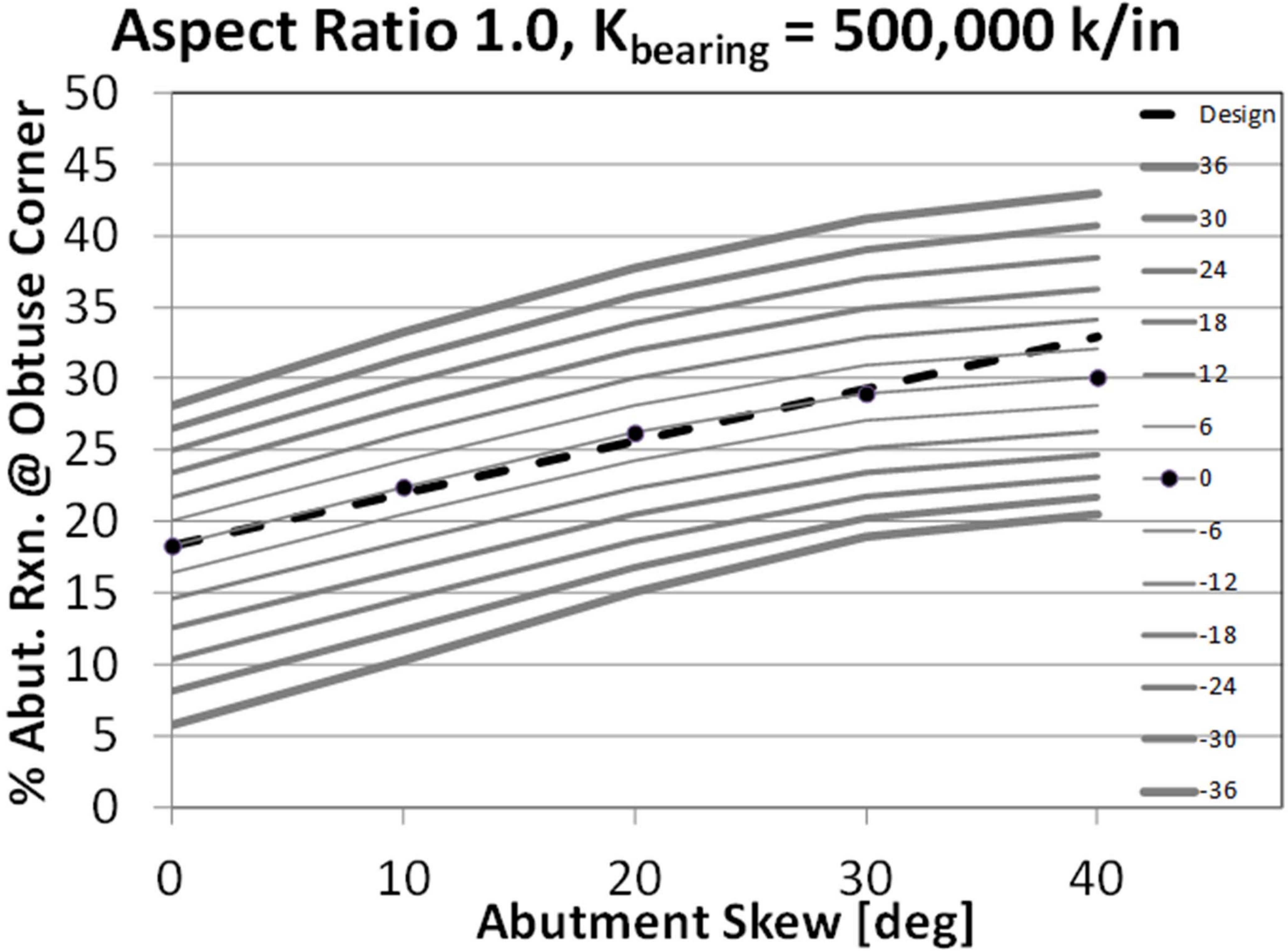
Skew Angle = 30°

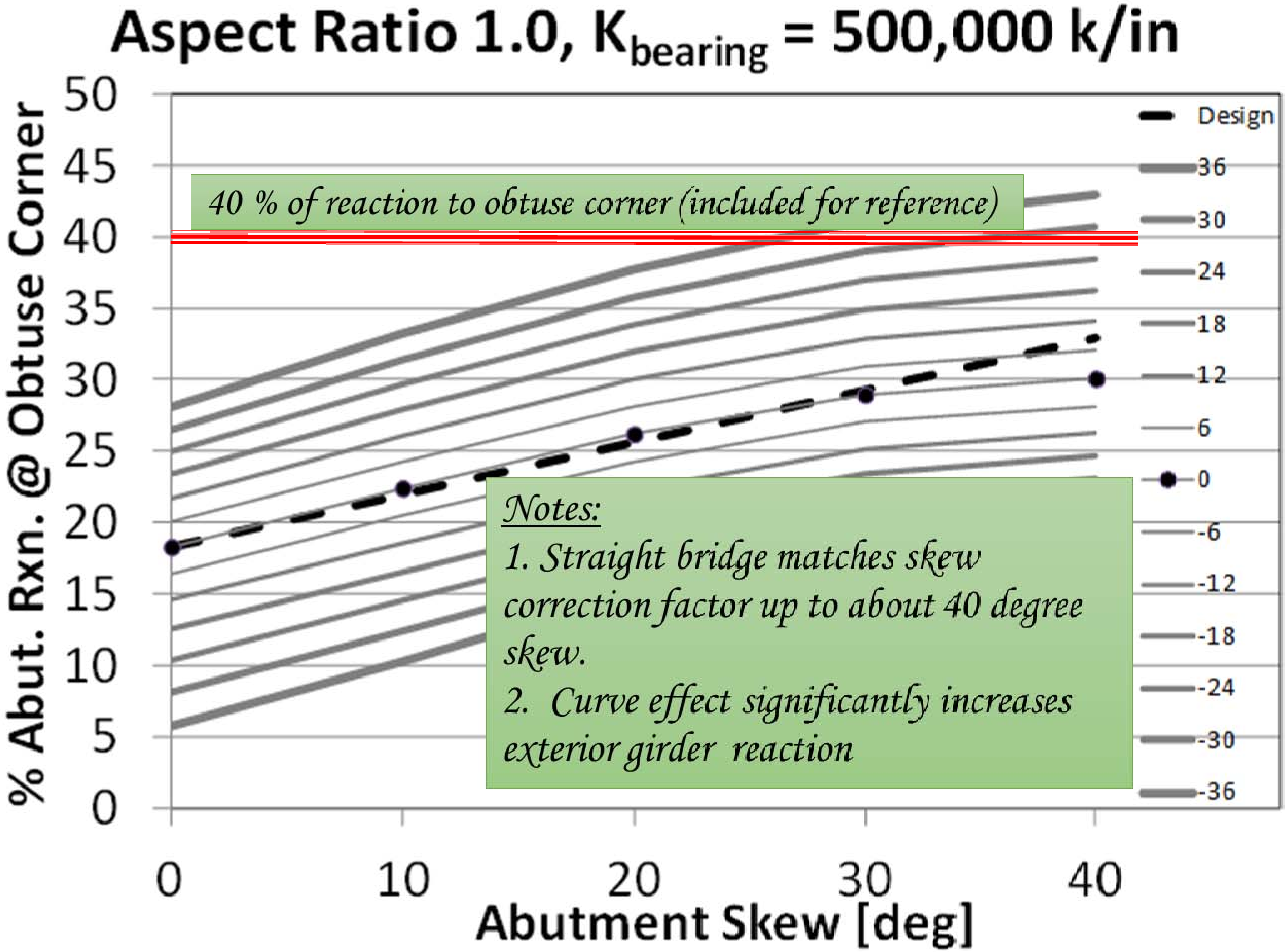


Aspect Ratio = 4.0

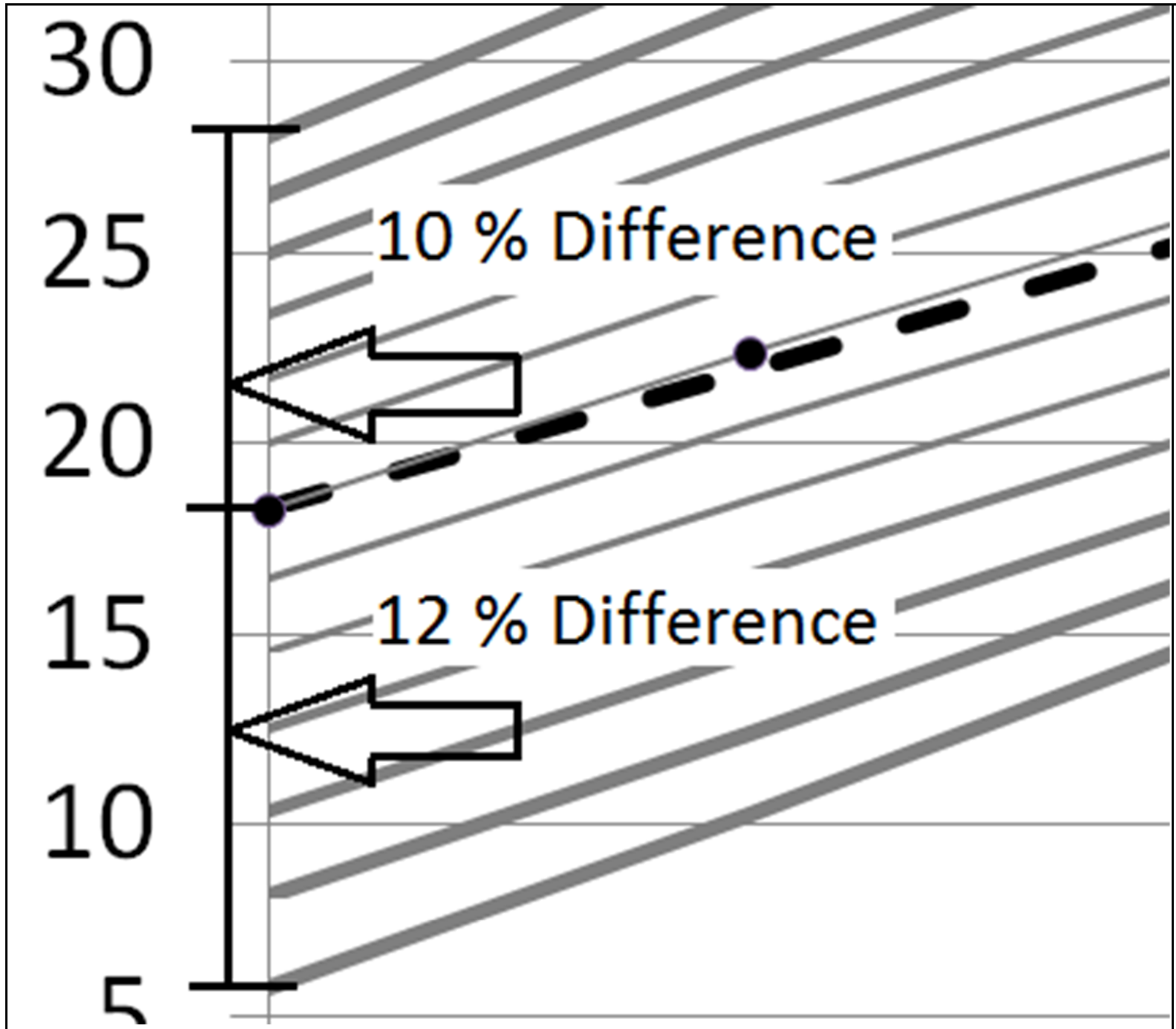
Central Angle = 48°

Skew Angle = 30°


Aspect Ratio 1.0, $K_{bearing}$ = 500,000 k/in
% Abut. Rxn. @ Obtuse Corner
Abutment Skew [deg]
0
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
Design
36
30
24
18
12
6
0
-6
-12
-18
-24
-30
-36



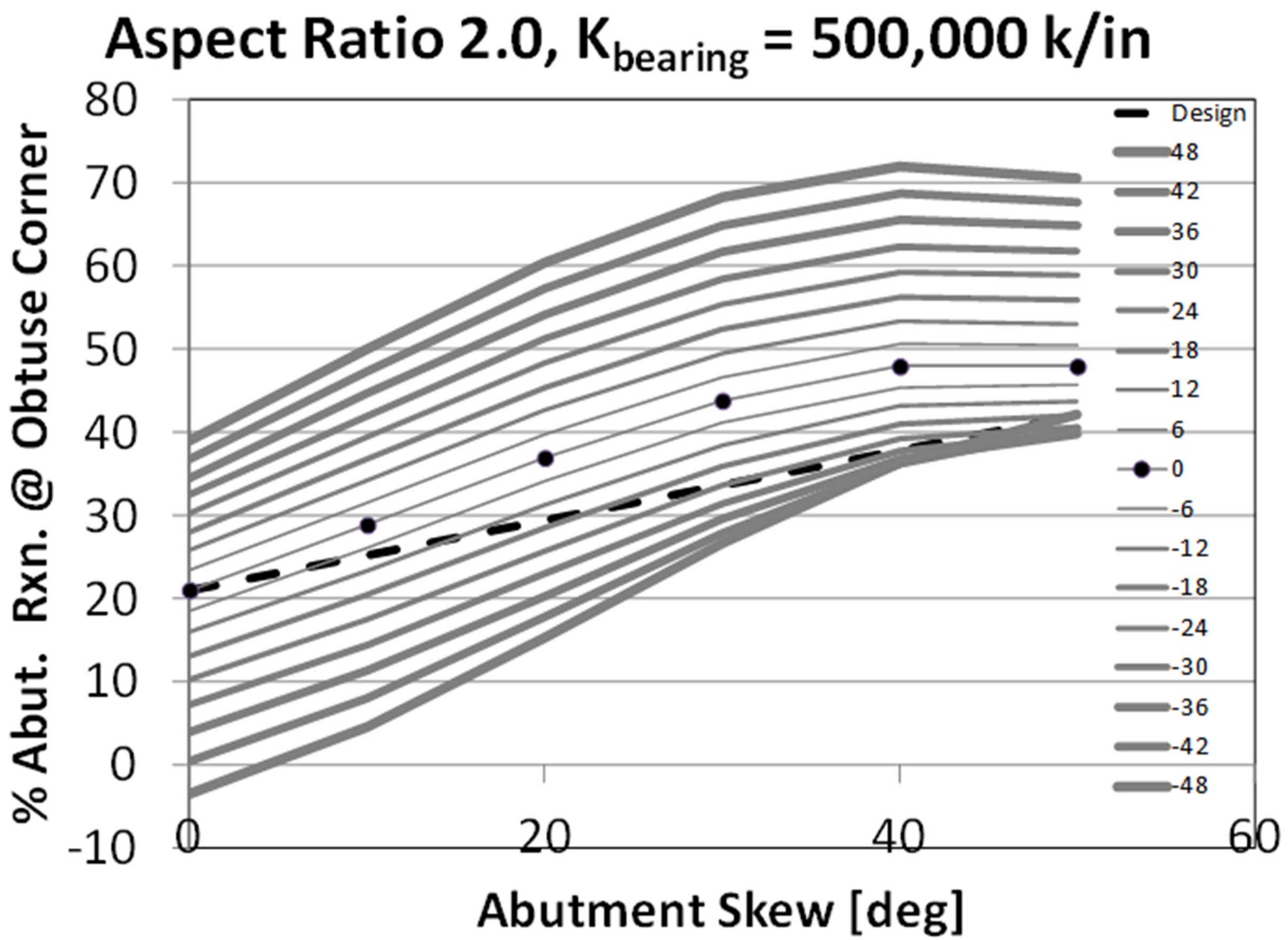
Aspect Ratio 1.0, K_bearing = 500,000 k/in
% Abut. Rxn. @ Obtuse Corner
Abutment Skew [deg]
0
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
Design
36
30
24
18
12
6
0
-6
-12
-18
-24
-30
-36
40 % of reaction to obtuse corner (included for reference)
Notes:
1. Straight bridge matches skew correction factor up to about 40 degree skew.
2. Curve effect significantly increases exterior girder reaction



The Curve Effect is more pronounced for negative central angles than for positive central angles.

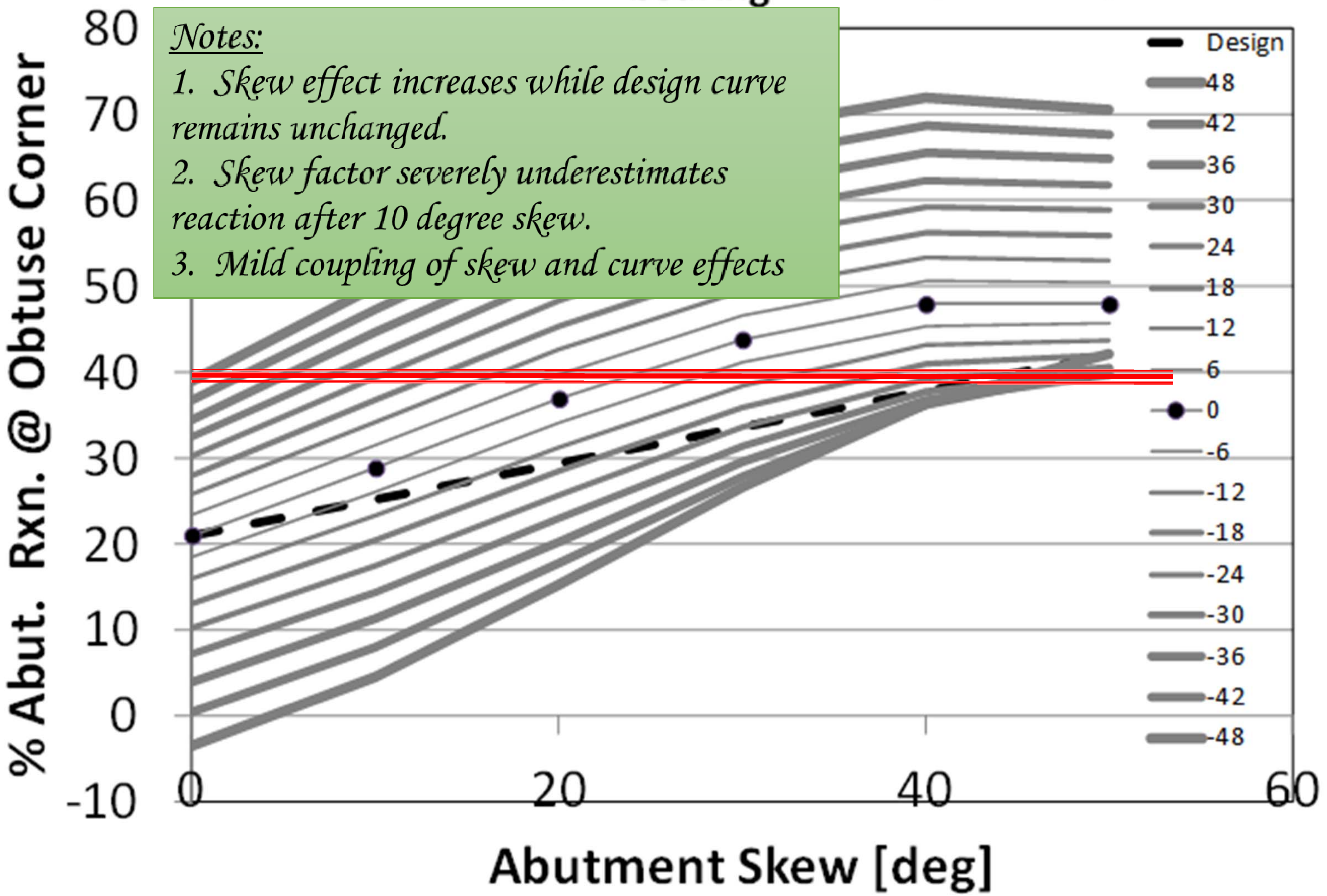
The top curve (36º) starts at 28%, the middle curve (0º) starts at 18%, and the bottom curve (-36º) starts at 6%.

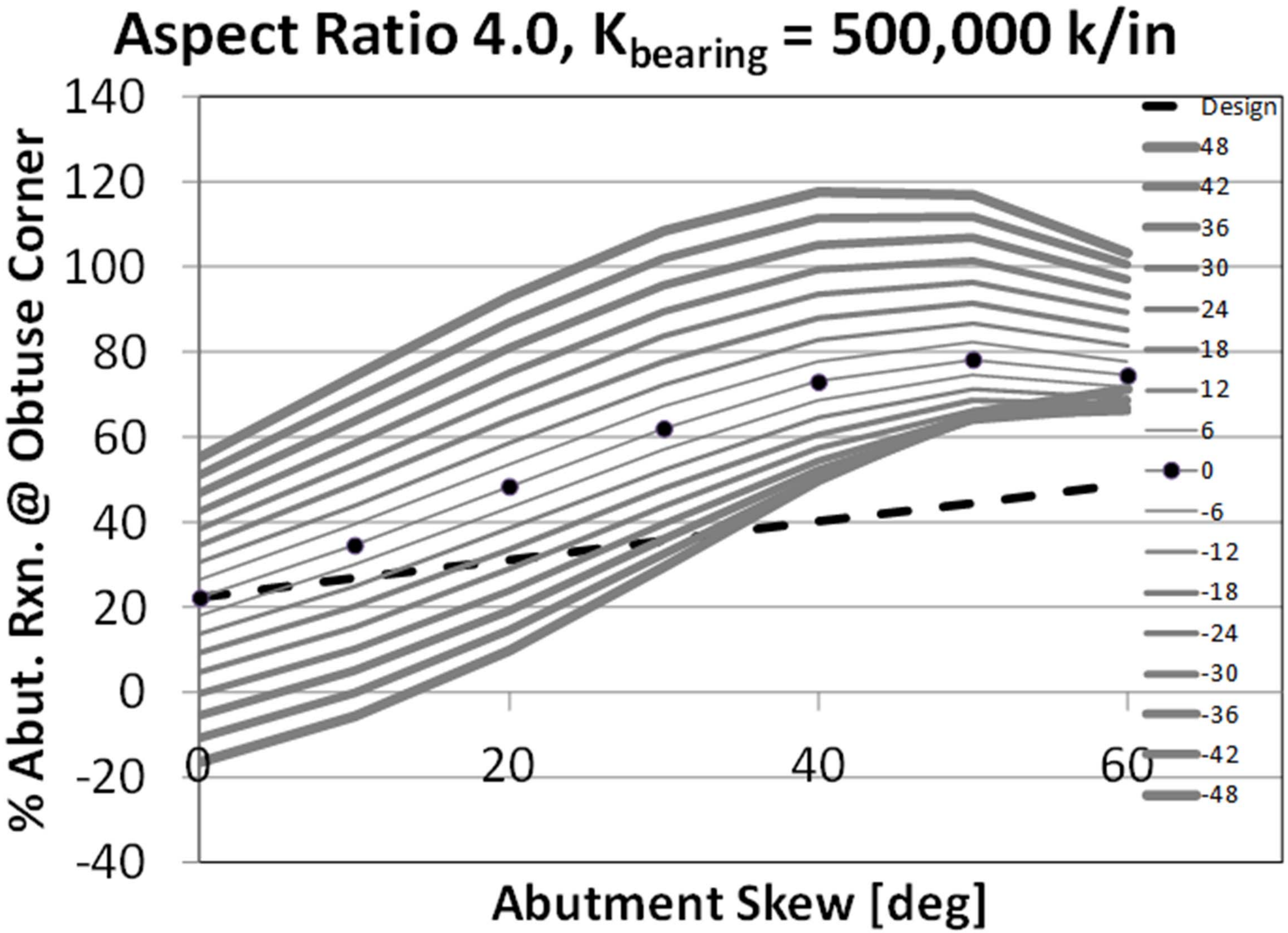
The distance between the lower curves (18 – 6 = 12) is greater than the distance between the upper curves (28 – 18 = 10).



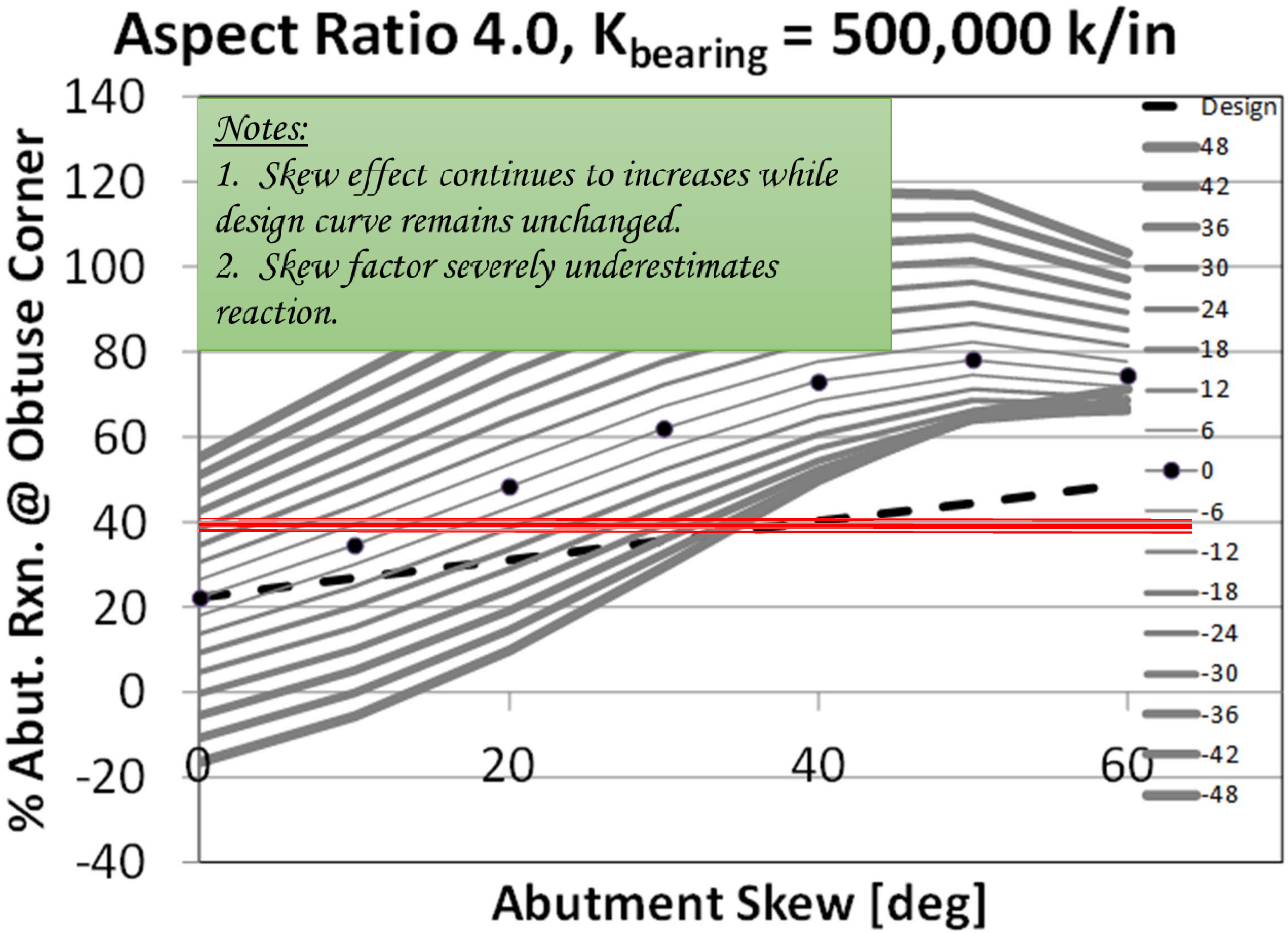
Aspect Ratio 2.0, $K_{bearing}$ = 500,000 k/in
% Abut. Rxn. @ Obtuse Corner
Abutment Skew [deg]
80
70
60
50
40
30
20
10
0
-10
0
20
40
60
Design
48
42
36
30
24
18
12
6
0
-6
-12
-18
-24
-30
-36
-42
-48

Aspect Ratio 2.0, $K_{bearing}$ = 500,000 k/in

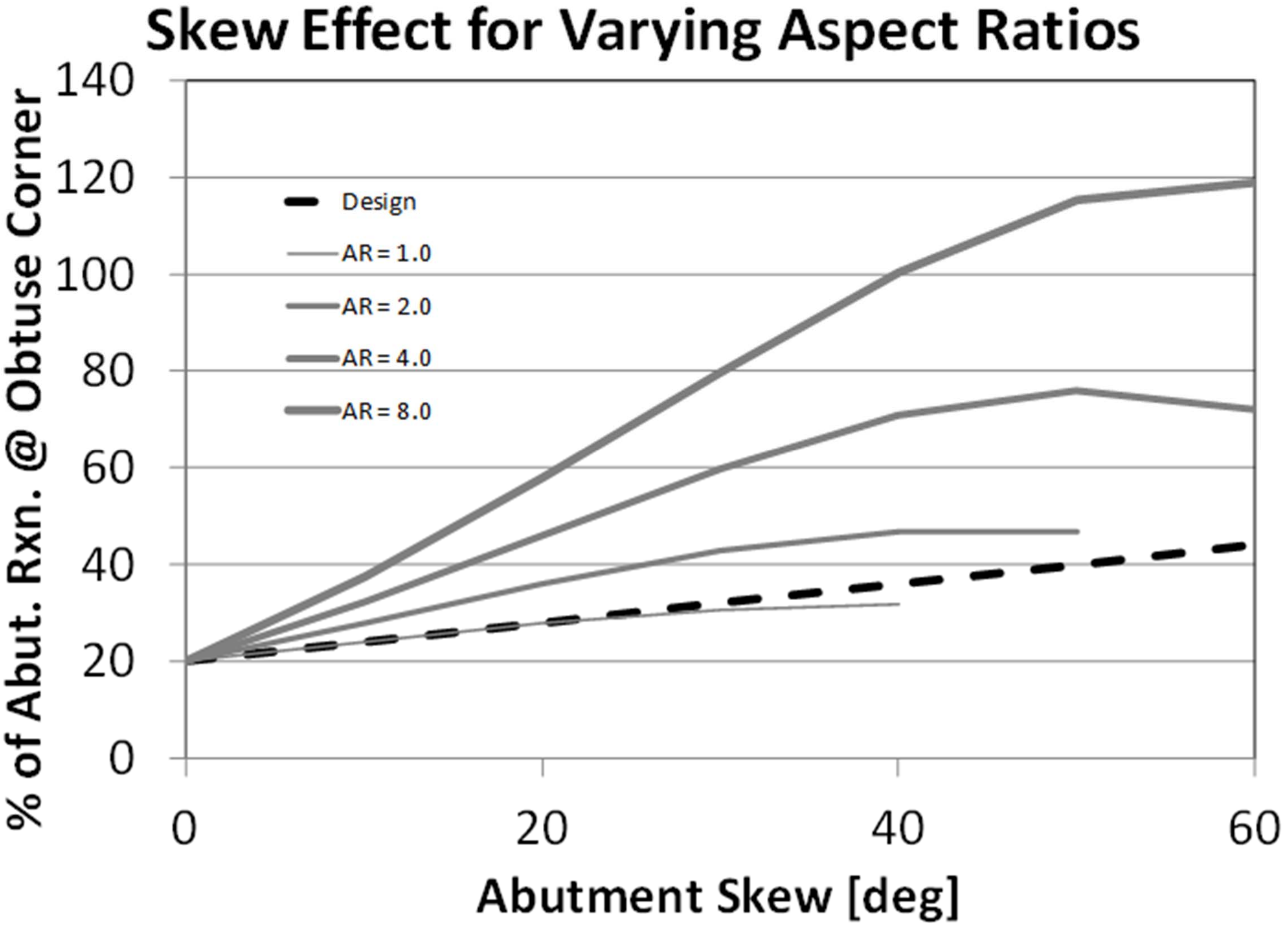




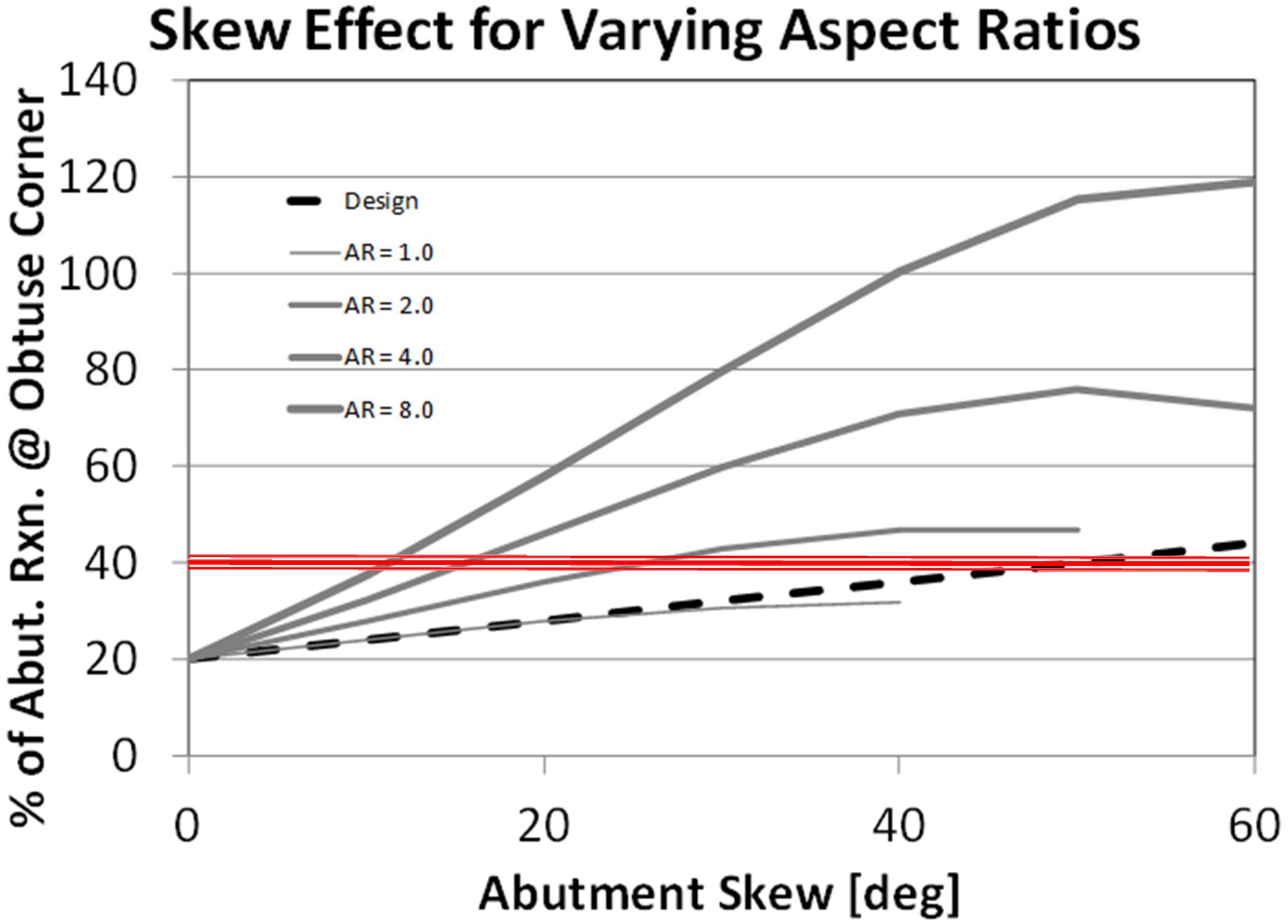
Aspect Ratio 4.0, $K_{bearing}$ = 500,000 k/in
% Abut. Rxn. @ Obtuse Corner
140
120
100
80
60
40
20
0
-20
-40
0
20
40
60
Abutment Skew [deg]
Design
48
42
36
30
24
18
12
6
0
-6
-12
-18
-24
-30
-36
-42
-48



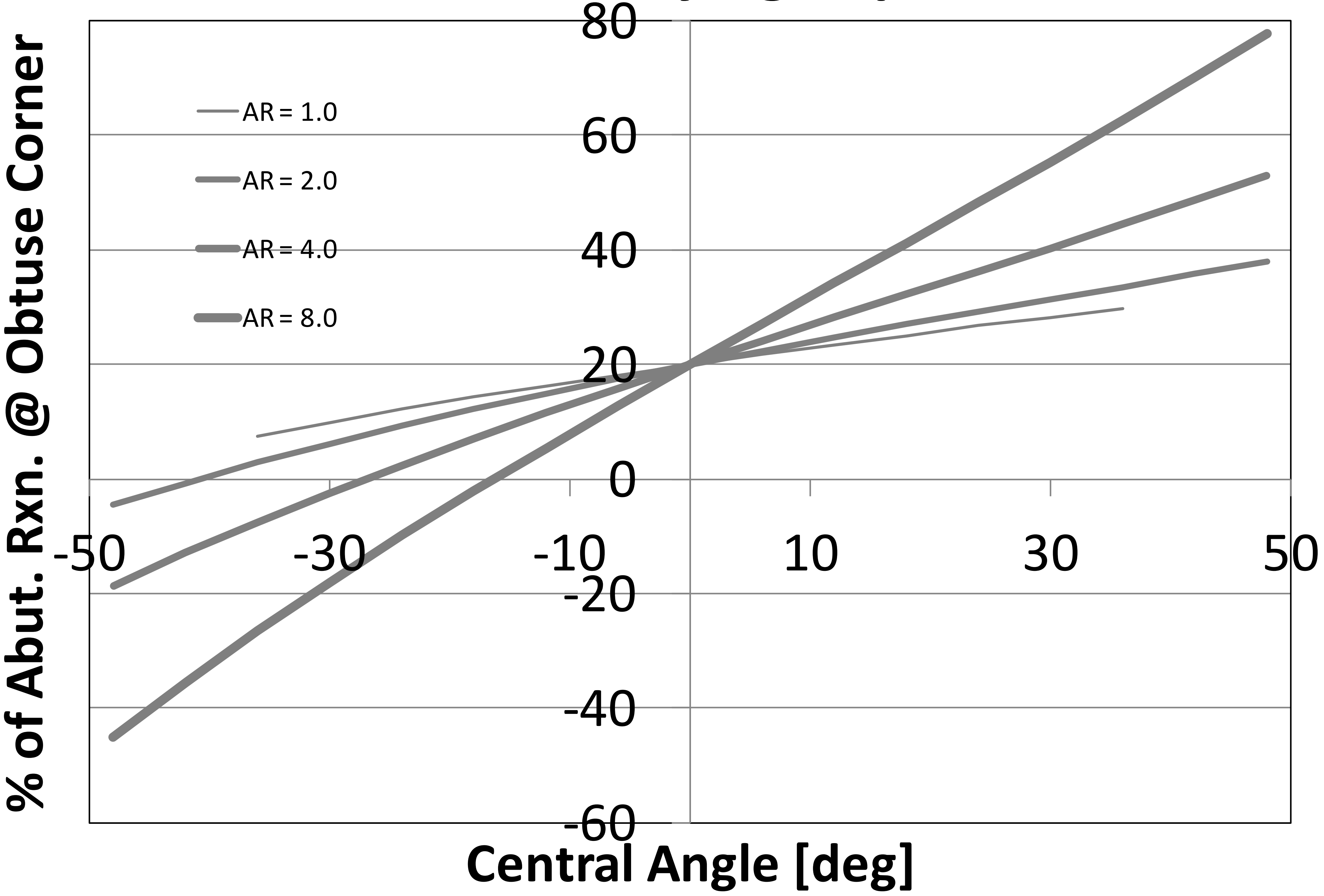
Aspect Ratio 4.0, $K_{bearing}$ = 500,000 k/in
Notes:
1. Skew effect continues to increases while design curve remains unchanged.
2. Skew factor severely underestimates reaction.
% Abut. Rxn. @ Obtuse Corner
140
120
100
80
60
40
20
0
-20
-40
0
20
40
60
Abutment Skew [deg]
Design
48
42
36
30
24
18
12
6
0
-6
-12
-18
-24
-30
-36
-42
-48



Skew Effect for Varying Aspect Ratios
Design
AR = 1.0
AR = 2.0
AR = 4.0
AR = 8.0
% of Abut. Rxn. @ Obtuse Corner
140
120
100
80
60
40
20
0
0
20
40
60
Abutment Skew [deg]


Skew Effect for Varying Aspect Ratios
% of Abut. Rxn. @ Obtuse Corner
140
120
100
80
60
40
20
0
0
20
40
60
Abutment Skew [deg]
Design
AR = 1.0
AR = 2.0
AR = 4.0
AR = 8.0

Curve Effect for Varying Aspect Ratios



Empirical Formulas

- At small skew angles and small central angles:
  - Curve effect is not dependant on skew angle
  - Skew effect is not dependant on central angle

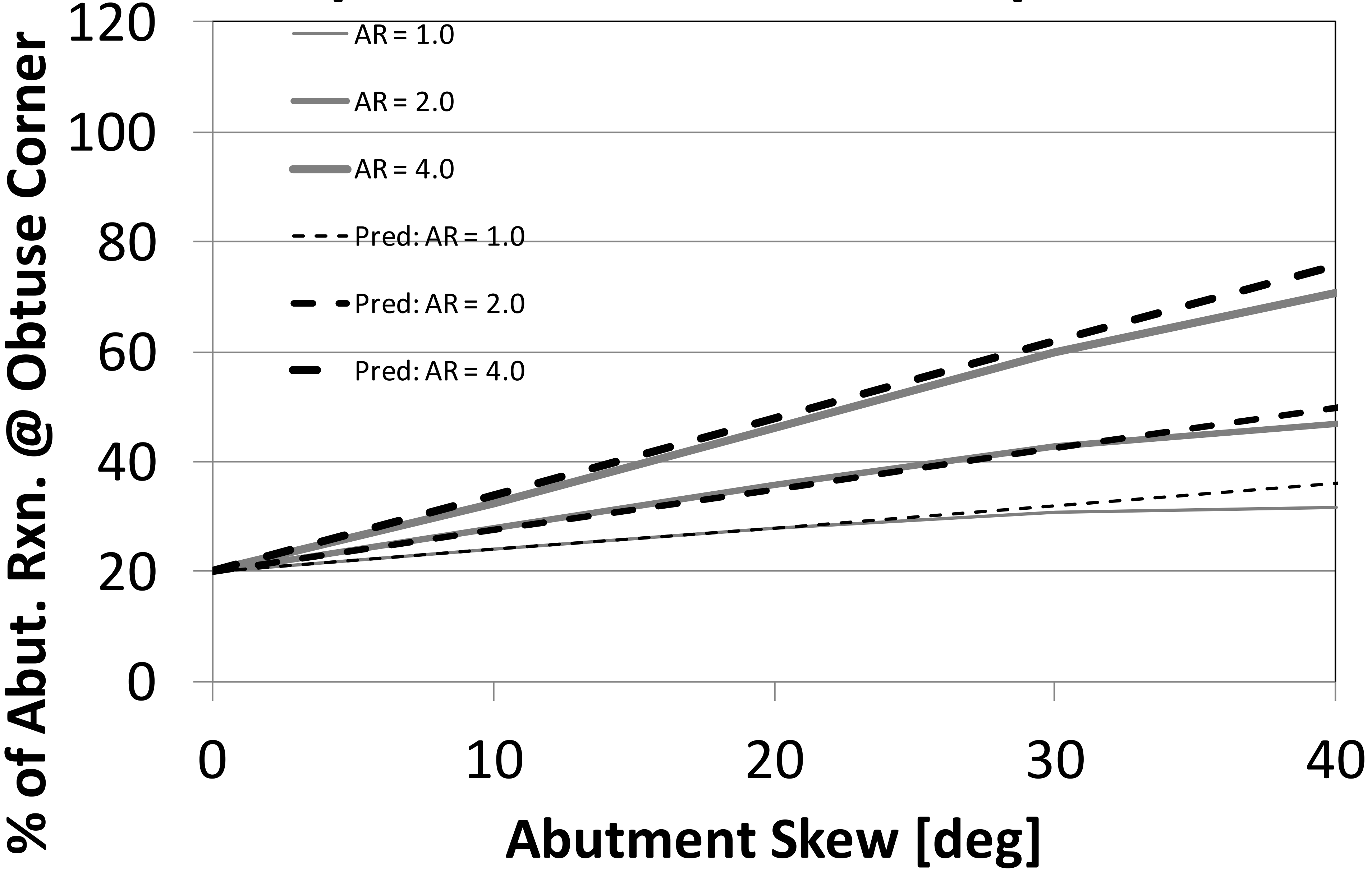
  - Outside Corner

$$SkewCurve\ Correction\ Factor = 1 + \frac{\theta}{50} * AR^{0.9} + \frac{\alpha}{100} * AR$$

  - Inside Corner

$$SkewCurve\ Correction\ Factor = 1 + \frac{\theta}{50} * AR^{0.9} + \frac{\alpha}{50} * AR^{0.4}$$

Proposed Correction Formulas Compared to 3D Model Response



Summary and Conclusions

- Aspect ratio (length to width ratio) influences skew effect on reaction forces and, therefore, also influences shear forces
- Aspect ratio influences curve effect
- Aspect ratio influences coupled skew-curve effect
- Bearing pad stiffness (support stiffness) influences skew effect, curve effect, and skew-curve effect
- Spine model analysis with code modifications may not yield conservative reaction forces for skewed and curved bridges with high aspect ratios (> 1.0).

Future Work

- Shear Force and Bearing Reactions:
  - Effect of Bearing Position
  - Other Bridge Types and Configurations
  - Multi-Span Bridges
  - Effects of Prestressing
  - Lab Experimentation

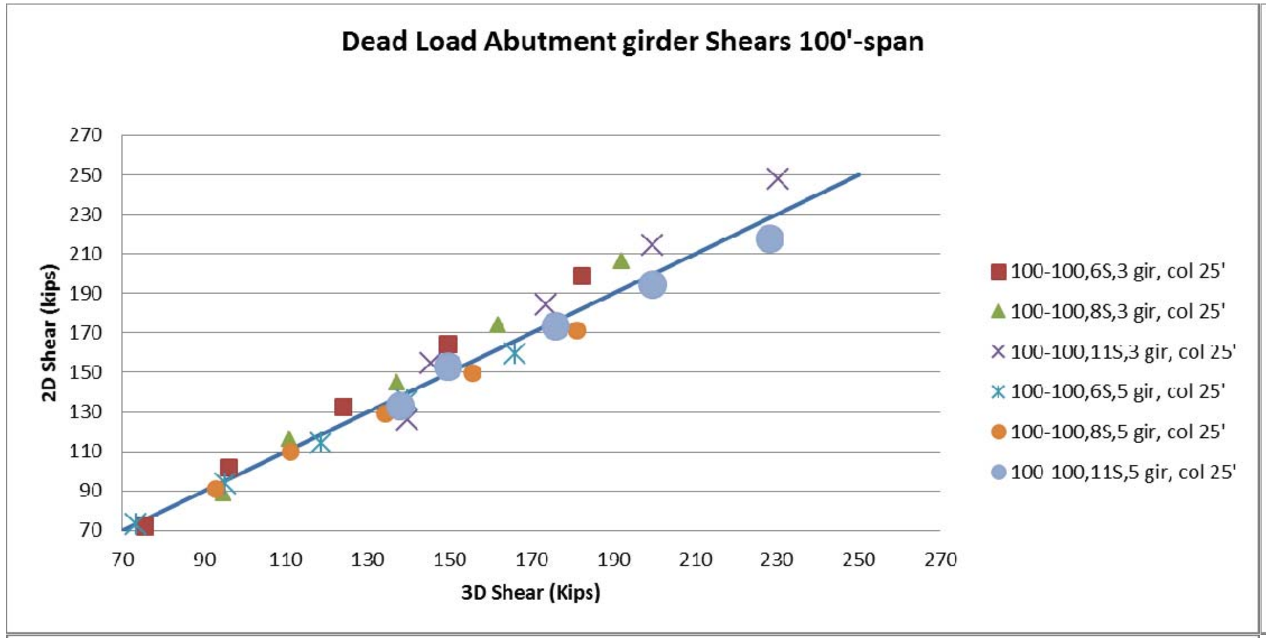
- A fuller perspective of the differences in 2D spine model analysis vs. 3D shell model analysis

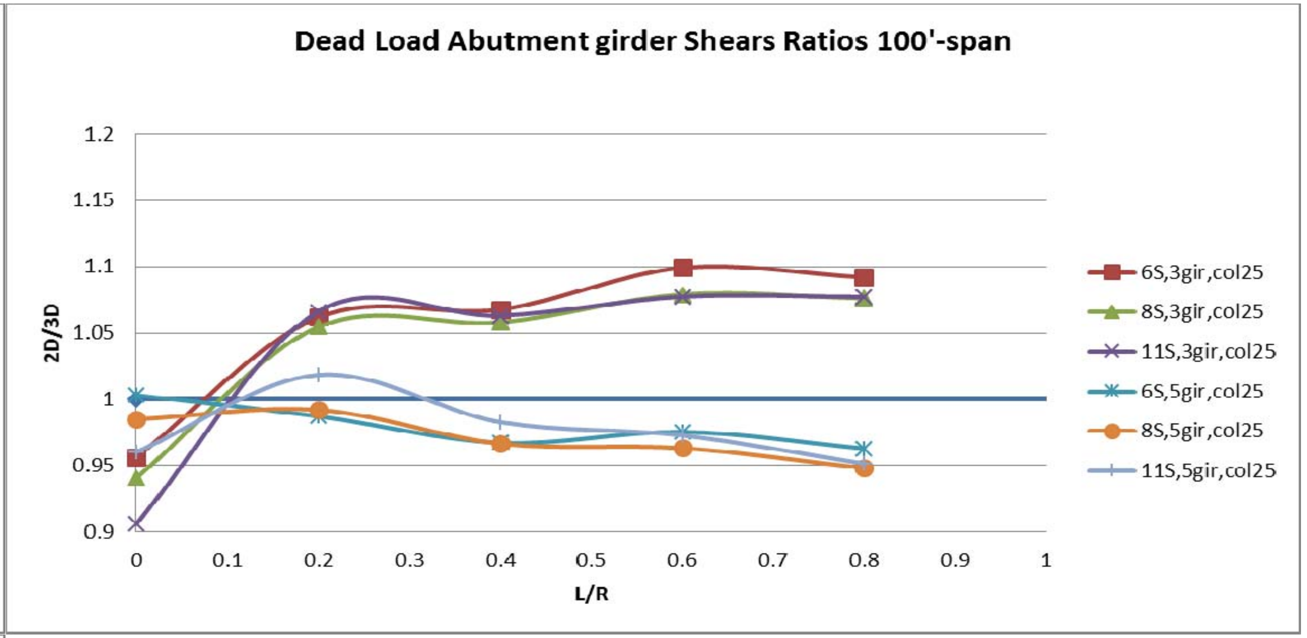
Work in Progress

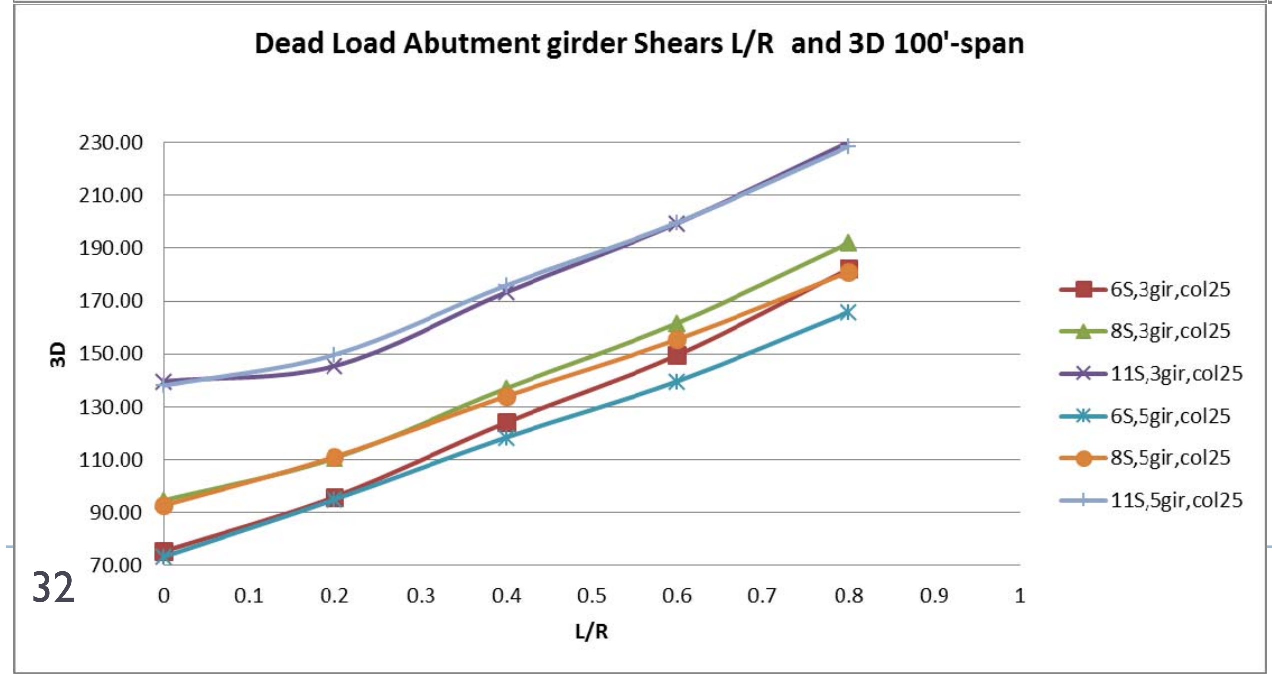
- Caltrans Structural Analysis Committee (Chair: Toorak Zokaie, PE)

- Curved Bridge Superstructure Response
  - Dead Load, Live Load, and Post-tensioning responses
    - Girder End Shear
    - Girder Stress
    - Column response
      - Longitudinal Moment
      - Transverse Moment

Results: Dead Load Abutment Shear … 1-Span

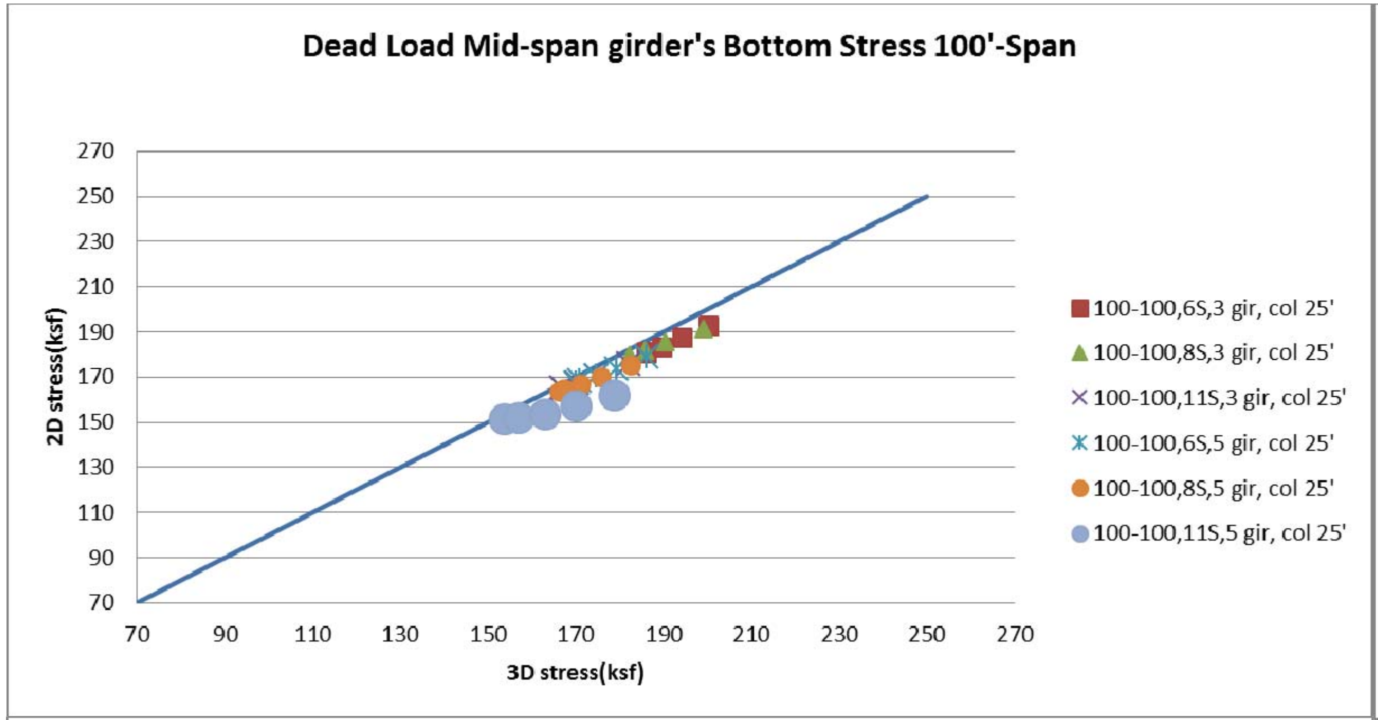


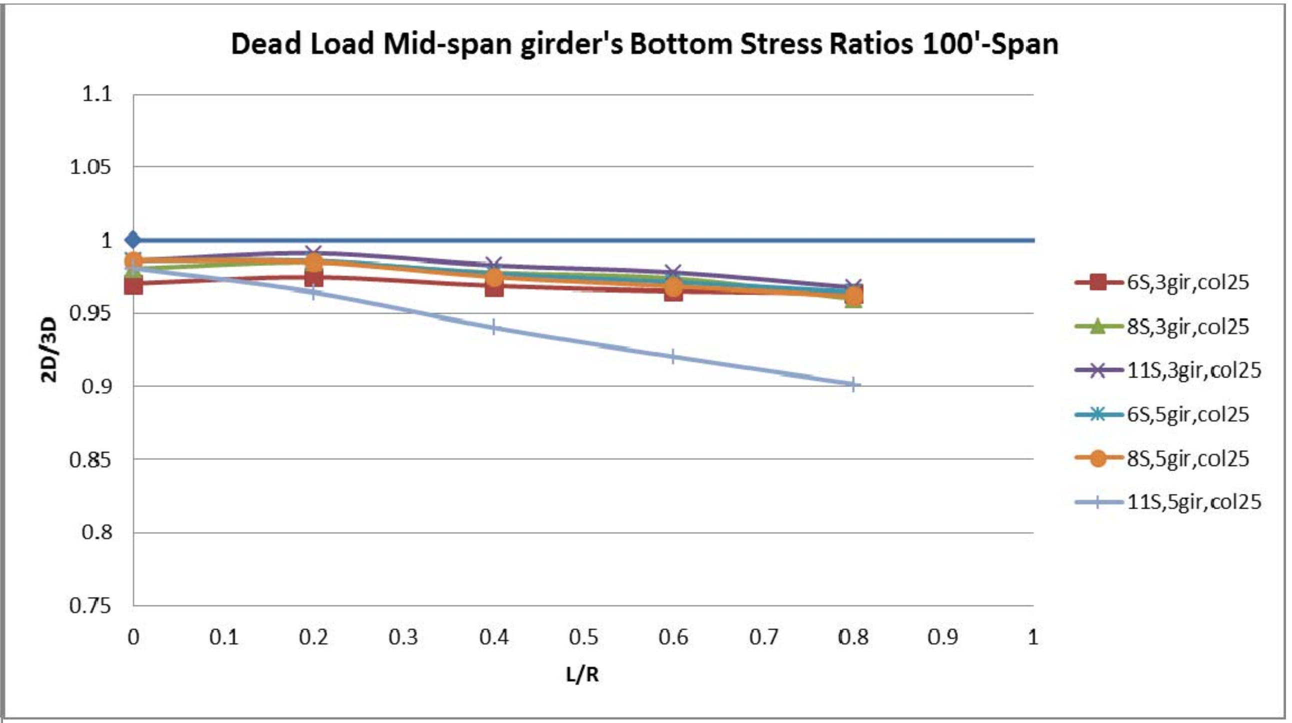


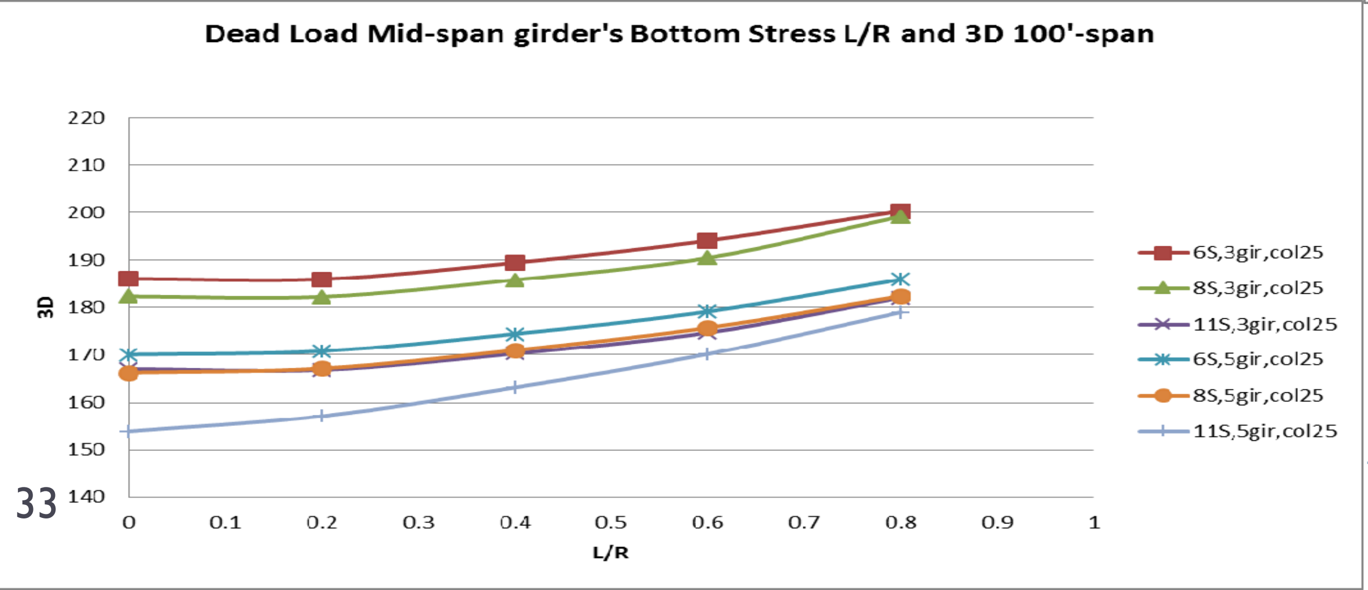


Caltrans

Dead Load Mid-span Bottom Stress … 1-Span

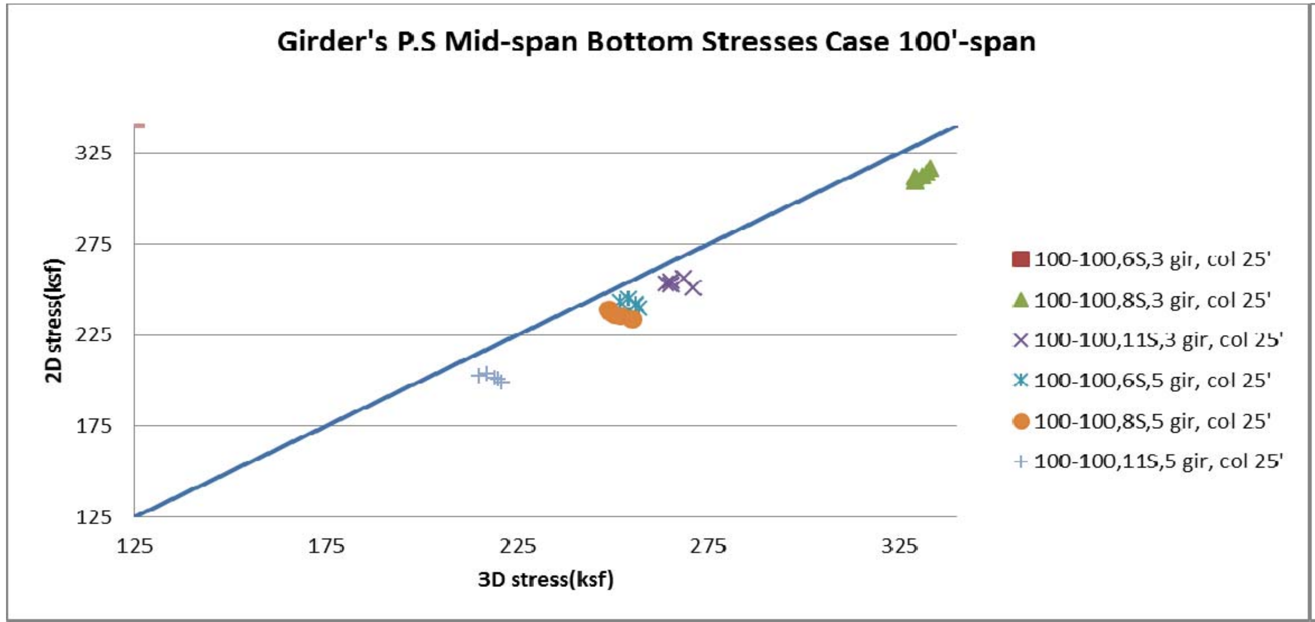


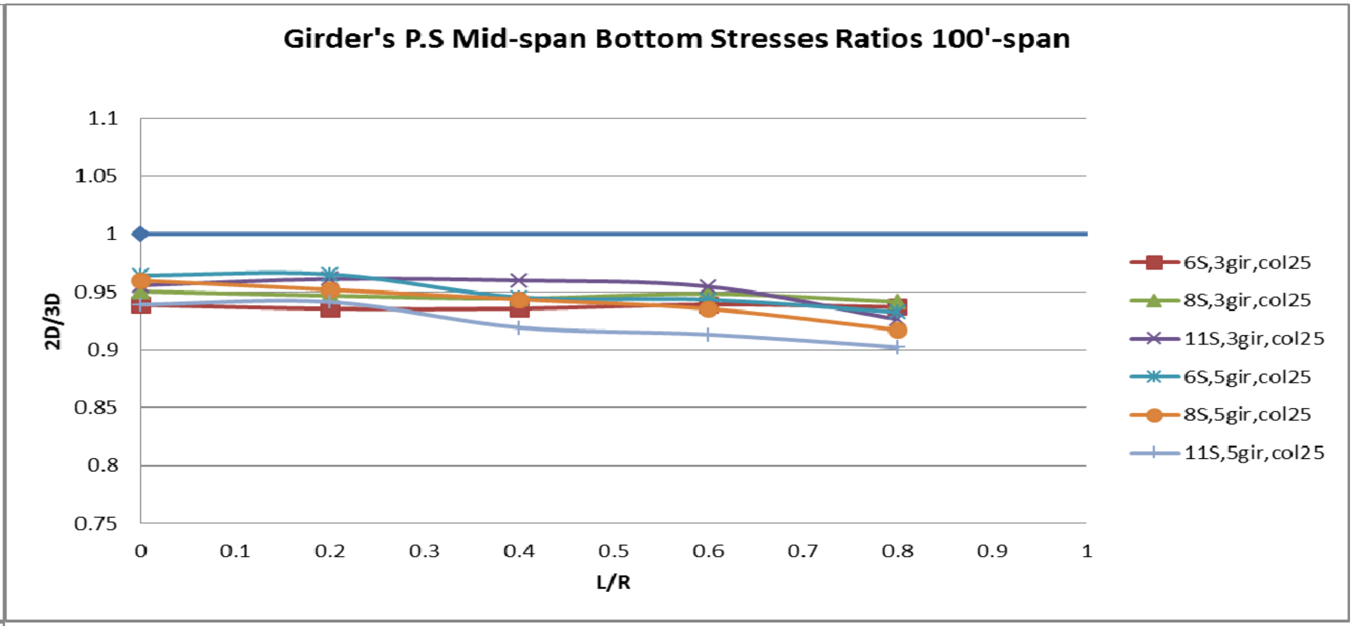


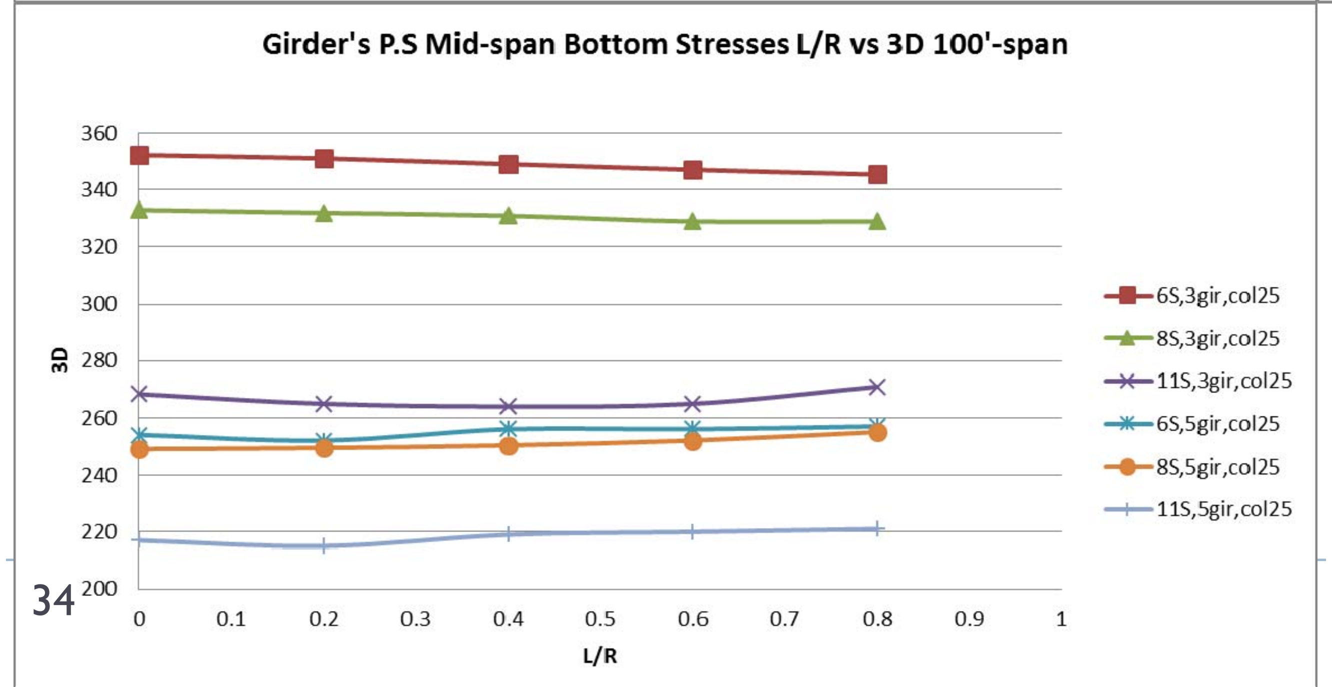


Caltrans

Pre-stress Mid-span Bottom Stress … 1-Span







Caltrans

Work in Progress: Preliminary Findings

- Superstructure Study Work in Progress
  - DL, PS and LL moments increase slightly with L/R, 2D analysis is slightly under 3D
  - DL shear & normal stress increase greatly with L/R, 2D gives acceptable accuracy
  - PS stresses do not change much with L/R
  - DL bent shear has same accuracy regardless of curvature but could be low due to section geometry

Questions or Comments?