Effect of Skew on Support Length Demands of Bridges with Seat-Type Abutments

Suiwen Wu and Ian G. Buckle

Department of Civil and Environmental Engineering

University of Nevada, Reno, United States of America

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Outline

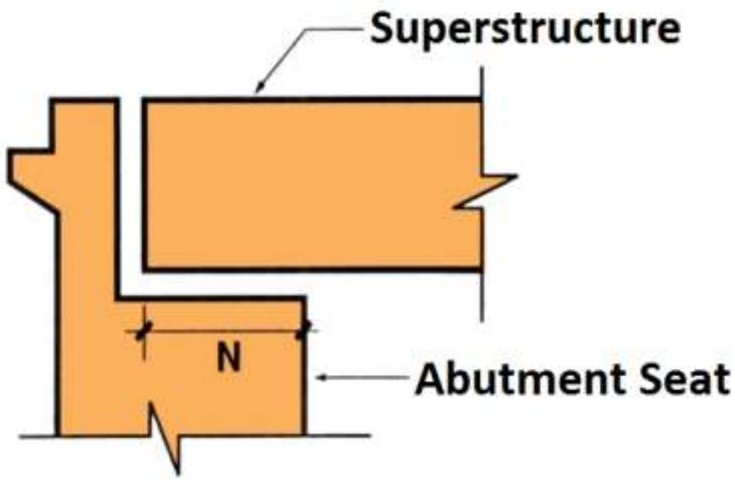
- Background (seismic damage to skew bridges)
- Skew factors in current specifications and manuals
- Shake table experiment
- Experimental validation of a numerical model
- Parameter study
- Comparison of skew factors
- Summary and Conclusions
- Recommendations
- Acknowledgements

Background: seismic damage to skew bridges

I-5 Overpass at Gavin Canyon (66º)
1994 Northridge Earthquake, CA

Hospital Overpass
2010 Maule Earthquake, Chile

Skew factors in current specifications and design manuals



In AASHTO:

$$N_\theta = (8 + 0.02L + 0.08H)(1 + 0.000125\theta^2)$$

$$i.e., N_\theta = N_0(1 + 0.000125\theta^2)$$

$$f(\theta) = \frac{N_\theta - N_0}{N_0} = 0.000125\theta^2$$

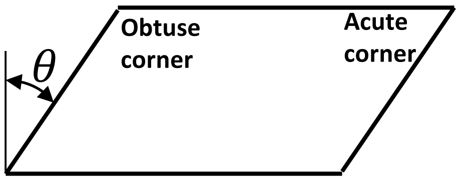
where:

$f(\theta)$ = skew factor, which is the ratio of additional support length due to skew to support length of straight bridges

N_0 = minimum support length for straight bridges (in)

N_θ = minimum support length for skew bridges (in)

θ = skew angle (°), which is measured from the line perpendicular to the longitudinal axis to the centerline of the support



Skew factors in current specifications and design manuals

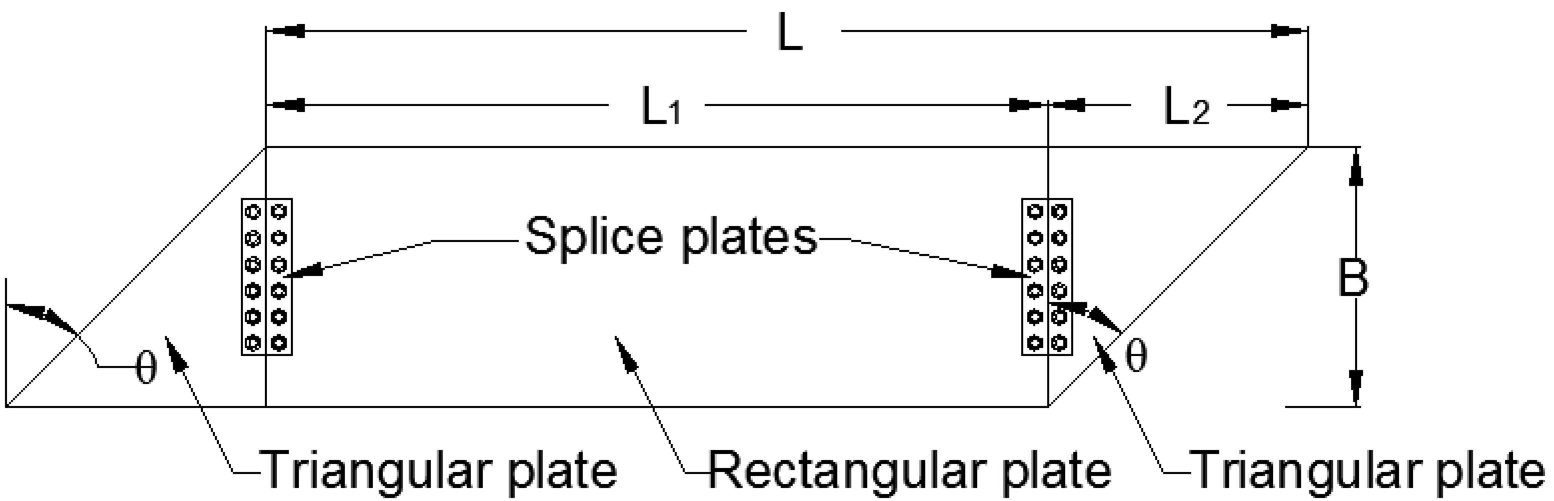
FHWA Retrofit Manual (Buckle et al. 2006) & Caltrans SDC 2.0

$$f(\theta) = \frac{1 - cos\theta}{cos\theta}$$

Note that these skew factors are based on engineering judgment.

Shake table experiments - bridge models

Cases	θ (^{0})	B (ft)	L (ft)	L (in)	L_1(in)	L_2(in)	L/B	h(in)	W (kips)
Case 1	0	3.5	10.50	126	126	0.00	3.00	2.0	3.3
Case 2	30	3.5	12.50	150	126	24	3.57	2.0	4.1
Case 3	45	3.5	14.00	168	126	42	4.00	2.0	4.6
Case 4	60	3.5	16.50	198	126	72	4.71	2.0	5.3

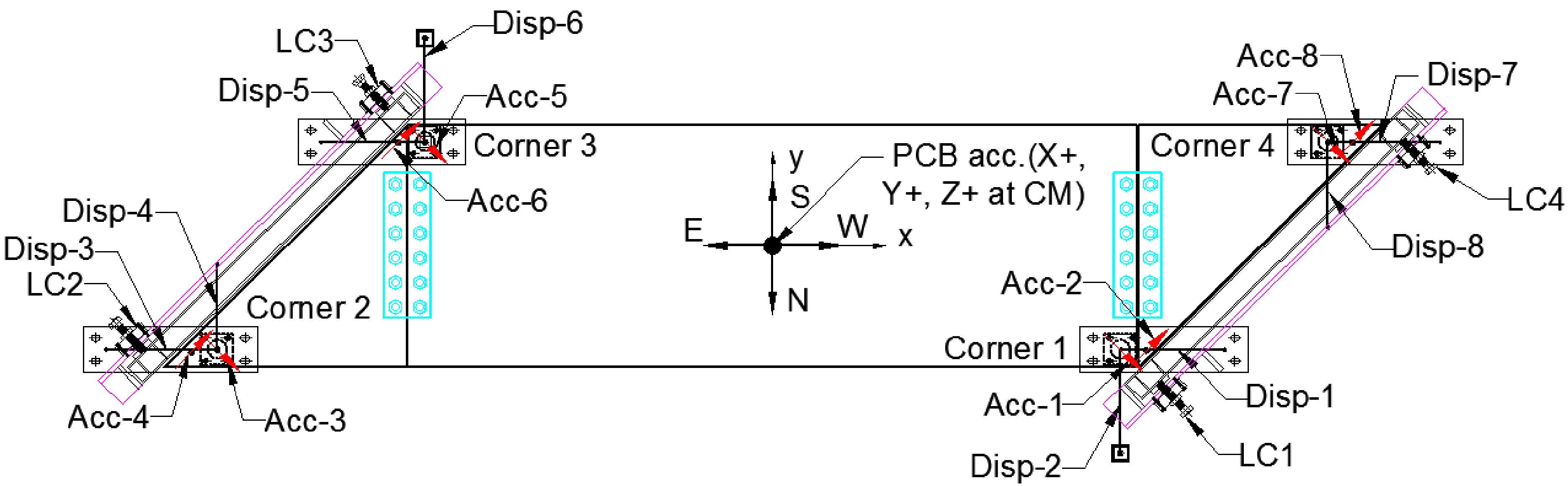


Model scale = 3.5/40 ≈ 1/10

Shake table experiments - instrumentation

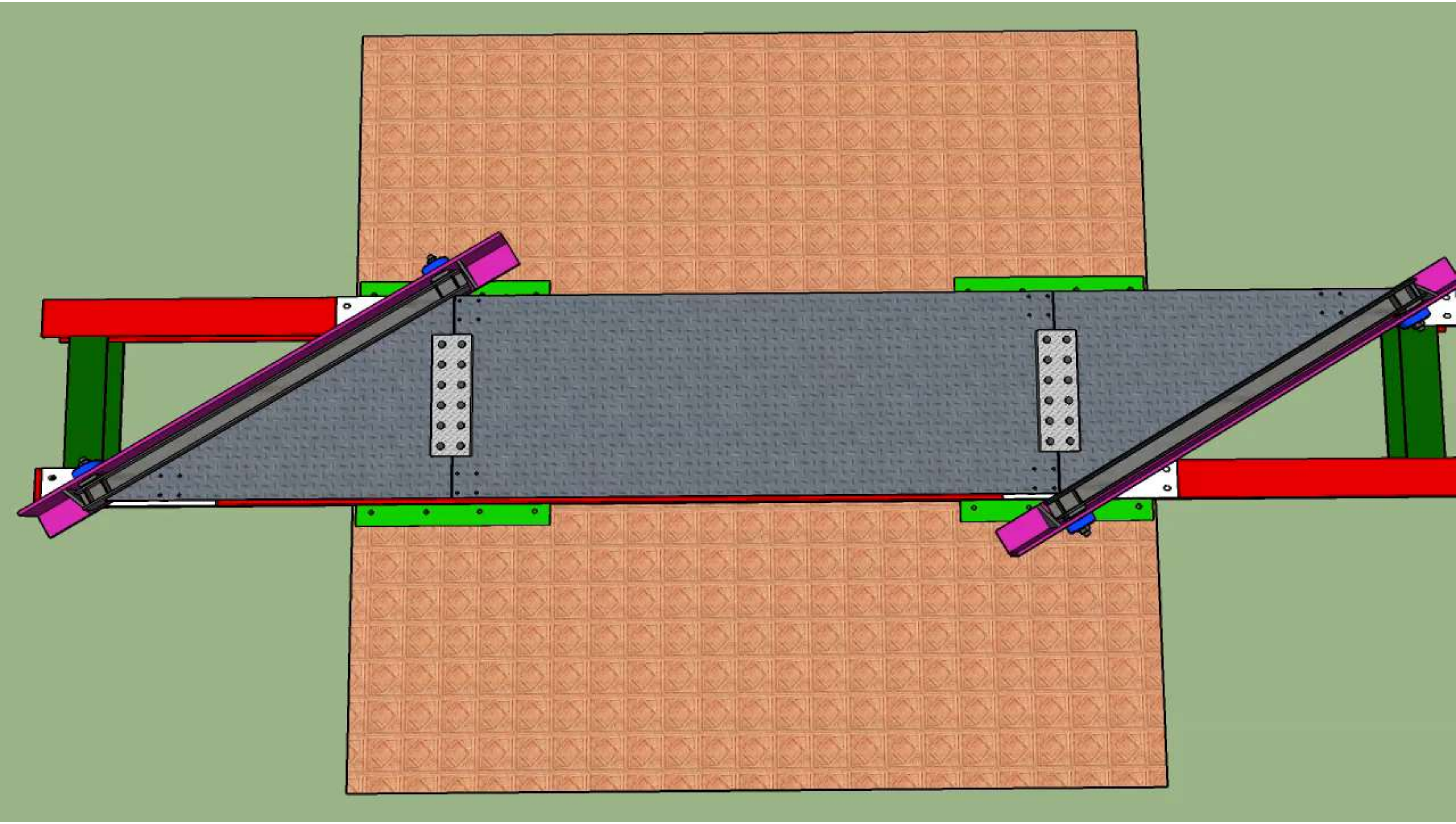
Transducers used to measure:

- displacements
- accelerations and
- impact forces between bridge deck and abutments



Plan view of instrumentation for 45^0 model (other models similar)

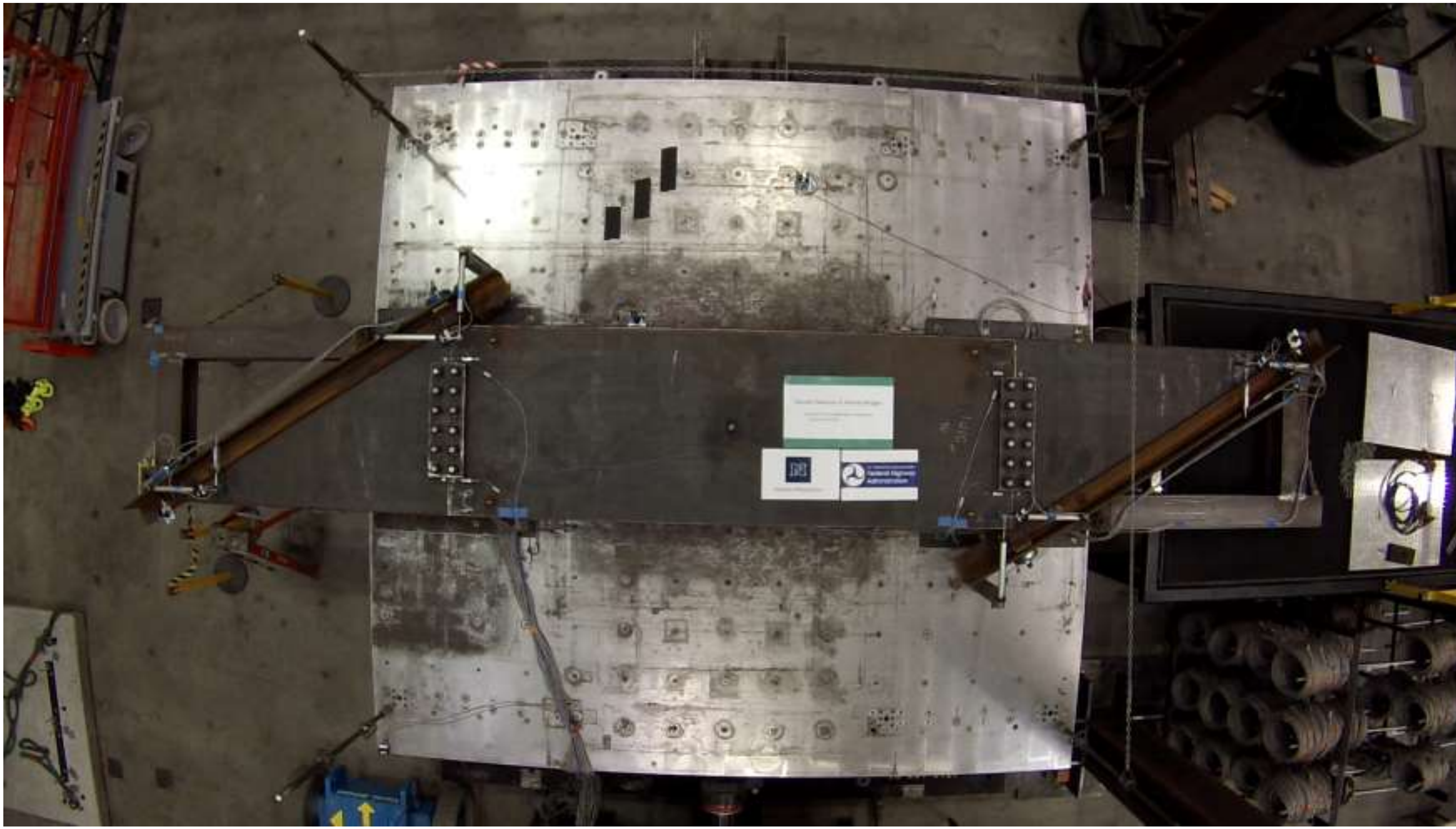
Schematic of skew bridge model on shake table



Shake table experiments - test matrix

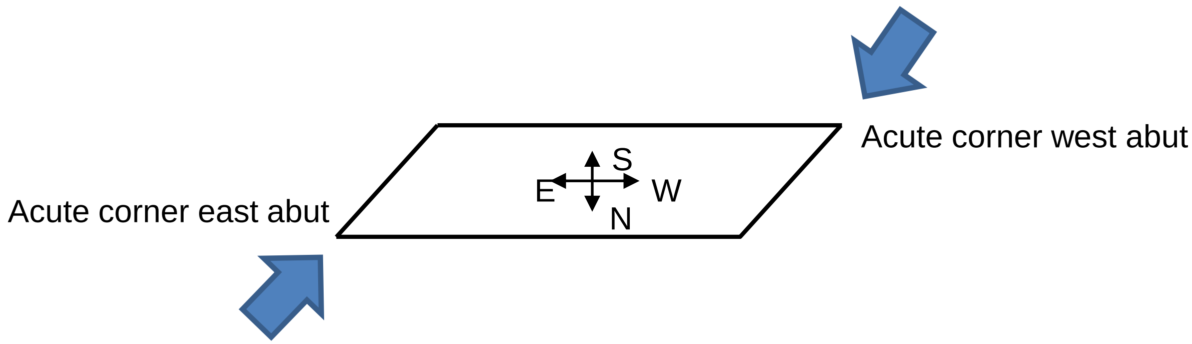
Skew, θ	0^0, 30^0, 45^0, 60^0
Abutment gap	0", 1/16", 1/8", 3/16", 1/4" (0 to 3" in prototype bridges)
EQ record	El Centro (1940), Century City (1994), Sylmar (1994)
EQ levels	50%DE, 75%DE,100%DE, 150%DE, 200%DE,
EQ input direction	Transverse only, Longitudinal only, Biaxial
Total runs	876

Shake table experiments (plan view)



θ=60^0, gap=1/8 in, SYL1994, biaxial input, 200%DE

Shake table experiments (side views)

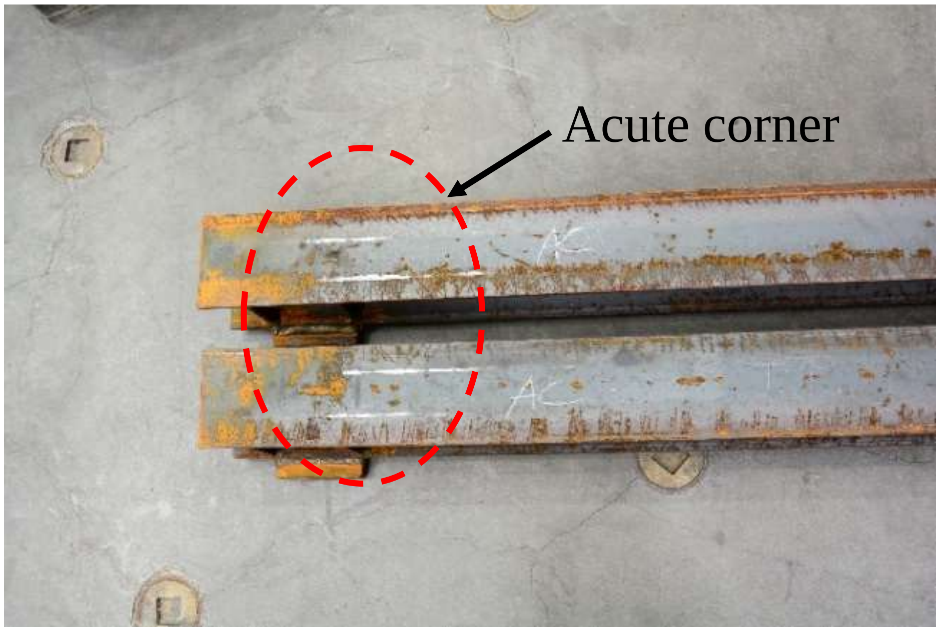


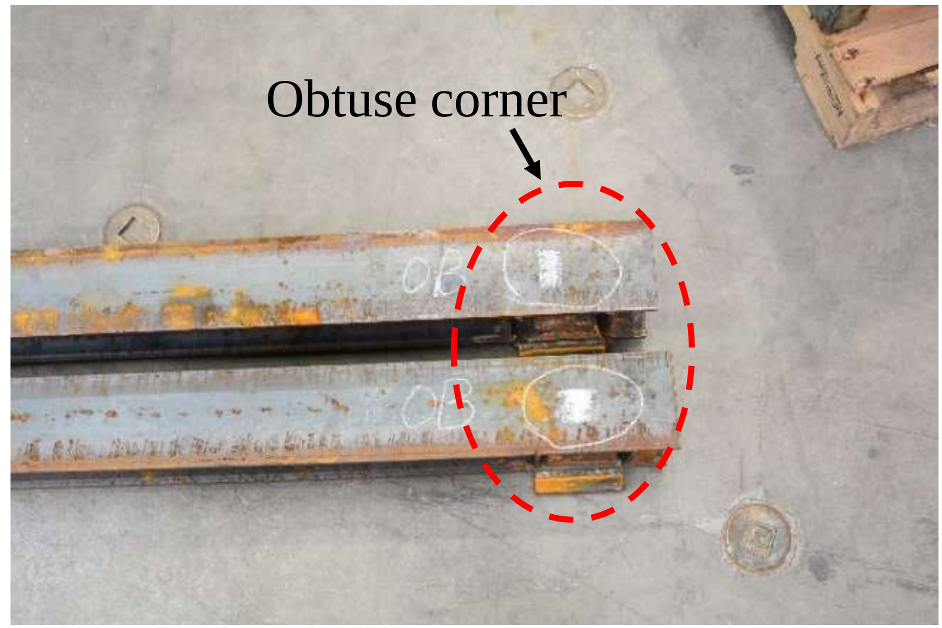
Acute corner east abutment

Acute corner west abutment

$\theta=60^0$, gap=1/8 in, SYL1994, biaxial input, 200%DE

Shake table experiments (face beams)



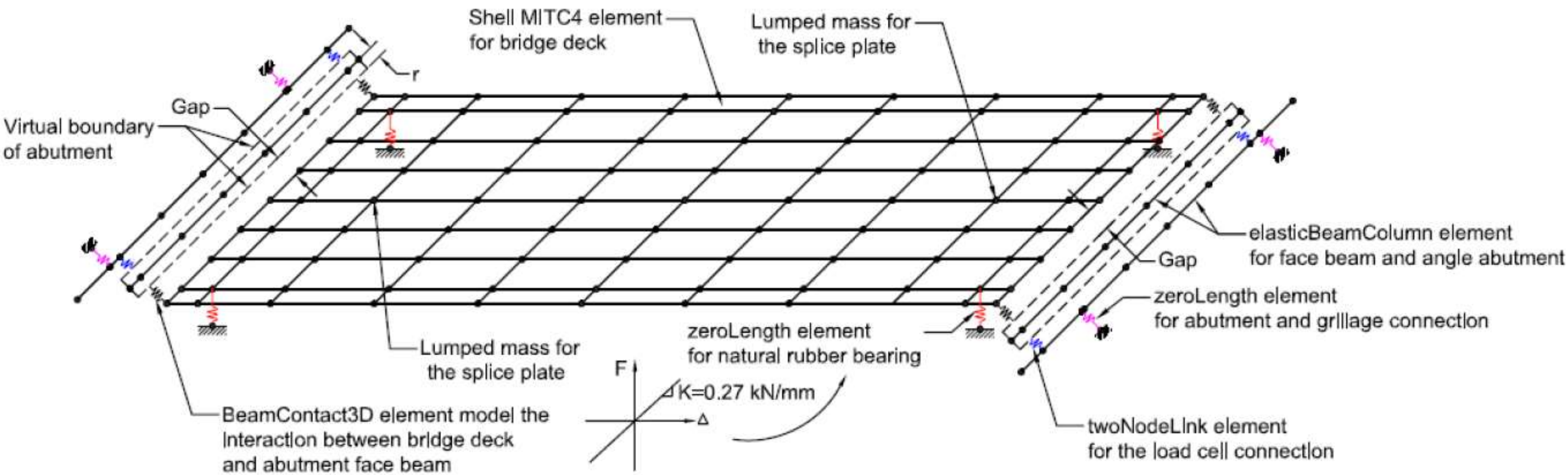


Abrasion marks on face beams from the 60^0 model (other models similar)

Complete dataset of this experiment is stored in:

- Wu, S., Buckle, I.G., Itani, A.M., and Istrati, D. (2019). “Experimental datasets from large-scale shake table experiments on skew bridges.” https://doi.org/10.17605/OSF.IO/2Q3DP.

Validation of the numerical model in OpenSEES

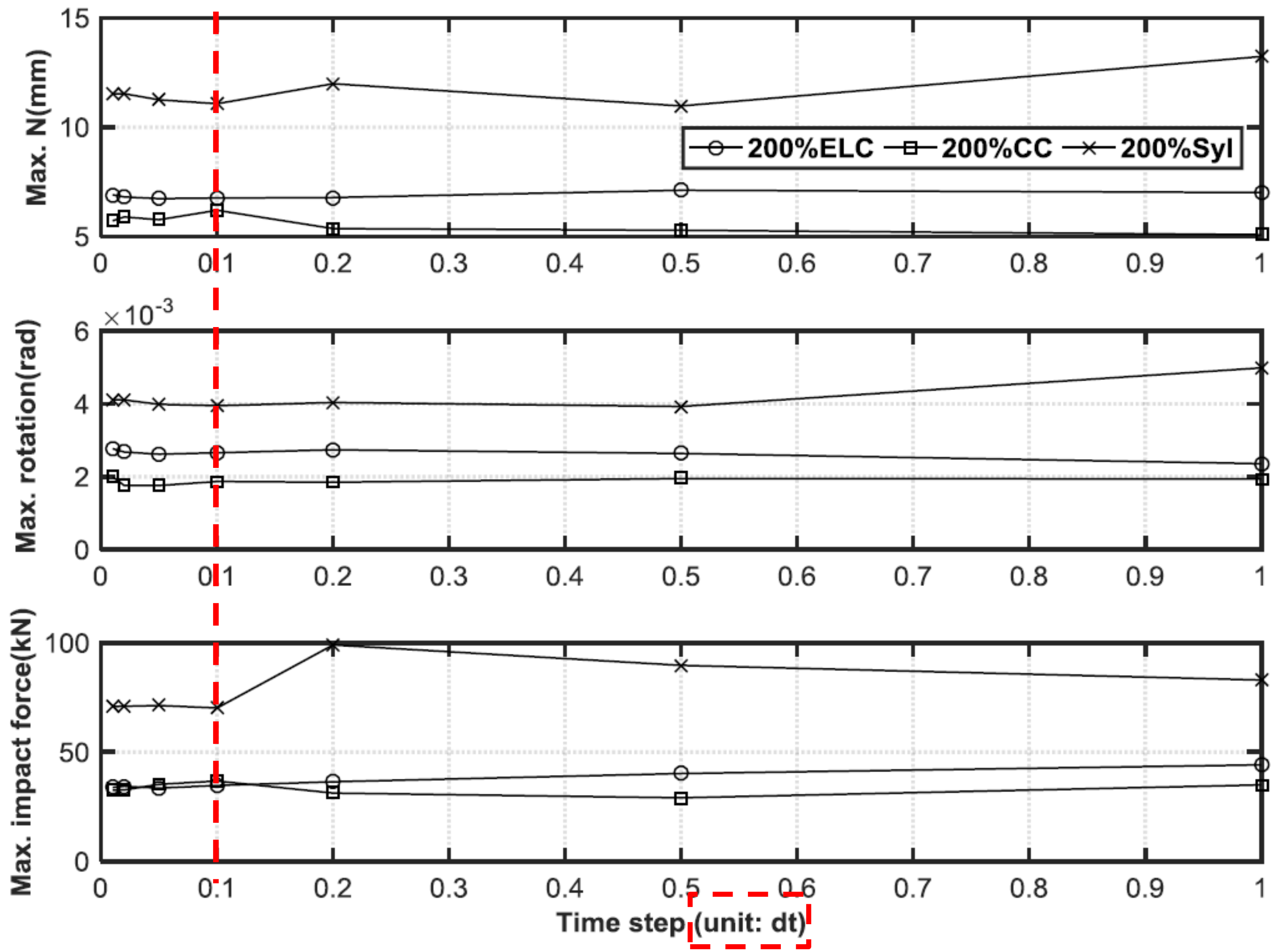


Validation of the numerical model in OpenSEES

- Shell elements with distributed mass were used to model the bridge deck
- Elastomeric bearings were represented by linear springs based on the properties estimated from quick-release tests which are corresponding to 50% shear strain of the bearings
- "BeamContact3D" elements were used to model the gap, impact, and friction effects between deck and abutments. Friction coefficient = 0.3 for steel-on-steel.
- Damping assumed to be same in first translational and first rotational modes, and based on the quick-release tests (50% shear strain of the bearings).

Validation of the numerical model in OpenSEES

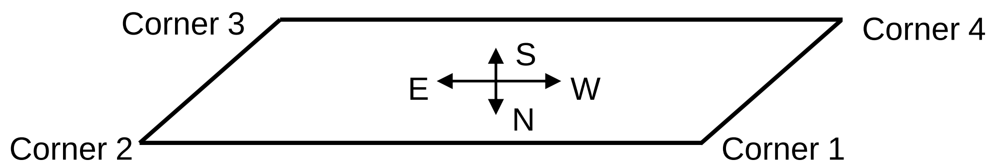
- dt=1/256 sec
- Results were converged when time step reduced to dt/10
- Dt/10 was used for the analysis.

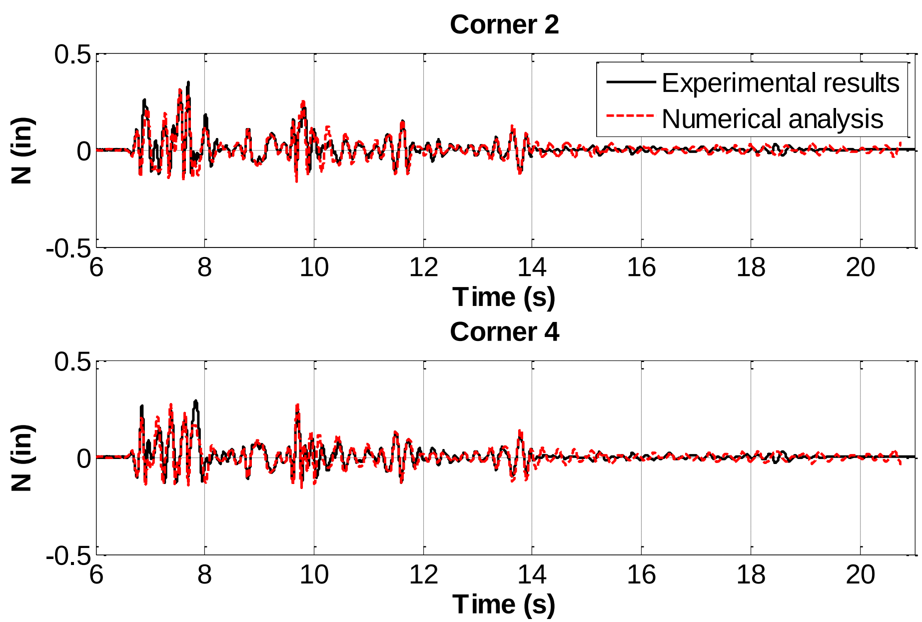


Maximum response quantities vs time step dt

Validation of the numerical model in OpenSEES

Run 125, 45^0 model: Gap=1/8 in, 200%DE, El Centro, biaxial input:

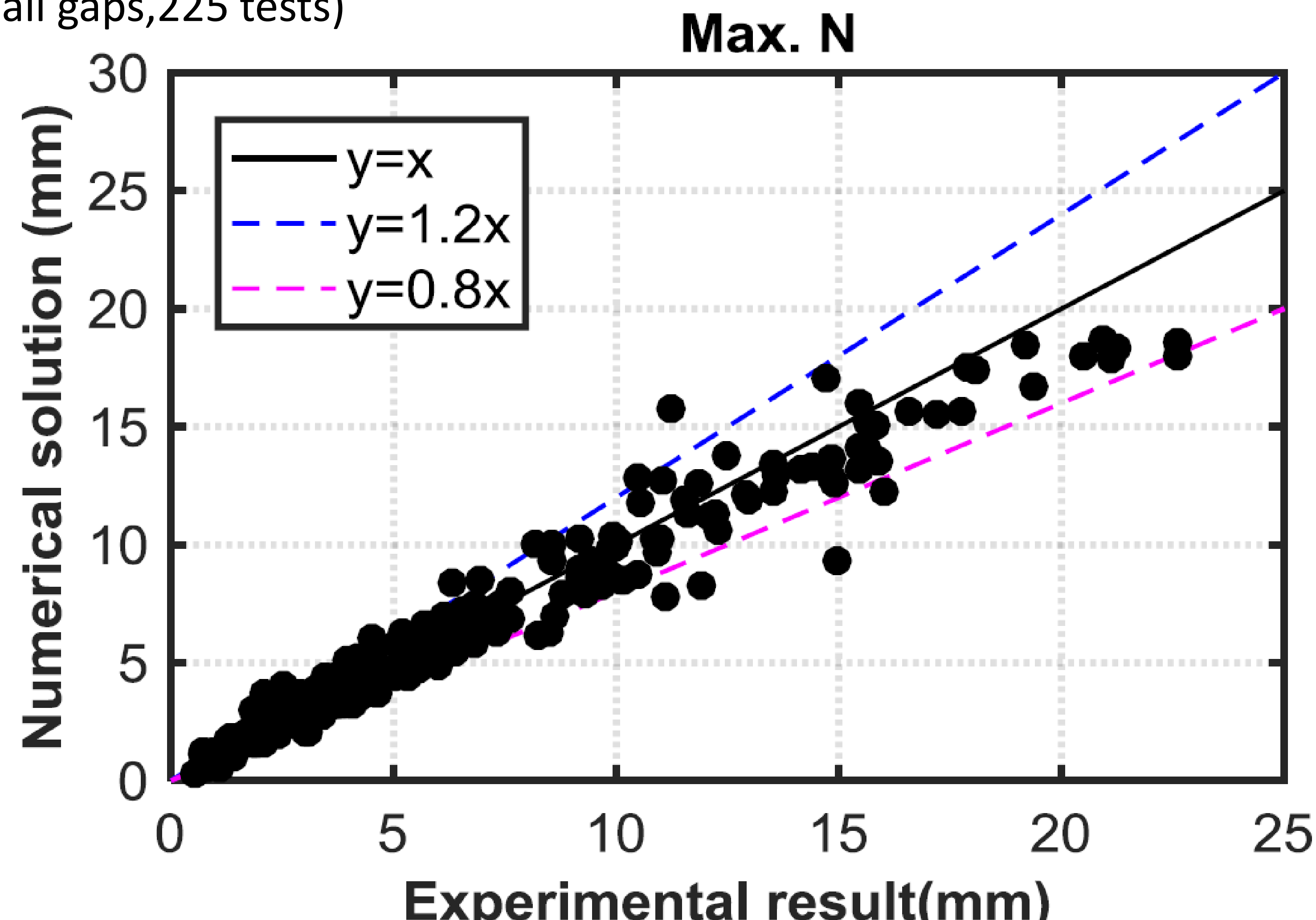




Normal displacements at acute corners

Validation of the numerical model in OpenSEES

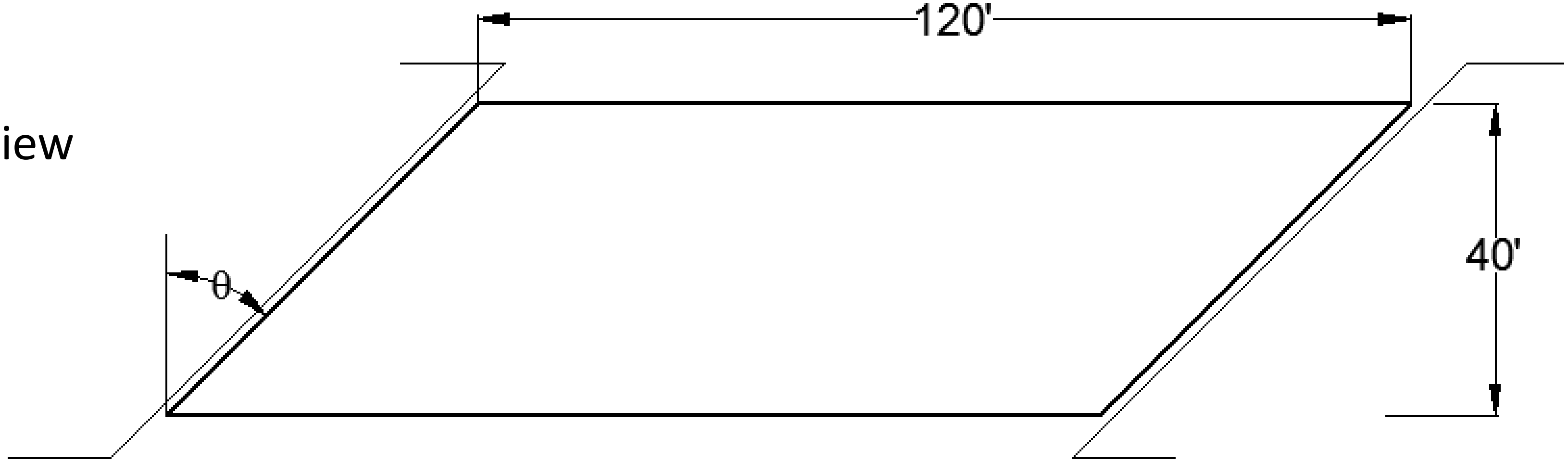
Maximum normal displacement (numerical vs experimental results) for 60^0 model (all EQs and all gaps,225 tests)

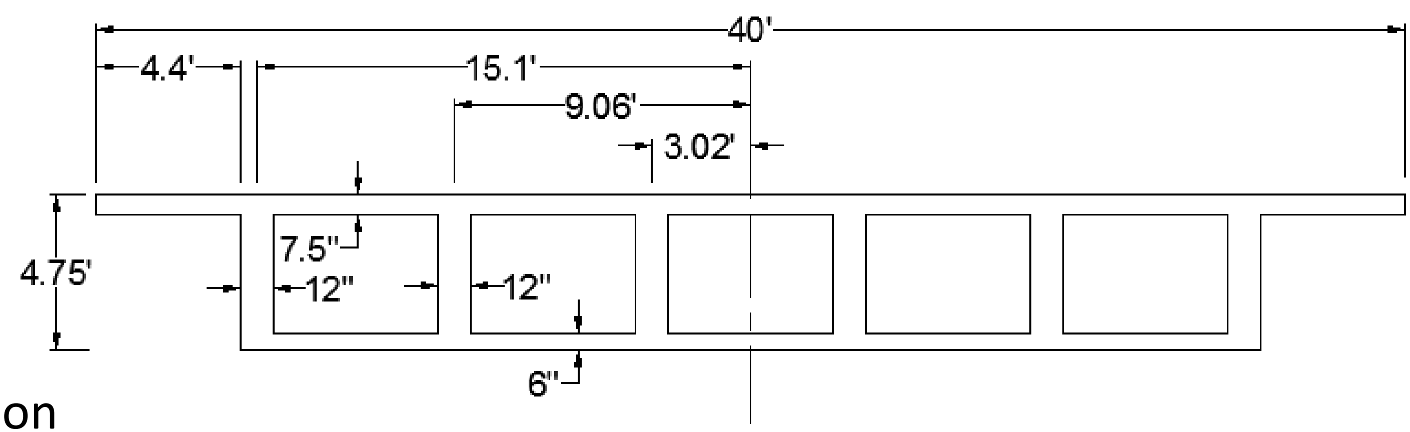


Parameter study - basic bridge geometry

Prototype bridge: single-span, seat-type abuts, T= 0.85s, Δ_{temp} = 1.05 in

Plan view





Cross section

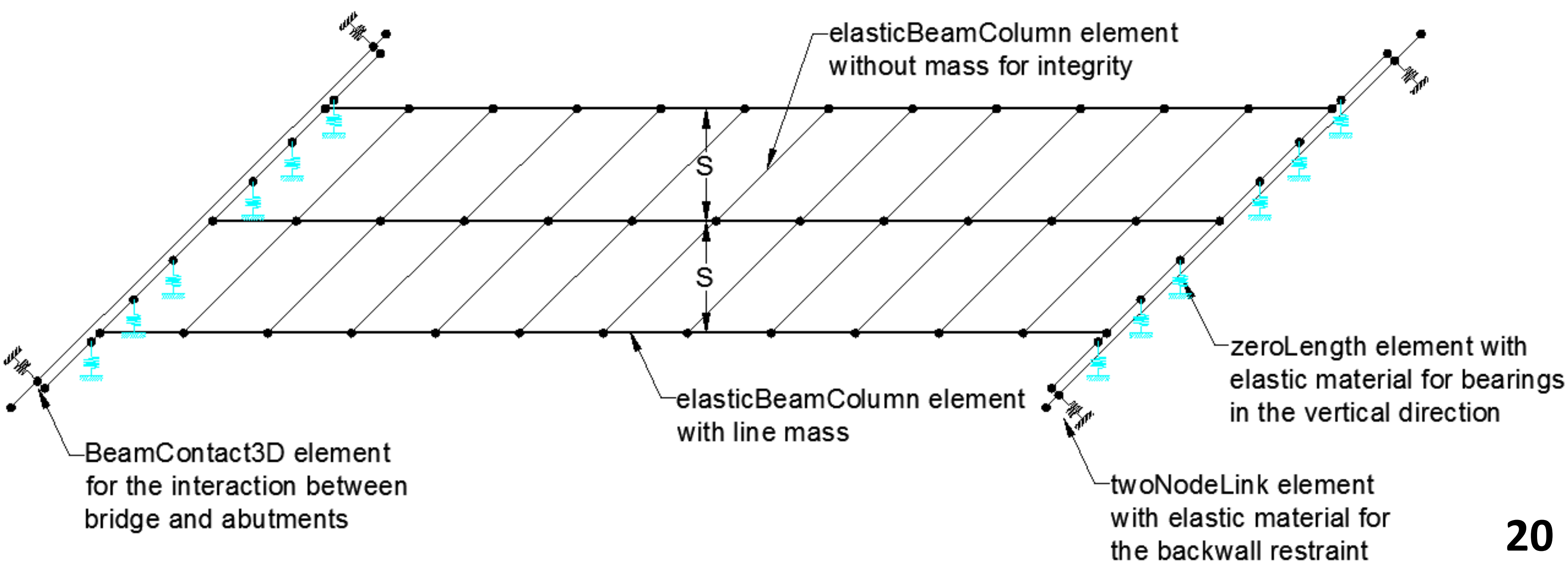
Parameter study – analysis cases

For each configuration, skew varied from 0^0 to 60^0 in steps of 5^0

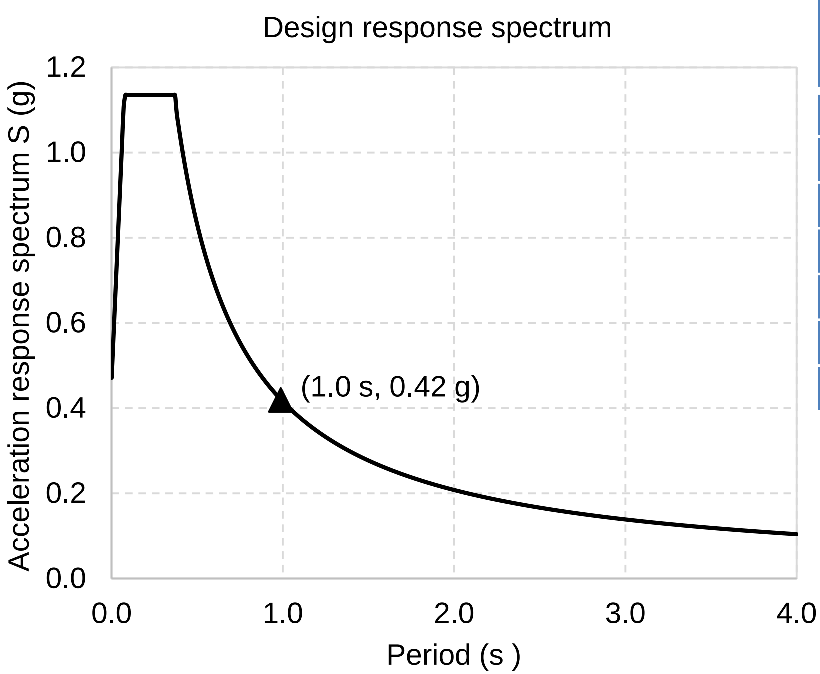
Group 1 (Constant B=40 ft)										
Case #	L (ft)	B (ft)	L/B	d (ft)	Gap (in)	N_0 from AASHTO (in)	Total weight (kips)	K (kip/in /bearing)	# of bearings	T (s)
1	100	**40**	**2.5**	4.5	0.5	15	913	10.76	12	**0.85**
2	120	**40**	**3**	4.75	0.5	15.6	1122	13.23	12	**0.85**
3	140	**40**	**3.5**	6.3	0.75	16.2	1505	17.73	12	**0.85**
4	160	**40**	**4**	7.2	0.75	16.8	1849	21.79	12	**0.85**
5	180	**40**	**4.5**	8.1	1	17.4	2226	26.23	12	**0.85**
6	200	**40**	**5**	9	1	18	2636	31.06	12	**0.85**
Group 2 (Constant L=120 ft)										
Case #	L (ft)	B (ft)	L/B	d (ft)	Gap (in)	N_0 from AASHTO (in)	Total weight (kips)	K (kip/in /bearing)	# of bearings	T (s)
7	**120**	48	**2.5**	4.75	0.5	15.6	1350	14	14	**0.85**
8	**120**	40	**3**	4.75	0.5	15.6	1122	13	12	**0.85**
9	**120**	34	**3.5**	4.75	0.5	15.6	936	13	10	**0.85**
10	**120**	30	**4**	4.75	0.5	15.6	855	12	10	**0.85**
11	**120**	27	**4.5**	4.75	0.5	15.6	729	13	8	**0.85**
12	**120**	24	**5**	4.75	0.5	15.6	668	12	8	**0.85**

Parameter study-OpenSEES model

- Rigid abutment assumed
- BeamContact3D element used to model impact and friction between bridge and abutment
- Coefficient of friction taken as 1.0 for concrete-on-concrete
- 5% damping in first translational and first rotational modes



Parameter study – ground motions



Design response spectrum for **seismic zone 3**

Far field ground motions

Record #	EQ	Year	Station	Distance (km)
1	Imperial Valley	1940	El Centro Array #9	6.09
2	San Fernando	1971	Castaic	22.63
3	Friuli, Italy	1976	Tolmezzo	15.82
4	Northridge	1994	Sun Valley	10.05
5	Northridge	1994	Century City	23.41
6	Loma Prieta	1989	Anderson Dam	20.26
7	Imperial Valley	1979	El Centro Array #11	12.56

Near field ground motions

Record #	Record Name	Year	Station Name	Distance (km)
1	Imperial Valley	1979	El Centro Array #3	12.85
2	Northridge	1994	Sylmar	5.3
3	Loma Prieta	1989	Gilroy Array #2	11.07
4	Landers	1992	Lucerne	2.19
5	Northridge	1994	Pacoima Dam	7.01
6	Duzce, Turkey	1999	IRIGM 487	2.65
7	Chi-Chi, Taiwan	1999	TCU053	5.95

Average results from 7 ground motions used to draw conclusions

Parameter study – $f(\theta)$

For purpose of this study, take:

$$N_\theta = n_\theta + a$$

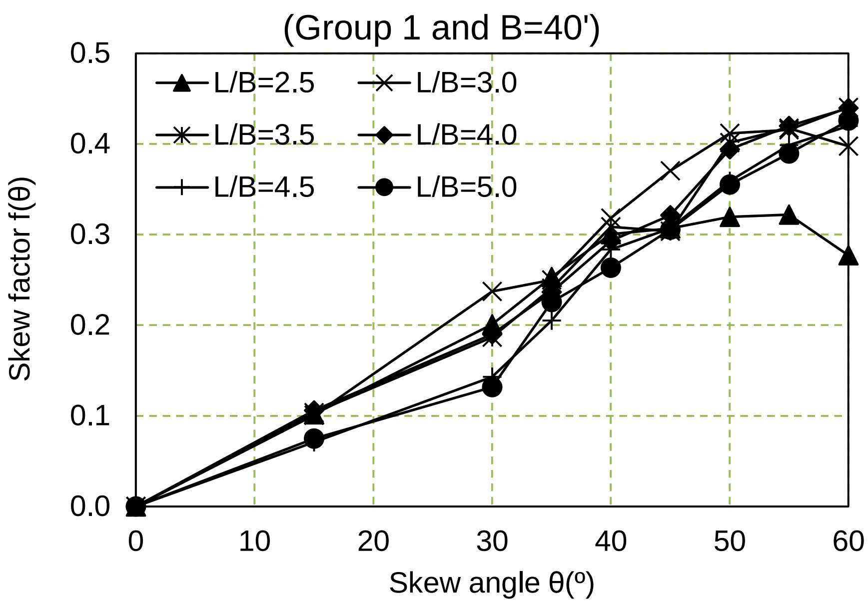
$$N_0 = n_0 + a$$

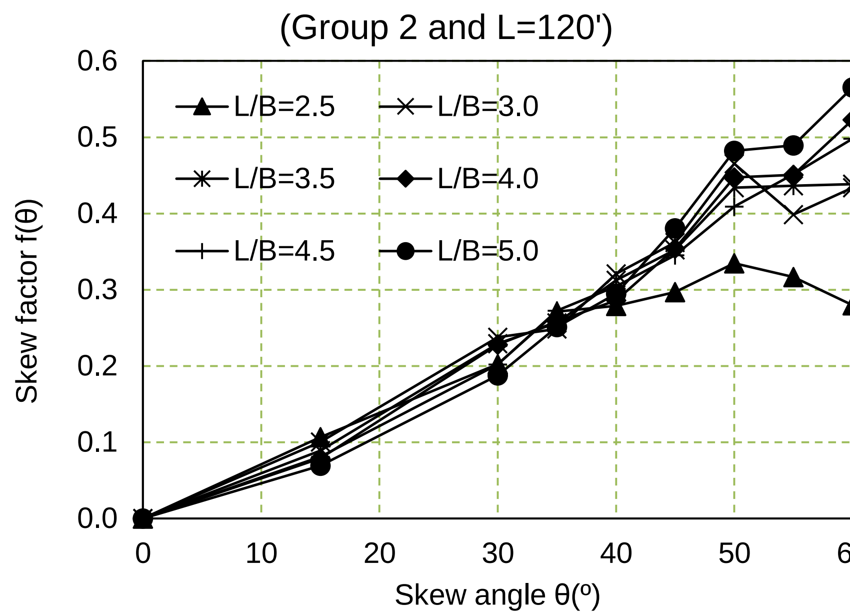
where n_θ and n_0 are the calculated displacement demands normal to the abutments at the supports of skewed and straight bridges respectively, and a is allowance for the cover concrete at the edge of the seat.

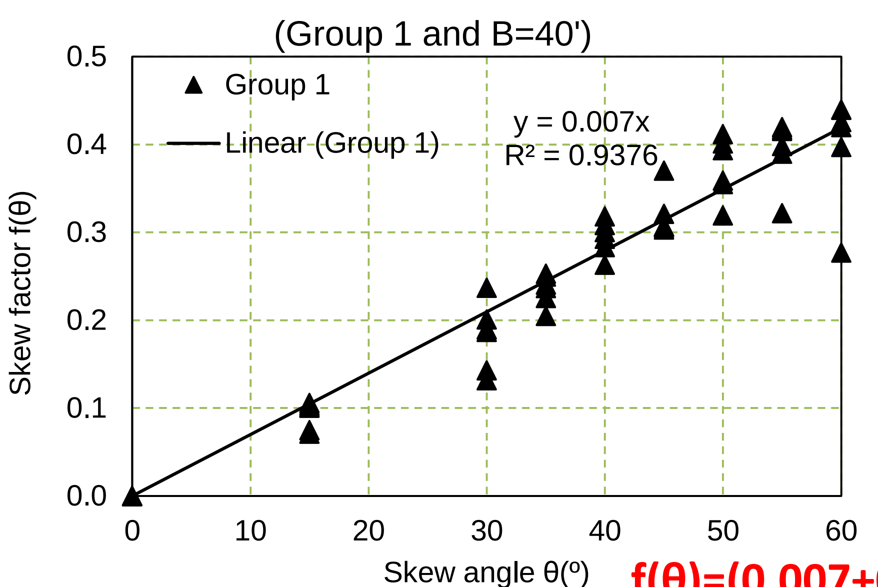
$$a = 76.2\ mm\ (3.0\ in)(cover) + 25.4\ mm\ (1.0\ in) rebar\ diameter$$
$$= 101.6\ mm\ (4.0\ in)$$

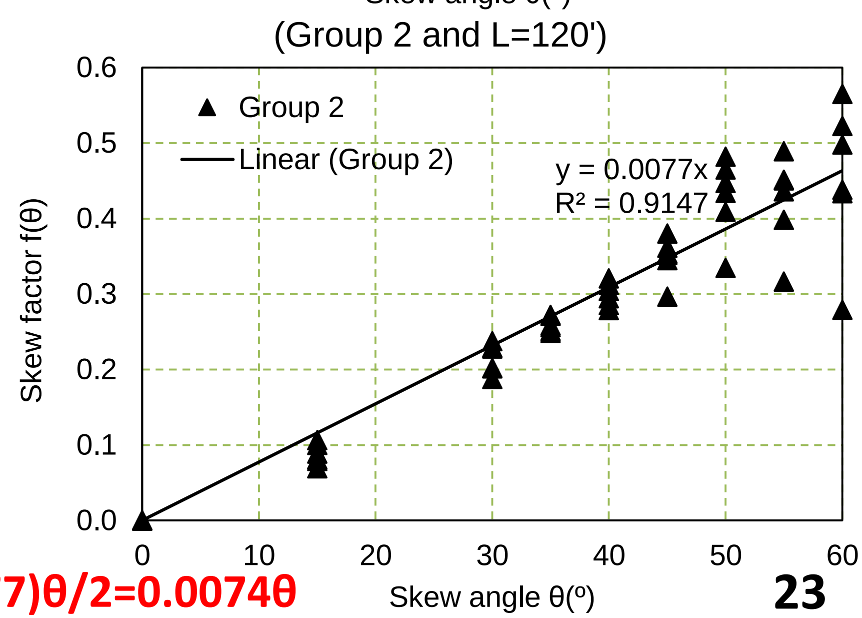
Then skew factor, $f(\theta) = \frac{N_\theta - N_0}{N_0} = \frac{n_\theta - n_0}{n_0 + 101.6}$

Parameter study –$f(\theta)=\delta N/N_0$ (far-field GMs)



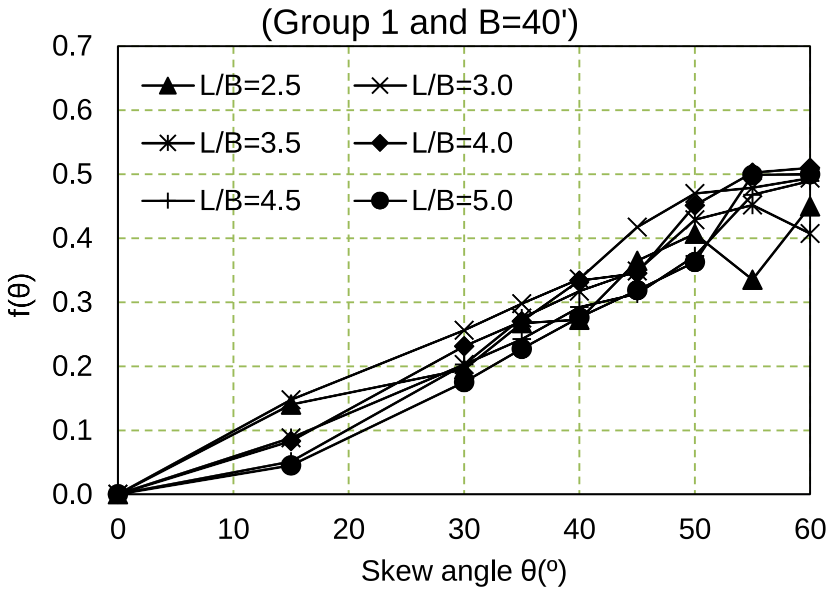


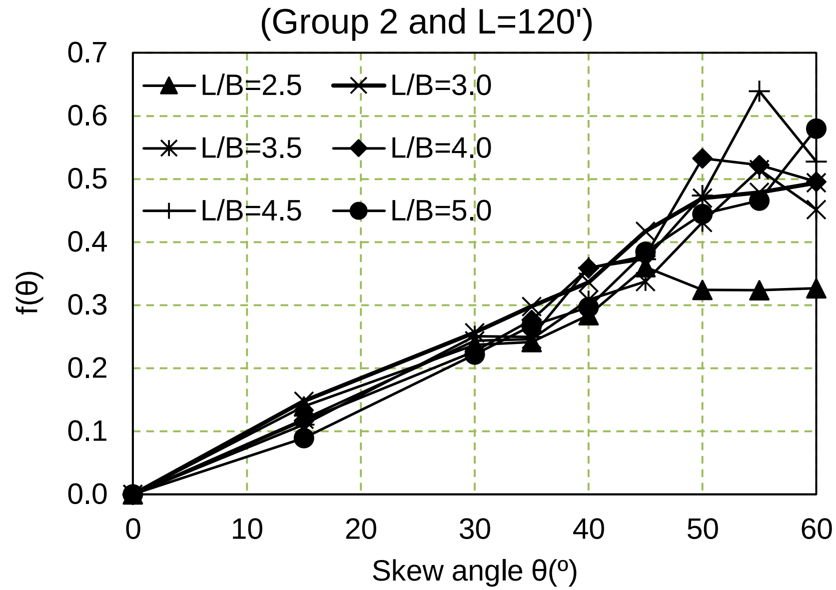


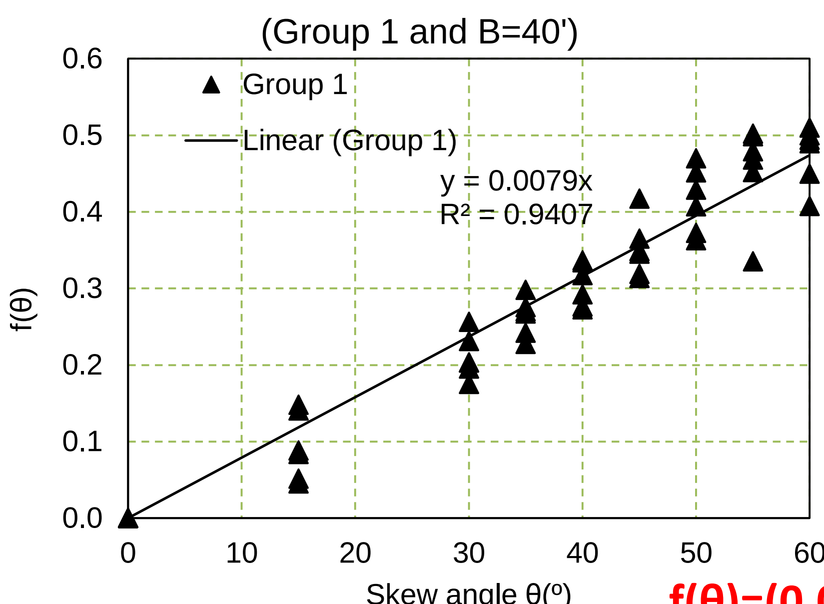


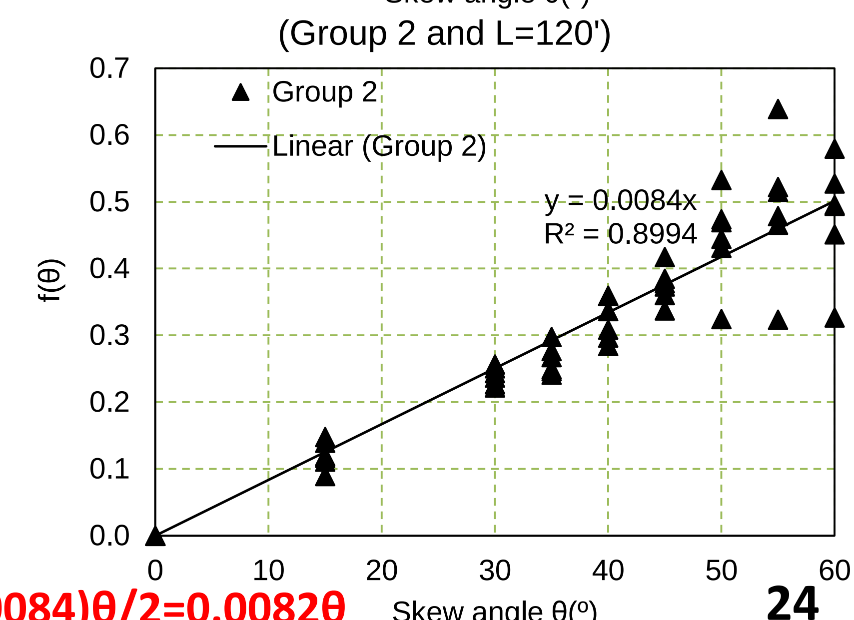
$f(\theta)=(0.007+0.0077)\theta/2=0.0074\theta$

Parameter study –$f(\theta)=\delta N/N_0$ (Near-field GMs)



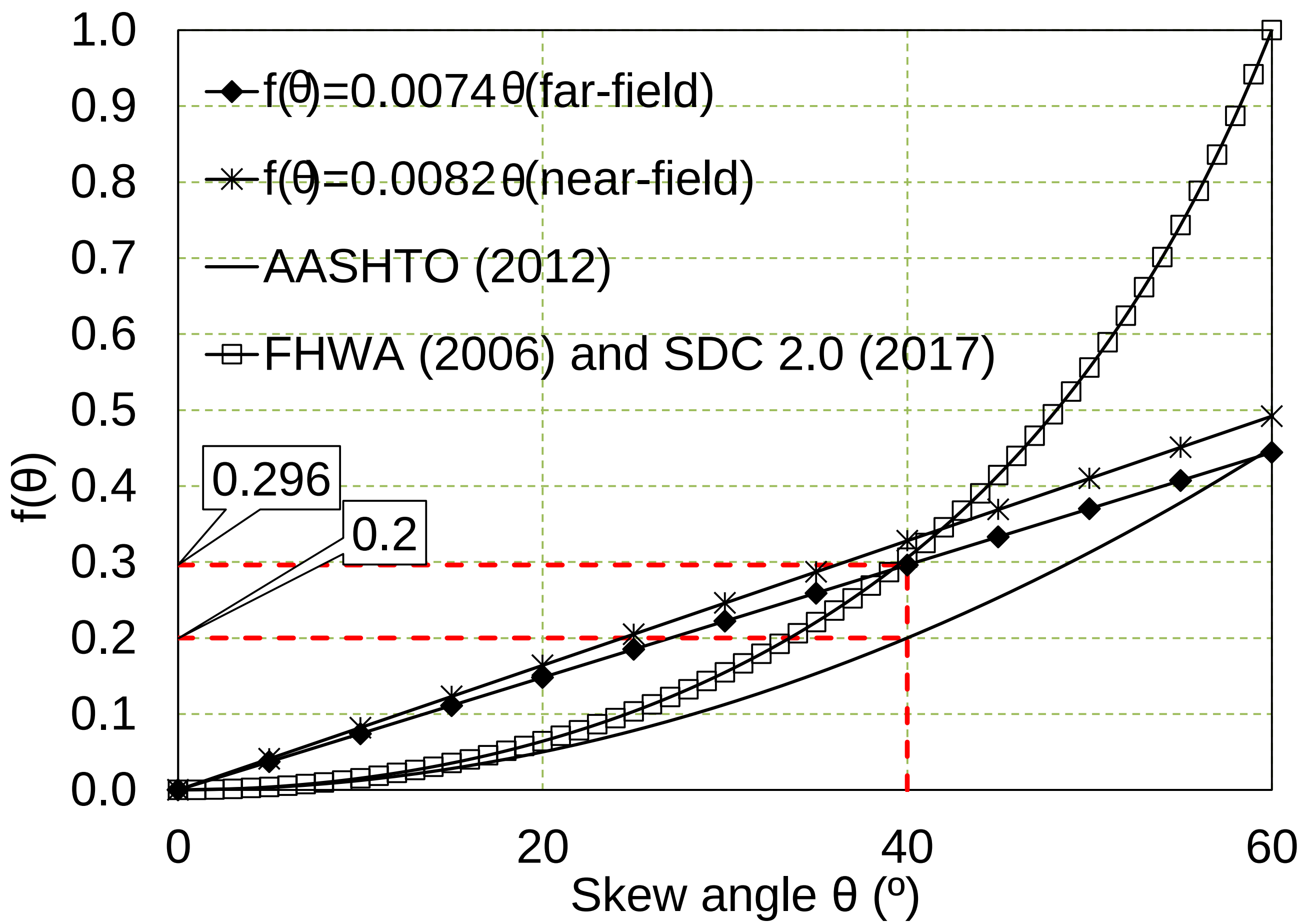






$f(\theta)=(0.0079+0.0084)\theta/2=0.0082\theta$

Comparison of skew factors



Skew factor $f(\theta)=(N_\theta-N_0)/N_0$

At 40^0 skew, f_{recomm} / f_{AASHTO} = 0.296/0.2 = 1.5

Summary and conclusions – analytical investigation

- The numerical models with and without abutment pounding, show good correlation with the experimental results and therefore can be used with confidence to investigate the seismic response of skew bridges

- The skew factor f(θ) for the minimum support length increases linearly with skew angle from 0º to 60º for both near-field and far-field ground motions.

- The skew factor for the minimum support length of skewed bridges is larger for near-field ground motions than that for far-field ground motions.

- The skew factor in AASHTO Specifications ($0.000125\theta^2$) is un-conservative particularly for skew angles in the range 15 to 45 degrees.

Recommendations

- $f(\theta) = 0.0074\theta$ (far-field bridges)
- $f(\theta) = 0.0082\theta$ (near-field bridges)

Acknowledgements

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    - Ms Sheila Duwadi
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Thank you!

Any questions?