Progress on the Development of Generation-2 Fragility Relationships for California Bridges

Phase-1: Feasibility Studies (2010-2012)

Phase-2: Production - Concrete Bridges (2013-2017)

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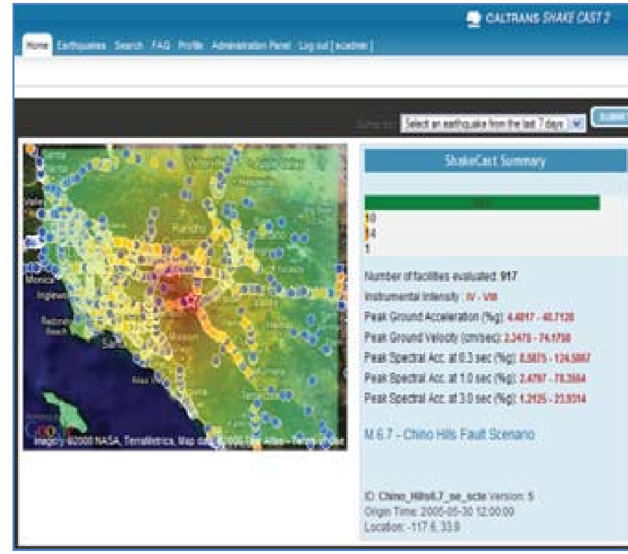
g2 Bridge Fragility: Project Background

Need:

- Caltrans Uses ShakeCast to Support Post-Earthquake Response
- ShakeCast Currently Uses HAZUS-Based Fragility (Early 1990's)
- HAZUS Taxonomy is Coarse & Not Optimized for CA Bridge Types

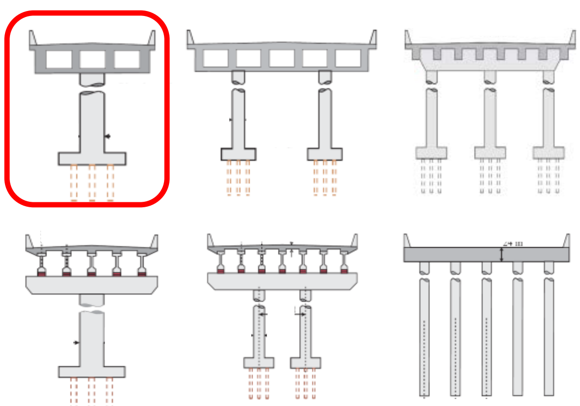


Goals:

- Phase 1: Demo Feasibility & Value of Improving Fragility Models
- Phase 2: Production Fragility Models for Most Concrete Bridge Types

Benefits:

- Improved Rapid Predictions of Earthquake Damage
- CT: Improved Situational Awareness and Decision-Making
- Public: Faster & More Effective Emergency Response



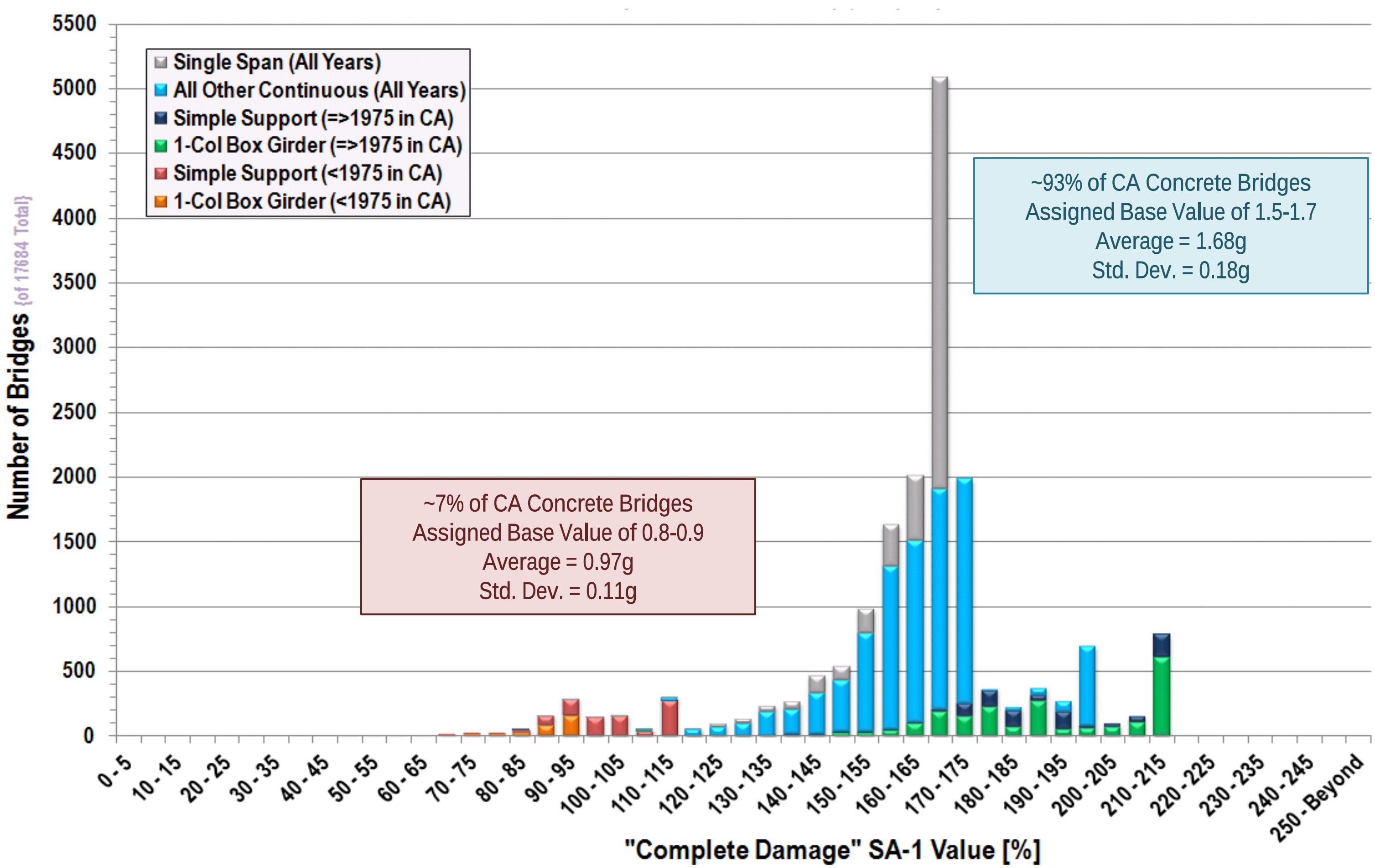
HAZUS Fragility Models				Approx. % of Concrete Bridges in CA
Description	Conventional (<1975 in CA)	Seismic (>=1975 in CA)	"Complete" Damage State	
Single Span	HWB3, Eq1, 1		1.70	26%
		HWB4, Eq1, 1	"	
Simple Support	HWB6/18, Eq1, 0		0.90	5%
		HWB7/19, Eq1, 0	1.70	5%
Cont. Single-Col Box Girder	HWB8/20, Eq2, 0		0.80	2%
		HWB9/21, Eq3, 0	1.60	11%
All Other Continuous	HWB10/22, Eq2, 1		1.50	51%
		HWB11/23, Eq3, 1	"	

HAZUS Fragility: Current Fragility Assignments in ShakeCast

HAZUS "Complete Damage" SA-1 Median = Base Value * Skew Factor * 3D Factor

Skew: (Factor varies from 1.0 to 0.7 as skew varies 0 to 60 degrees)

3-D: (Factor varies from 1.0 to 1.33 with higher values for fewer spans)



g2 Bridge Fragility: Opportunities for Improvement

Analytical Methodology:

- Allows explicit consideration of engineering demand parameters meaningful to bridge designers
- Allows consistent in-depth exploration of bridge systems / details where little empirical data is available

Component & System Fragility:

- Highlight components (e.g. columns, hinges, bearings, restrainers, etc.) for inspectors where greatest damage expected
- Combine components to have common performance implications (i.e. traffic state, emergency repairs)
- Supports future enhancements for rapid cost estimation, traffic modeling, and transportation-network planning

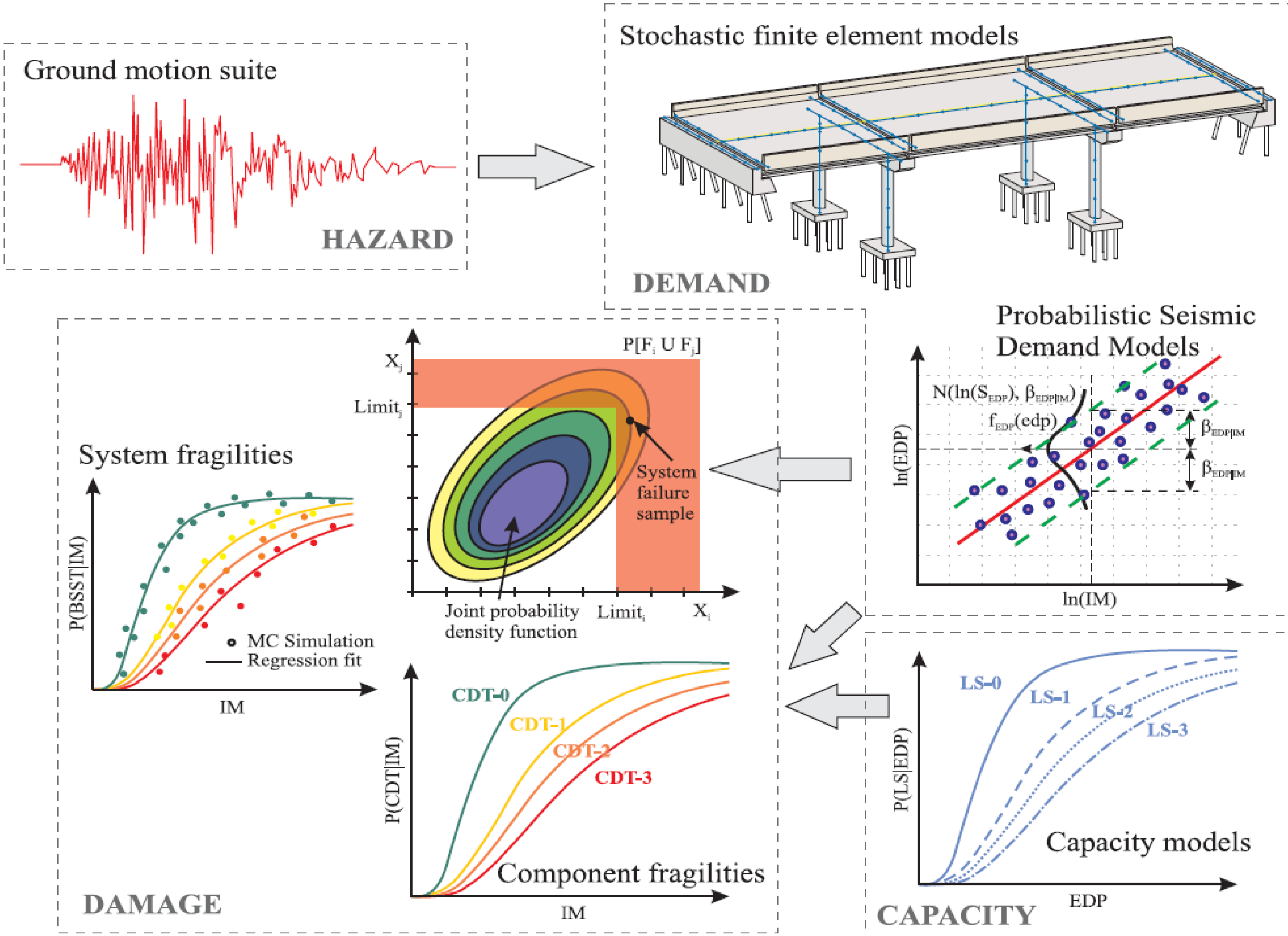
CA Centric:

- MOTIONS: Designed for CA hazard levels and GM metrics
- BRIDGE SYSTEMS: Customize for common CA bridge classes / subclasses
- INFORMATION RESOURCES: Utilize available bridge information assets unique to CA

Finer Bridge Taxomomy:

- CONVENTIONAL BRIDGE CLASSES: More systems/combinations (e.g. tee-girder on MC bent vs. on pile extensions)
- SEISMIC PERFORMANCE SUBCLASS: Additional factors thought to influence seismic performance (e.g. skew, curve, balance)

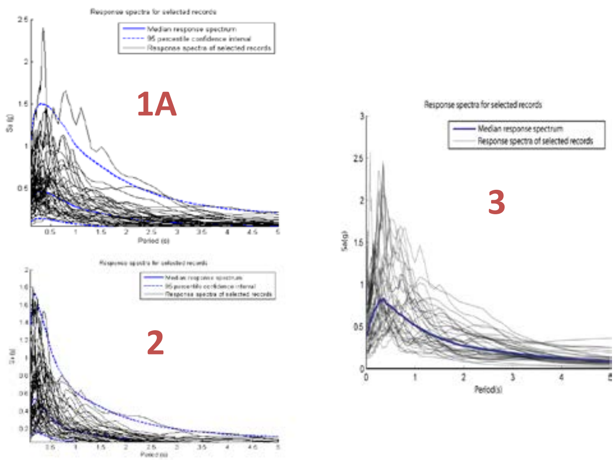
g2F Methodology: Overview



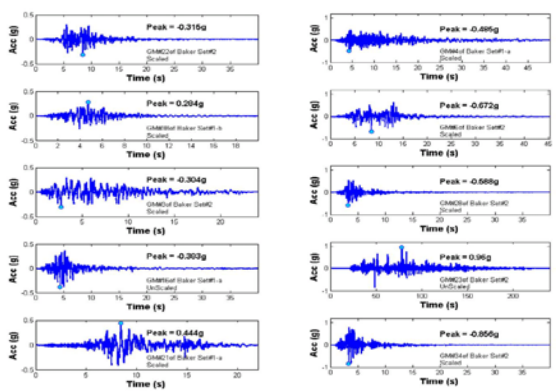
g2F Methodology: Ground Motions

Baker et al. (2011) – PEER Transportation Research

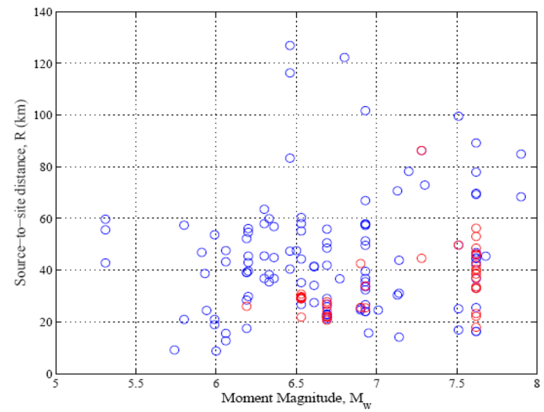
- Bin 1A: Broad-band GMs for soil site (M_w=7, R=10, soil)
- Bin 1B: Broad-band GMs for soil site (M_w=6, R=25, soil)
- Bin 2: Broad-band GMs for rock site (M_w=7, R=10, rock)
- Bin 3: Pulse-like GMs



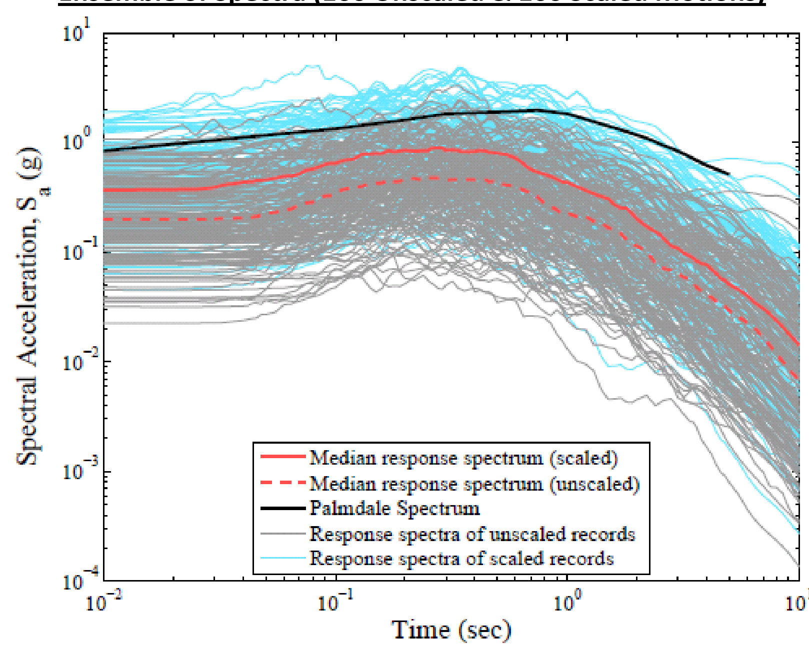
Sample of 10 of 160 Time Histories



Magnitude – Distance Distribution

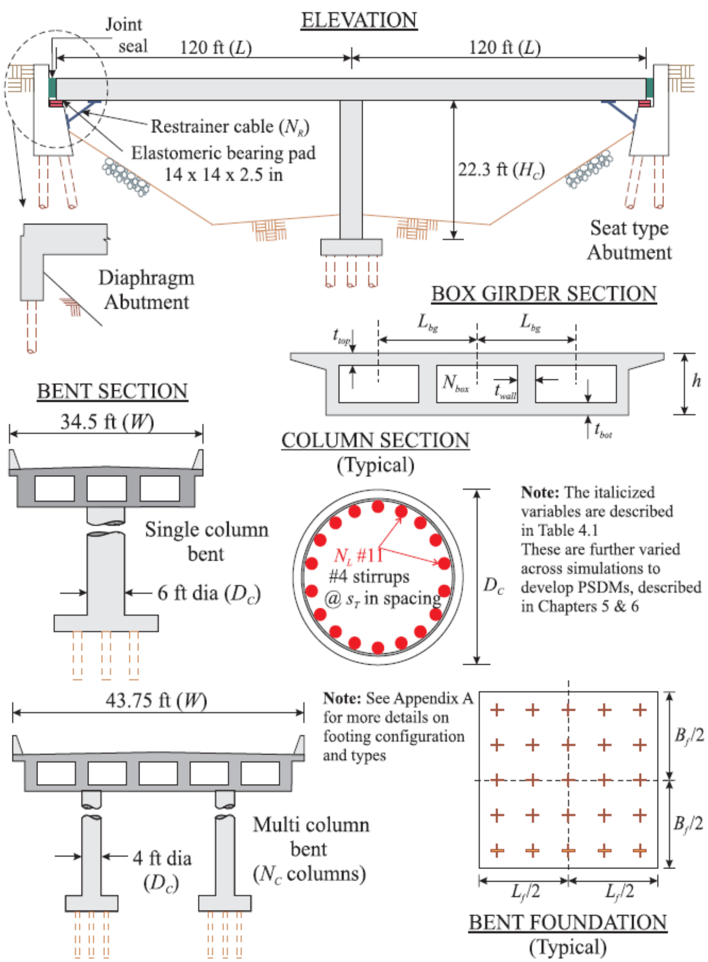


Ensemble of Spectra (160 Unscaled & 160 Scaled Motions)



g2F Methodology: Stochastic Bridge Models

Define Bridge Class/Subclass



Review Plans/Design Guides to Establish Class Design Basis

Table 5.1: Distributions for longitudinal and transverse reinforcement ratios in bridge columns

Bridge class	Design era	Longitudinal reinforcement ratio		Transverse reinforcement ratio	
		u_1*	u_2*	u_1*	u_2*
MSCC-BG	Pre 1971	1.4	2.4	N.A.	N.A.
	1971-1990	1.0	3.7	0.30	0.90
	Post 1990	1.0	3.5	0.40	1.70
MSCC-IG	Pre 1971	1.08	3.61	N.A.	N.A.
	1971-1990	1.18	5.31	0.31	1.07
	Post 1990	1.49	5.35	0.31	1.61
MSCC-TG	Pre 1971	1.08	3.61	N.A.	N.A.
	1971-1990	1.18	5.31	0.31	1.07
	Post 1990	1.49	5.35	0.31	1.61

*u_1, u_2 are the parameters describing a uniform distribution representing lower and upper bounds.

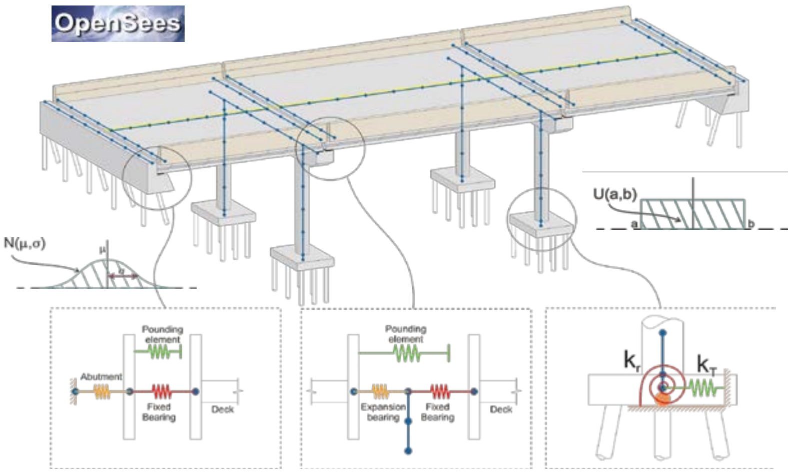
Table 4.1: Deterministic bridge model attributes for MSCC single frame box-girder bridges

Attributes	Pre 1971		1971-1990				Post 1990				
	SCB	MCB	SCB	MCB			SCB	MCB			
Column details											
Number per bent (N_C)	1	2	1	2	3	4	1	2	3	4	5
Column height (ft) (H_C)	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3
Diameter (ft) (D_C)	6	4	6	5	5	5	6	5	5	5	4
Longitudinal reinforcement (#11 bars) (N_L)	50	22	62	44	44	44	58	42	42	42	26
Transverse reinforcement spacing (in) (#4 stirrups) (s_T)	12.0	12.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Superstructure details											
Span length (ft) (L)	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0
Deck width (ft) (W)	34.5	43.75	35.25	43.75	90.0	110.0	35.25	43.75	70.0	90.0	127.5
Box-girder details											
Number of boxes (N_{box})	3	5	3	5	9	11	3	5	7	9	15
Total superstructure depth (in)* (h)	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6
Top flange depth (in) (t_{top})	8.875	7.875	8.875	7.875	8.375	8.375	8.875	7.875	8.375	8.375	8.375
Bottom flange depth (in) (t_{bot})	6.0	6.0	6.5	6.5	6.5	6.5	7.0	7.0	7.0	7.0	7.0
Wall thickness (in) (t_{wall})	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Cell center-to-center spacing (ft) (L_{bg})	11.5	8.75	11.75	8.75	10.0	10.0	11.75	8.75	10.0	10.0	8.5
Number of restrainers (N_R)	10	12	10	12	20	32	10	12	20	26	34
Column footing details – Spring stiffnesses											
Translational (kip/in)	1700	800	1400	1200	1200	1200	1400	1200	1200	1200	800
Rotational (kip-in/rad)	4.1×10^7	0	6.5×10^7	0	0	0	6.5×10^7	0	0	0	0

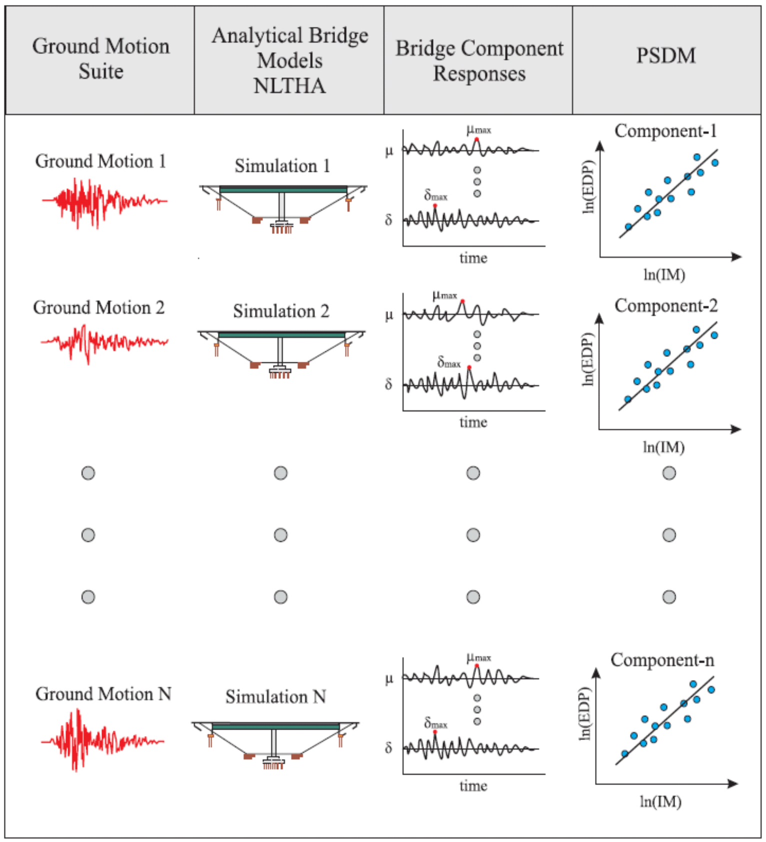
*Proportioned based on permissible depth-to-span ratio: 0.055 for CIP reinforced concrete and 0.04 for CIP prestressed concrete

g2F Methodology: Analysis for Demand Models

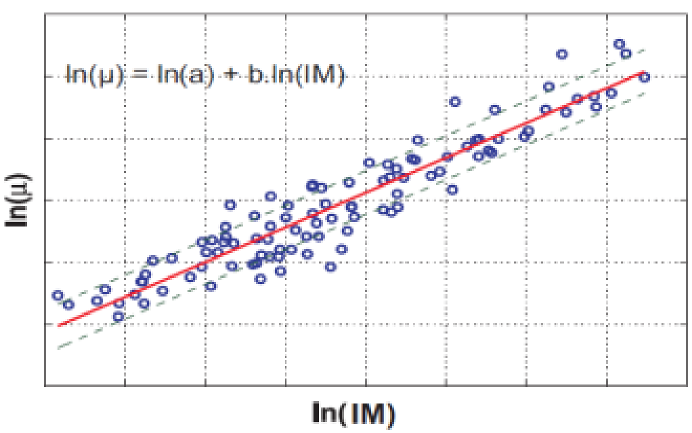
Non-Linear Time-History Analysis



Stochastic Method



Seismic Demand Model (1 Per Component Response)



g2F Methodology: Phase-1 Damage State Framework

Damage State Criteria

BSST-0 BSST-1 BSST-2 BSST-3

ShakeCast Inspection Priority Levels	None[1]	Low	Medium	Medium-High	High
Bridge System States[2] ("Inspecting for possible ...")	BSS-0 No Bridge Damage	BSS-1 Slight Bridge Damage	BSS-2 Moderate Bridge Damage	BSS-3 Extensive Bridge Damage	BSS-4 Complete Bridge Damage
Component Damage Range[3]					
Primary Components[4]	Below CDT-0	CDT-0 to CDT-1	CDT-1 to CDT-2	CDT-2 to CDT-3	Above CDT-3
Secondary Components[5]	Below CDT-0	CDT-0 to CDT-2	Above CDT-2	na	na
Likely Immediate Post-Event Traffic State	Open to Normal Public Traffic - No Restrictions	Open to Normal Public Traffic - No Restrictions	Open to Limited Public Traffic - Speed/Weight/Lane Restrictions	Emergency Vehicles Only - Speed/Weight/Lane Restrictions	Closed (Until Shored/Braced) - Potential for Collapse
Traffic Operations Implications[6]					
Closure/Detour Needed?	Very Unlikely	Very Unlikely	Unlikely	Likely	Very Likely
Traffic Restrictions Needed?	Very Unlikely	Unlikely	Likely	Very Likely	Very Likely - Detour
Emergency Repairs Implications[6]					
Shoring/Bracing Needed?	Very Unlikely	Very Unlikely	Unlikely	Likely	Very Likely
Roadway Leveling Needed?	Very Unlikely	Unlikely	Likely	Very Likely	Very Likely - Detour

Components Considered

Primary Components (Affects ALL System States)
- a) Columns
- b) Joint Seat/Gap Combinations

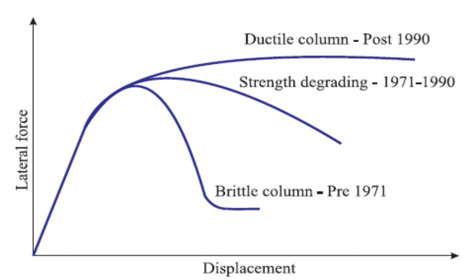
Secondary Components (Affects LOWER System States)
- a) Joint Seals
- b) Bearings
- c) Restrainers

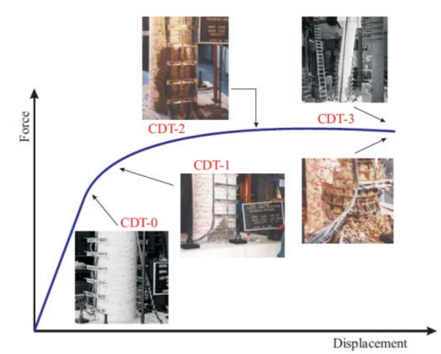
General Distress Indicators (Like Secondary w/o Damage Model)
- a) Overall Bridge Response @ Deck Level
- b) Foundation Response
- c) Abutment Response

OVERALL BRIDGE SYSTEM

Example for Columns:

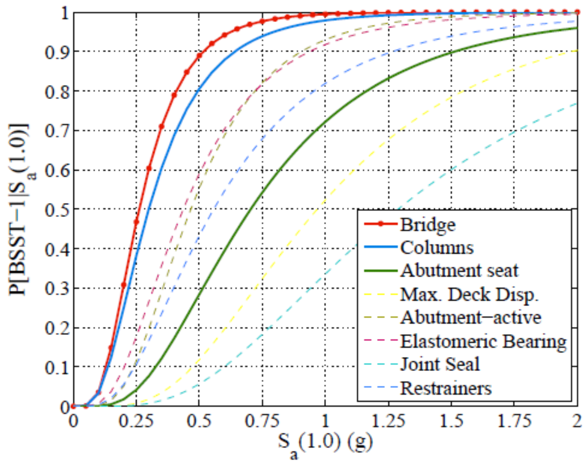
Component Performance Group	Group Common Name	Engineering Demand Parameter for CDT's	Component Damage Threshold CDT-0	CDT-1	CDT-2	CDT-3	Lognormal Dispersion Value	+2σ/μ Ratio
Columns		Curvature Ductility (μ_ϕ)						
DU	Ductile Column		1.0	4.0	8.0	12.0	0.35	2.0
SD	Strength-Degrading Column		1.0	2.0	3.5	5.0	0.35	2.0
BR	Brittle Column[1]		0.8	0.9	1.0	1.2	0.35	2.0



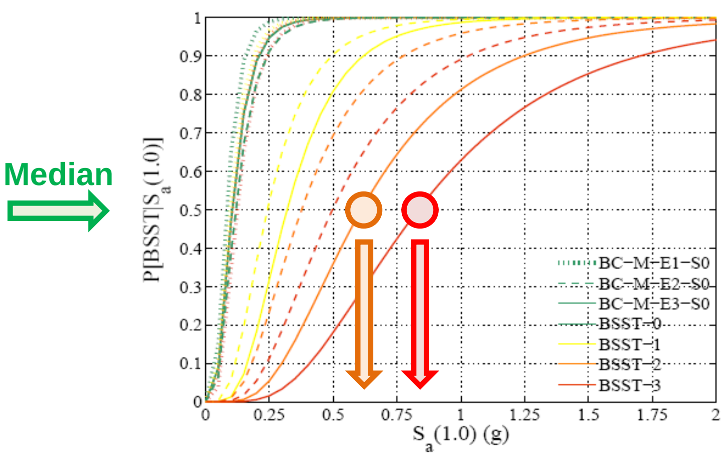


g2F Methodology: Example Outputs

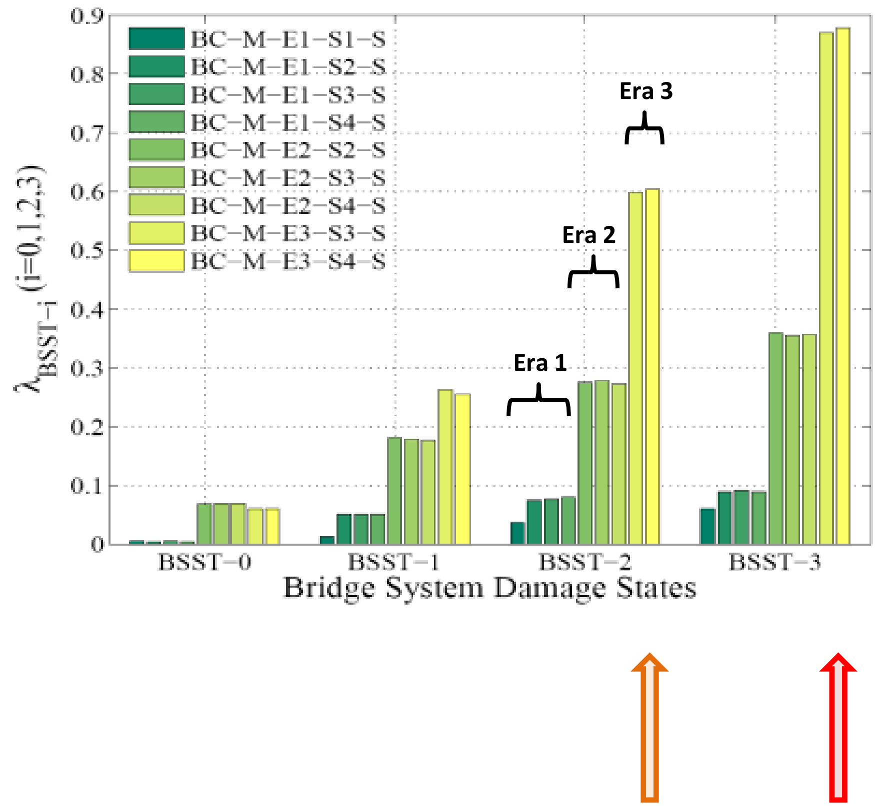
Component Fragility Curves
(1 System State, 1 Era)



System Fragility Curves
(4 System States, 3 Eras)



Trends - Illustrating Influence of Design Era & Seat Type
(4 System States, 3 Eras, 4 Seat Options)



Phase-1 Feasibility Study: Systems Considered

ALL Systems

Abutment Types: Diaphragm; Seat (4 Widths, 2 Gaps)

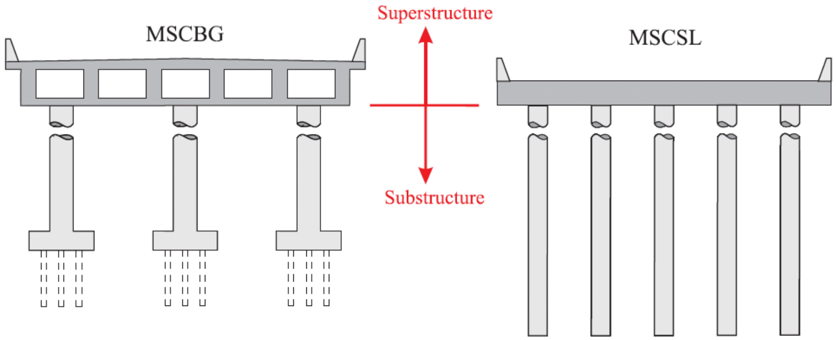
Design Eras: E1 (pre-1971); E2 (1971-1991); E3 (post-1991)

Box Girder (2-Span):

Interior Support: Multi-Column & Single-Column Bents

Slab (3-Span):

Interior Support: Pile Extensions Only

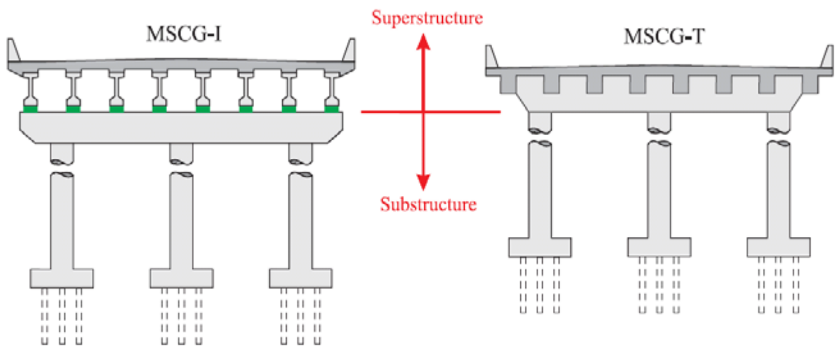


I-Girder (3-Span):

Interior Support: Multi-Column & Single-Column Bents

T-Girder (3-Span):

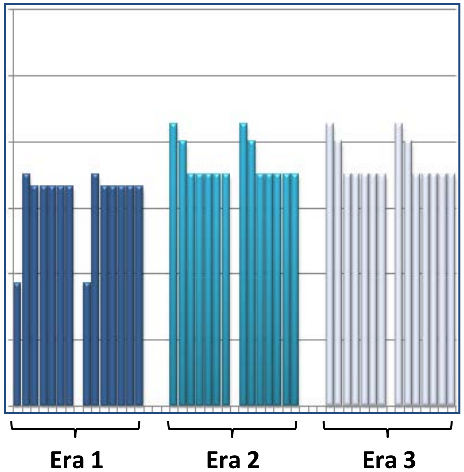
Interior Support: Multi-Column Bent & Pile Extensions

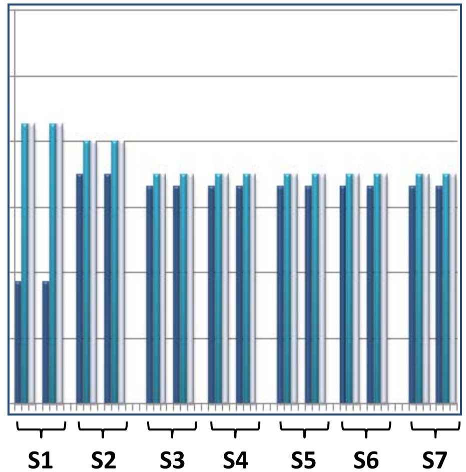


Ph-1 Results: Preliminary Trends for Different Bridge Systems & Eras

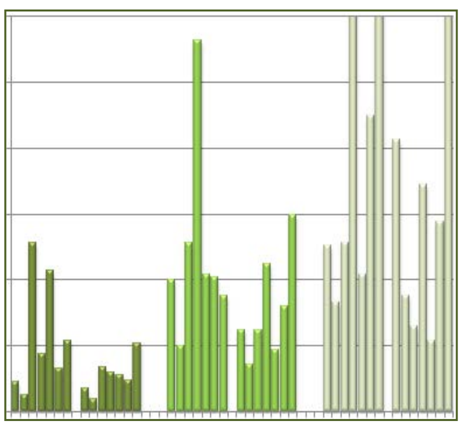
Multiple Systems by Era / 3 Era's Grouped by System

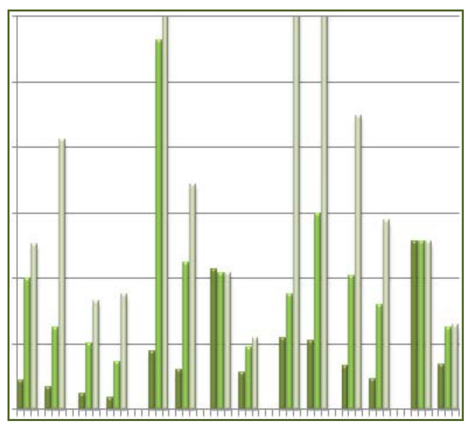
HAZUS MR4





Phase-1 g2F (Prelim)





All results shown are for "Complete Damage" state and zero skew.

Key Observations

- HAZUS treats most[1] continuous concrete bridge systems as essentially the same class:
  - Design Era (pre-1971, 1971-1991, post-1991)
  - Design Type (box-girder, tee-girder, I-girder, slab)
  - Subsystems (abutment, interior support)
- g2F *numbers* are preliminary, but *general trends regarding variability* are valid:
  - Numbers will certainly change as capacity models are revised in Phase-2
  - May be refinements to bridge classes/sub due to g2F taxonomy revisions
  - May be refinements to assumptions/details of bridge models used in Phase-1 NLTHA
  - Trends based on consistent and thorough methodology
- Phase-1 g2F vs. HAZUS:
  - g2F shows much greater increase in resiliency with design era[2] (say >4x)
  - g2F shows much greater variability between systems/sub within same era (also say 4x)

[1] Pre-1975 single-column box girder treated as much different system by HAZUS

[2] Exception are systems supported by pile extensions which were assumed to have the same capacity model for all eras.

g2F Project: Transition to Phase 2

Key Outcomes from Phase-1:

- Feasibility of overall methodology was successfully demonstrated for simple bridge systems.
- ID'ed significant potential for improved fragility models using more *granular* g2F taxonomy.
- Challenges exist for classifying bridges using available information resources (w/o plan review).
- Capacity models need to be refined/optimized.

Initial Directions for Phase-2:

- Refine g2F bridge taxonomy:
  - a) Develop basis of elements *thought to be important* to seismic bridge performance
  - b) ID elements that *can be assigned* using existing/emerging information assets
- Conduct sensitivity studies:
  - a) ID elements *demonstrated to be important* to performance (unique and significant effect)
  - b) Optimize computational workplan (combine PSDM's as possible)
  - c) Anticipate deployable form (base models and adjustment factors)

Emerging g2F(alpha) Taxonomy: Background

Form:

- Two Code Strings: CBC (~6-7 Elements) & SPS (~6-9 Elements)
- Each Element *Thought to* Contribute to Seismic Performance of Class (Know More as Project Progresses)
- Confidence Metric for Each Element Assignment and for Overall Code

Generation-2 Fragility (g2F) Taxonomy Summary	Code	Code Confidence Metrics: Code Component (3 max each)	Code Confidence Metrics: Completeness [%]	Code Confidence Metrics: Combined Index (3 max)
Conventional Bridge Class (CBC)	M-CG-TG-MU-Xx-CD-MB	3-3-3-1-1-2-3		
Seismic Performance Subclass (SPS)	X-X-X-X-X-X-X-X-X	0-0-0-0-0-0-0-0-0		

Data Sources:

- SMART (NBI+ Parameters, Structure Description, etc.)
- ELI Elements (Counts of Columns, Seals, Bearings, etc.)
- Joint Data (Location, Movement Rating, etc.)
- Yashinsky DB (Retrofit Years, STRAIN Vulnerabilities, etc.)
- ARS Online (Estimate of Design Ground-Motion)
- Other

Uses:

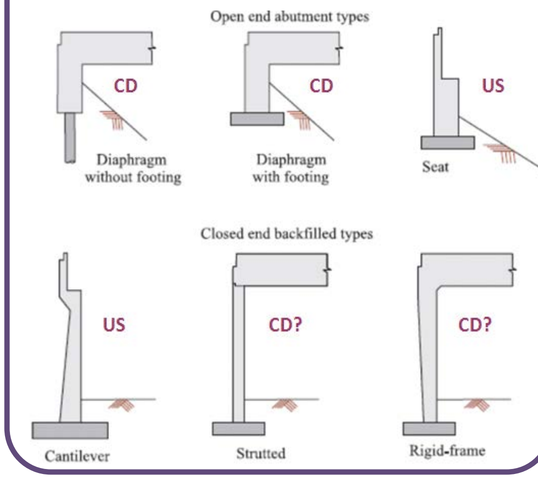
- Counts – ID Most Common Systems & Realistic Combinations
- Look Up Plans – Create Bridge Lists – Sampled Randomly to Capture Class/Sub Statistics for Modeling
- ShakeCast Assignment of g2F Models (NOTE: Multiple Taxonomy Subclasses May Be Assigned Same Fragility Model)
- Confidence Metrics Used To:
  - Aid ShakeCast Assignment – ID Bridges Needing Plan Review
  - Quantify Information Needs (Along with Importance Informed by Sensitivity Study)
  - Track Information Quality Over Time (As Improvements Incorporated)

Emerging g2F(alpha) Taxonomy: CBC Elements

Elements of Conventional Bridge Class (CBC):

- Span Range
- Bridge Material {Concrete, Steel, Mixed, Other}
- Bridge Type {Box Girder, T-Girder, I-Girder, Slab, Culvert, Other}
- Bridge System {Multispan Simple, Multispan Continuous Options}
- Connectivity @ Supports {Non-Integral Options, Integral Options}
- Abutment Coupling {Coupled-Diaphragm, Uncoupled-Seat}
- Interior Support {Single & Multi-Column Bent, Pier Walls, Extensions}

Options for Abutment Coupling



Options for 'Multispa Continuous' Bridge System & Connectivity

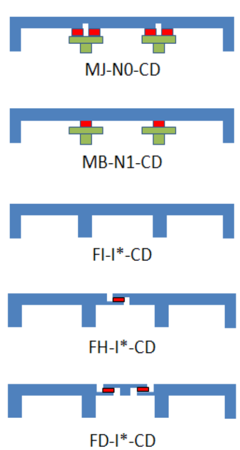
Multispan Continuous: Multiple Joined Beams[2]

Multispan Continuous: Supported Single Beam[2]

Multispan Continuous: Integral Frame[2]

Multispan Continuous: Hinged Frame[3]

Multispan Continuous: Frame w/ Drop-In Span[3]



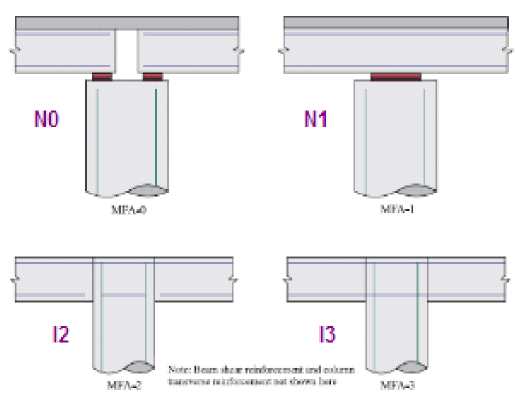
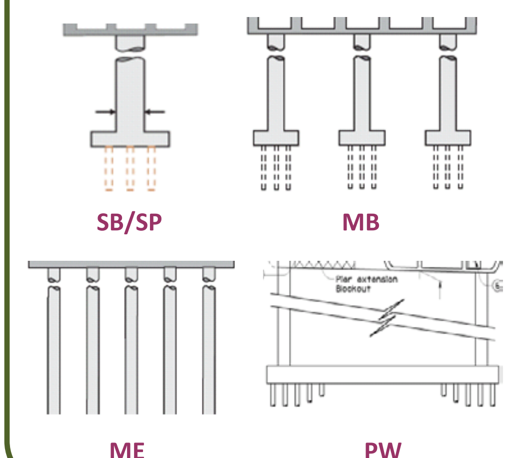


Figure 3.9: Schematic of superstructure to substructure connectivity types

Options for Interior Support



Emerging g2F(alpha) Taxonomy: SPS Elements

Elements of Seismic Performance Subclass (SPS):

- **Seismic Code Era** {E1: pre-1971, E2: 1971-1991, E3: post-1991}
- **Support Ductility** {Brittle, Strength Degrading, Ductile}
- **Seat Width (Abut, Joint)** {S0: None, S1: <12”, S2: 12”-18”, S3: 18”-24”, S4: >24”}
- **Joint Gap** {None, Small: MR <= 2”, Large: MR >2”}
- **Design Motion** {Low: SA1 <0.3g, Moderate: 0.3g-0.75g, High: >0.75g}
- **Skew** {Low: <15 deg, Moderate: 15-30 deg, High: >30 deg }
- **Curved Bridge** {TBD – Flag Y/N or Curvature Based}
- **Balanced Frame** {TBD – Flag Y/N}
- **STRAIN Vulnerabilities** {TBD – Grouped by SCORE Rating}

Ph-2 Challenge: Balanced Model Granularity

Bridge Information Constraints:

- Unusual Bridge
- Insufficient or Conflicting Information

g2F Bridge Type		g2F Bridge Material: Concrete CG	Concrete MC	Steel SG	Steel MS	Misc./Mixed Materials MD	Misc./Mixed Materials OT	Misc./Mixed Materials UK	Total by Type
Main Types									
Box Girder	BG	7839	163	23	0	3	0	0	8028
Tee Girder	TG	2901	14	0	0	0	0	2	2917
I Girder	IG	1015	52	2133	4	8	539	0	3751
Slab	SL	5703	35	15	0	6	20	3	5782
Culvert	CV	3307	0	264	0	3	9	10	3593
Misc. Types	MX	180	323	70	4	262	28	1	868
	OT	351	0	252	0	1	51	38	693
	NC	265	10	37	1	9	13	0	335
Error Types	UK	33	0	18	0	1	4	52	108
	ER	8	0	1	0	0	0	0	9
Main Types Total:		20765	264	2435	4	20	568	15	24071
Total by Material:		21602	597	2813	9	293	664	106	26084

Interior Support	Simple Supp (all Spans) MS	Unjointed (FI, MJ, MB) MU
NA3	0	0
NA2	0	0
NA1	0	0
SB3	3	583
SB2	0	193
SB1	0	36
SP3	0	19
SP2	0	0
SP1	0	47
PW3	0	124
PW2	4	212
PW1	1	67
MB3	11	2433
MB2	1	48
MB1	4	172
ME3	0	5
ME2	0	0
ME1	0	6
OTHER	1118	7
Total by System:	26	5063

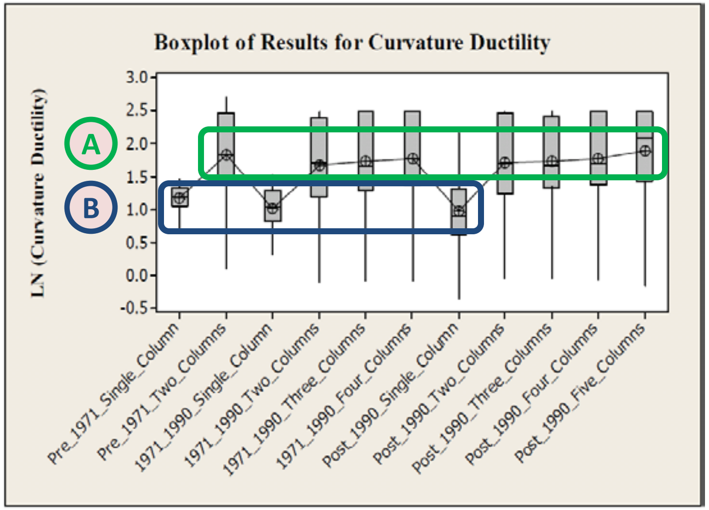
Model Complexity:

- Importance of class element (toward isolating *distinct* response … within other uncertainties)
- Handling in model: BSSTx = Base Value for Class/Subclass * Adjustment Factors (Class/Global)

Scenario	Is Element Important?	Can Element Be Assigned?	Action
A	Yes	Yes	Incorporate into g2F models
B	Yes	No	Incorporate *capability* into g2F models, and provide model for current uncertainty
C	No	Yes/No	Remove from g2F models (may or may not retain in taxonomy)

GT Sensitivity Study Example: 2-Span Box Girder – Diaphragm Abutments

Grouping Based on Column Ductility Only



Level	Number of observations (N)	Mean value (µ)	G A by Fischer M	B
Post_1990_Five_Columns	25	6.606	A	
Pre_1971_Two_Columns	24	6.246	A	
1971_1990_Four_Columns	26	5.859	A	
Post_1990_Four_Columns	27	5.830	A	
Post_1990_Three_Columns	26	5.686	A	
1971_1990_Three_Columns	27	5.607	A	
Post_1990_Two_Columns	26	5.485	A	
1971_1990_Two_Columns	27	5.349	A	
Pre_1971_Single_Column	21	3.222		B
1971_1990_Single_Column	23	2.773		B
Post_1990_Single_Column	28	2.659		B

Considering All EDP's (Same Method)

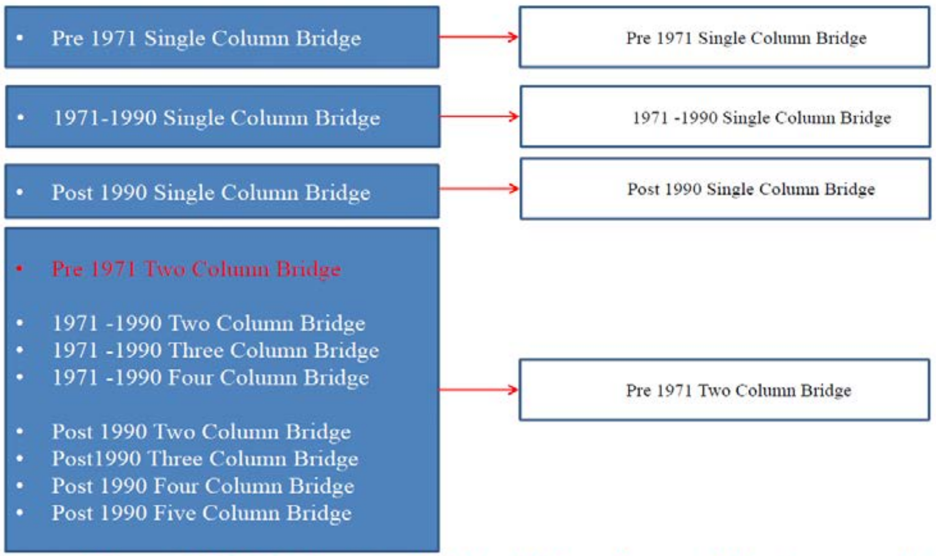
Mean Value of at least one bridge configuration is different for

- *Column Ductility*
- *Foundation Translation*
- *Foundation Rotation*

Mean Value of bridge configuration is same for

- *Deck Displacement*
- *Abutment Passive*
- *Abutment Active*
- *Abutment Transverse*

Overall Grouping (Considering All EDP's)

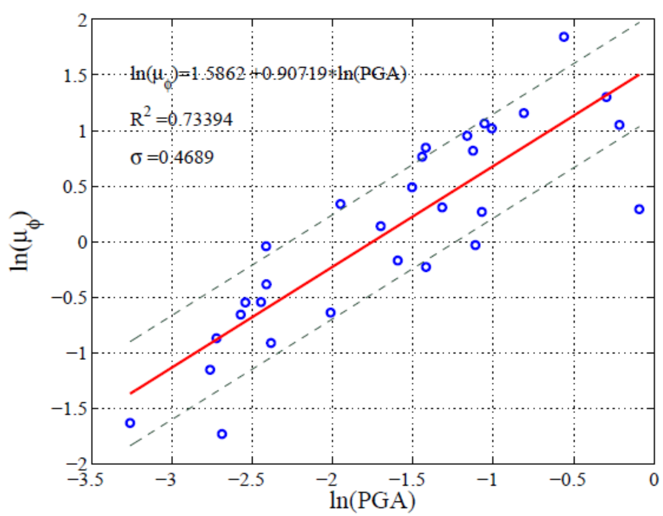


Current ANOVA study states that 4models (one from each box) are enough to calculate the demand models instead of 11 models

GT Sensitivity Study Example: 2-Span Box Girder – Diaphragm Abutments

Sanity Check – Compare PSDM Coefficients

$$\ln(demand) = a + b*\ln(intensity)$$



PSDM curve for 1971-1990 Single column bridge

A

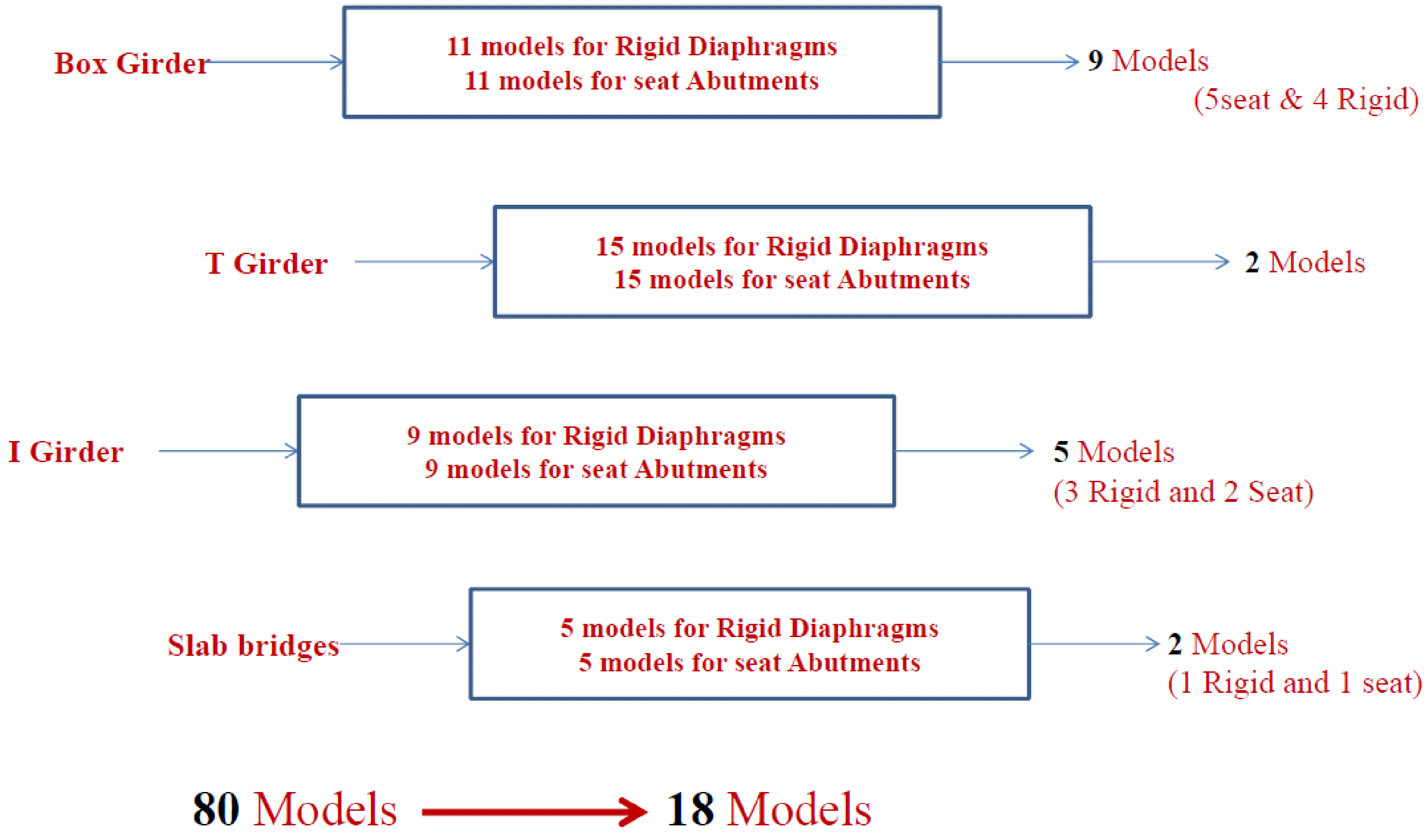
Column ductility	Regression coefficient	
	a	*b*
Pre 1971 Two Column	2.587	1.1428
1971-1990 Two Column	2.182	1.1385
Post 1990 Two Column	2.235	1.1333
1971-1990 Three Column	2.212	1.1159
Post 1990 Three Column	2.284	1.1191
1971-1990 Four Column	2.342	1.1185
Post 1990 Four Column	2.320	1.1384
Post 1990 Five Column	2.498	1.0999

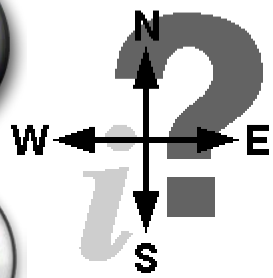
	Column ductility	Regression coefficient	
		a	*b*
B	Pre 1971 Single Column	1.6308	0.8479
C	1971-1990 Single Column	1.4334	0.9148
D	Post 1990 Single Column	1.8530	1.5154

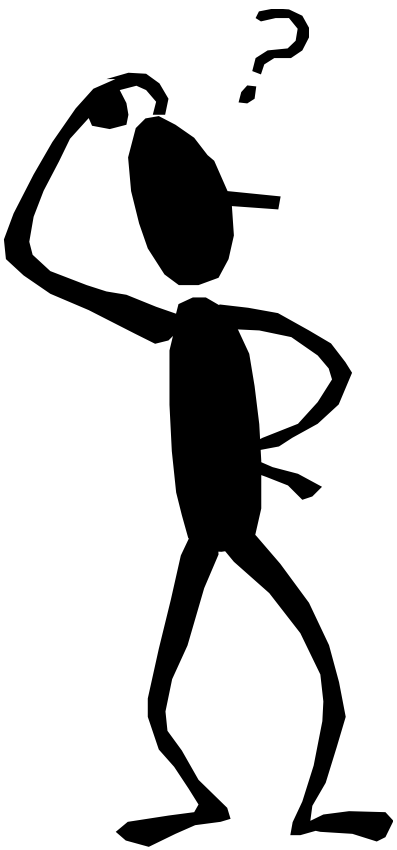
Interpretation

- **Only considering demand models here – There will be more fragility models once combined with capacity models for different eras.**
- **Single-column vs. multi-column bents clearly show distinct performance for *column ductility* demand. The effect of 'design era' has little effect on PSDM for 2-span case, especially for multi-column models.**
- ***Chose* to refine single-column models based on consideration of secondary EDP's (i.e. foundation translation/rotation).**

GT Sensitivity Study: Proposed PSDM Groups (2-3 Span Only)







Stay Tuned!

Questions?