Evolution of AASHTO-Based Bridge Design

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Topics

• Brief history of the AASHTO Bridge Specs
• How and why of AASHTO LRFD
• Continued evolution to date
• Near term future
• Learning Lesson From Failures
A Brief History of U.S. Bridge Design Codes

• 1870’s – Bridge Specs start to appear
  – Individual engineers
  – RR companies

• 1912 – Henry B. Seaman in T.ASCE says special specs used for each bridge conforming to loads and span

• 1924 – AASHO *Standard Specifications for Steel Highway Bridges* in USDA Bulletin
A Brief History (Continued)

• 1920’s - Special Committee on Specifications for Bridge Design and Construction
• Presented to ASCE on April 9, 1924
• Partially incorporated into 1St Edition of AASHO Standard Specifications - 1931
Start of Interstate Era – 1953
AASHTO Standard Specifications

• Impact – as in 1931
• Multiple Presence – 100%, 90%, 75%, never changed in Std Spec
• GDF – S/5.5 wheel loads
• Traffic Lanes – 12 ft with truck or lane in 10 ft more or less like now
A Brief History – Overview

• 1970’s AASHO becomes AASHTO
• 1971 AASHTO adopts LFD
• Late 1970’s OMTC starts work on limit-states based OHBDC
• 2nd Ed – 1983 - Seminal
1986 AASHTO Explores Need to Change

• NCHRP 20-7/31 “Development of Comprehensive Bridge Specs and Commentary”
• Assess the feasibility of a probability-based specification.
• Prepare an outline for a revised AASHTO specification.
May 1987 HSCOBS - A Turning Point

- Findings of NCHRP Project 20-7/31 presented.
- Funding requested to initiate NCHP Project 12-33 - “Development of Comprehensive Specification and Commentary”.
Development Objectives

- Technically state-of-the-art specification.
- Comprehensive as possible.
- Readable and easy to use.
- Keep specification-type wording – do not develop a textbook.
- Encourage a multi-disciplinary approach to bridge design.
- Use available past work – no new research intended
Constraints

• Do not allow for further deterioration.
• Do not explicitly allow future increase in truck weights.
• No requirement to make bridges uniformly “heavier” or “lighter”.
Major Changes

A new philosophy of safety - LRFD

• Identification of four limit states

\[ \Sigma \eta_i \gamma_i Q_i \leq \phi \quad R_n = R_r \]

• Calibration established a relationship among the chosen reliability level, the load and resistance factors, and load models
LRFD - Basic Design Concept

\[ \phi = \frac{\lambda \sum \gamma_i x_i}{Q + \beta \sqrt{\sigma_R^2 + \sigma_Q^2}} \]
Major Changes

- Revised calculation of load distribution

\[ g = 0.075 + \left( \frac{S}{2900} \right)^{0.6} \left( \frac{S}{L} \right)^{0.2} \left( \frac{K_g}{Lt^3} \right)^{0.1} \]

Circa 1990
Major Changes (Continued)

- Combine plain, reinforced and prestressed concrete.
- Modified compression field/strut and tie.
- Limit state-based provisions for foundation design.
- Expanded coverage on hydraulics and scour.
- The introduction of the isotropic deck design.
- Expanded coverage on bridge rails.
- Inclusion of large portions of the AASHTO/FHWA Specification for ship collision.
Major Changes (Continued)

• The development of a parallel commentary.
• New Live Load Model – HL93 - Continuation of a long story

“The customary loading assumed for the design of highway bridges in the past has been a certain uniform live load alone, possibly a typical heavy wagon or road-roller, or a uniform live load with a concentration….

But these older types of loading are inadequate for purposes of design to take care of modern conditions; they should be replaced by some types of typical motor trucks.”
1931 Edition Design Live Load

- 20 ton single unit “box truck” – H20
- H15, H10 for lesser roads
- Truck train for longer spans – groups of H15 with occasional H20
- Lane load specified for special circumstances – never updated
- Proportional lane loads for H<20
- Dynamic effect included
1923 AREA Specification

10-Ton  15-Ton  20-Ton
4k      6k      8k      16k      24k      32k
14'

VERY CLOSE TO 1931 Edition!!
1928-1929 Conference Specification

- 6k 24k 14' 30'
- 6k 24k 14' 30'
- 8k 32k 14' 30'
- 6k 24k 14' 30'
- 6k 24k 14' 30'

- 15-Ton
- 15-Ton
- 20-Ton
- 15-Ton
- 15-Ton

- 18,000 lb for Moment
- 26,000 lb for Shear

- 640 lb/ft
Design for Live Load is More Than Just the Truck or Lane Load

- 1931 Edition used:
- Impact – $50/(L+125)$
- Traffic Lanes – 9 ft – Crowd but don’t overlap
- Multiple Presence – Function of curb-to-curb width: Between 18 ft and 43 ft reduce LL by 1% per ft
- GDF – For 2 or more lanes and S up to 10 ft - $S/5.5$, for $S>10$ ft use lever rule
1941 AASHTO----HS20 (Almost)

- 8k
- 14'
- 32k
- 14'
- 32k

H20 - S16

640 lb/ft

32,000 lb for Moment

40,000 lb for Shear
1944 Agreement

• Much disagreement over HS Loading
• After 3 year study:
  • No HS Lane Load---use H20 Lane Load
  • Variable axle spacing adopted – more closely approximates “the tractor trailers now in use”
  • HS20-S16-44…..44 added to reduce confusion from so many changes
Mid 1940’s - H20-S16-44

Or the Lane Load

18,000 lb for Moment
26,000 lb for Shear

640 lb/ft
Live Load Continued to be Debated (Continued)

• Late 60’s – H40, HS25 and HS30 discussed
• 1969 – SCOBS unanimously opposed to increase “wasteful obsolescence” of existing bridges
• 1978 – HS25 proposed again
• 1979 – HS25 again – commentary –
  – need for heavier design load seems unavoidable
  – HS25 best present solution
  – 5% cost penalty
• Motion soundly defeated
Design vs. Operation

• 1956, U.S.C. Section 127, Title 23 Limited Loads on Interstate Highways
  – 18 K Single
  – 32 K Tandem
  – 73,280 Lb Max GVW

• Higher loads permitted if legal in a state prior to July 1, 1956 – “Grandfather Right” later termed “Exclusion Loads” in LRFD development
Further Increases

• Federal Amendments – 1974
  – 20 k axle
  – 34 k tandem
  – 80 k GVW
• Enforce Federal Bridge Formula
• 1980 – All states required to allow these loads on Interstates
• 1991 – Ratifies state practices for long combination (multi-trailer) vehicles – “LCV’s”
Federal Bridge Formula

\[ W = 500 \left\{ \left[ \frac{LN}{(N-1)} \right] + 12N + 36 \right\} \]

where:

- \( W \) = the maximum weight that can be carried on a group of two or more axles to the nearest 500 pounds (lb)
- \( L \) = the spacing between the outer axles of any two or more axles (ft)
- \( N \) = the number of axles being considered

Limits HS-15 bridge overstress to about 30%
LRFD LL - Configurations Considered

- AASHTO Rating Vehicle – 3
- NTWAC – 3
- Modified TTI – 4
- After Canadian Interprovincial – 5
- Extended Bridge Formula – 2
- Turner Trucks – 2
- “Exclusion” – 22
- Total – 38 Configurations
EXCL/HS20 Truck or Lane or 2 – 110 kN Axles @ 1.2 m
Selected Notional Design Load

“HL-93”

PROPOSED LOADS

- NEGATIVE MOMENT AND INTERIOR REACTIONS
- ≥ 50 FT
- FIXED WHEELBASE ON TRUCK = 14 FT
- 90%
EXCL/HL 93 – Moment (Shear Similar)
Reliability Calcs Done for M and V – Simulated Bridges Based on Real Ones

- 25 non-composite steel girder bridge simulations with spans of 30, 60, 90, 120, and 200 ft, and spacings of 4, 6, 8, 10, and 12 ft.
- Composite steel girder bridges having the same parameters identified above.
- P/C I-beam bridges with the same parameters identified above.
- R/C T-beam bridges with spans of 30, 60, 90, and 120 ft, with spacing as above.
Reliability of Standard Specifications vs. LRFD – 175 Data Points

RELIABILITY INDICES
1989 AASHTO

RELIABILITY INDICES
PROPOSED - PRELIM
Getting It Together

New LL

New GDF’s

New $\gamma$’s, $\phi$’s

Results
Summary of Live Load and Distribution

• What should you see in designs
  – Many designs will be similar, some won’t
  – If DF was “improved” the HL 93 will be muted
  – If DF unchanged HL 93 can be a big impact
  – Exterior often carries more LL
  – Shear often proportionately bigger change than moment
NCHRP 12-33 Project Schedule

- First Draft - 1990 – general coverage
- Second Draft - 1991 – workable
- Third Draft - 1992 – pretty close
- Fourth Draft - 1993 – ADOPTED!!
- 12,000 comments
- Reviewed by hundreds
- Available -1994
- First Major Bridge Opens In 1997
Evolution and Changes to 1990’s Technology

• 1996 foundation data reinserted.
• New wall provisions – ongoing upgrade.
• 2002 upgraded to ASBI LFRD Segmental Guide Specifications.
• MCF shear in concrete simplified and clarified several times – major updates in 2002 & 2007.
Evolution and Changes

- 2004 – major change in steel girder design in anticipation of………
- 2005 – seamless integration of curved steel bridges ending three decade quest
Evolution and Changes (Continued)

- 2005 – P/C loses updated
- 2006 – complete replacement of Section 10 – Foundation Design
- 2006 – more concrete shear options
- 2007 – big year
  - Streamline MCF for concrete shear design
  - 1,000 year EQ maps & collateral changes
  - Seismic Guide Spec - displacement based
  - Pile construction update
- 2008 – Coastal Bridge Guide Specifications
Near Term - Where Do We Go From Here?

• Calibration of Service Limit State
  – Often controls
  – Some action possible in 2015
• Quantification of redundancy
• Joint probability or multi-hazard events
  – Concurrent or cascading
Learning From Failures and Mistakes – their Influence on U.S. Bridge Codes and Practice
First Problem—Defining Failure

• Collapse – event easy to identify and agree on – cause is something else
• Inability to serve intended function
  – Lack of sufficient service strength
  – Misalignment
• Unsightly defect
  – Cracks
  – Misalignment
  – Discoloration
• Disproportionate future maintenance
• Shortened service life
How Does Profession React?

• Research
• Additions to design spec to design avoidance
• Changes to material specs
• Changes to fabrication or construction specs
• Add to Non-Spec “body of knowledge”
• Operational changes
• Policy changes
• Retrofits
• Mixtures

Let's look at some examples!!
Sunshine Skyway 1980
Sunshine Skyway

• Vessel hit side span pier which was not protected
• Response – design
  – Partly incorporated into AASHTO LRFD 1st ed
  – Updated in 2008
• Human factors and serendipity hard to eliminate
Webber Falls
Webber Falls

• Special structural features
  – Barge reversed-back exerts more load
  – Corner hit-less energy absorption
  – Hit weakest pier

• Reactions
  – Ops and Policy-Recommendation for alarms if active controls not sensed in some period of time
  – Retrofit-Similar bridges got pier protection added
Webber Falls - Retrofit
Silver Bridge

Point of failure initiation

(Close-up of the actual fractured eyebol)
Silver Bridge

• Reaction
  – Fracture Control plan
    • Materials-fracture toughness
    • Fabrication-welder quals and testing
    • Documentation
    • Weld repairs
  – Design Specifications
    • Identification of FCM and tension components
    • Toughness requirements identified but not used in design calcs
Silver Bridge

• Reaction-cont.
  – Policies
    • NBIS with special requirements for FCM’s
    • Redundancy stressed
    • Permit numerical demonstration of redundancy
  – Retrofits
    • Sister bridge demolished and replaced
    • Some redundancy enhancement
I-794 Hoan Bridge
(December 2000)
I-794 Hoan Bridge
I-794 Hoan Bridge

- All fractures were brittle (cleavage) initiation at the intersecting welds
- No fatigue crack growth was detected in the web at any shelf plate detail
- Lack of direct connection to the transverse connection plate created a large geometric crack like condition
- Crack like geometry and high triaxiality resulted in fracture
I-794 Hoan Bridge - Response

- FHWA Memorandum cites two criteria that can indicate fracture vulnerability
  - 1) Intersecting / Overlapping welds
  - 2) Evidence of rapid crack growth
- Body of Knowledge-Detailing guidance
  - ¼” RULE: Intersecting Weld Toes Must Have at Least ¼” of Clear Separation Toe-to-Toe to Allow Relief of Constraint
Fatigue

Yellow Millpond Bridge
Fatigue

- Response research on resistance & loads
- Much added to body of knowledge
Fatigue

- Response – Design Spec

\[ \gamma(\Delta f) \leq (\Delta F)_n \]

\[ N = (365)(75)n(ADTT)_{SL} \]

\[ (\Delta F)_n = \left( \frac{A}{N} \right)^\frac{1}{3} \]

\[ (\Delta F)_{n} = (\Delta F)_TH \]
Distortion Fatigue

- Tie Girder Exterior Web
- 3" Long Diaphragm Weld Crack
- Back Up Bar
- Stiffener
- Diaphragm
- Tie Girder Flange
Distortion Fatigue

• Response
  – Research
  – Body of knowledge from case studies
  – Specification – verboten details
  – No quantification in spec so far
Dynamic wind - First Tacoma Narrows
Wind - Response

• Research - identify Quasi-static pressure and understand dynamic phenomena
• Design Spec – “static” wind pressure and overturning line load
• Body of Knowledge on dynamic actions
  – Section models
  – Aeroelastic models
  – Terrain models
  – Computational methods
  – A variety of potential fixes
Section Model
Japanese Aeroelastic Tests
Wind/Rain - Cables
Reducing Cable Movement

- Various methods used to control cable movement
- Use of energy absorbing pads between cables and end of anchor pipes.
- Cross-tying the cable together.
- Modifying the cable shape to change the aerodynamic conditions.
- Installation of energy absorbers (or dampers) on the cables to reduce the cable vibration.
San Fernando 1971

• Response
  – Research-
    • Lab tests, particularly on column cyclic behavior
San Fernando 1971

- Response Cont.
  - Capitalize on building research – ATC 2, NEHRP
  - Shear failures
  - Bond and development
San Fernando 1971

- Response Cont
  - Design Specifications
    - ATC 6 Document lead to Div. I-A of Std Spec
    - SPC
    - Design Spectrum
    - R factors
    - Site factors

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\[
C_{sm} = \frac{1.2AS}{T_m^{2/3}} \leq 2.5A
\]

Note: Dotted line shows form of coefficient for Soil Type III when \( A_m \) is less than 0.3.
San Fernando 1971

• Response Cont
  – Design Specifications
    • Seat widths
    • Confinement
    • Plastic hinging
    • Bond and development
    • Methods of analysis

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Improvements to Seismic Spec

• 2007 AASHTO Changes to LRFD Spec
  – About 1000 yr event
  – New Maps-PGS and Peak Horiz spectral response Acceleration coefficient
Improvements to Seismic Spec

- 2007 AASHTO Changes to LRFD Spec
  - New response spectrum
  - Revised site factors
  - Uniform load method
  - More on $P - \Delta$
  - New provisions for Columns, foundations and much more
- New Guide Spec - Displacement based
Recent Observations

• Apparent good behavior of retrofits
  – Column Wrapping
  – Longitudinal Restrainers
Hurricane Damage

Over $2 Billion in bridge damage

09/09/2005
Coastal Design Spec

• Developed under FHWA research project
• Product of analysis and experimental work
Coastal Design Spec

- Empirical design equations based on extensive simulations using newly developed model of wave forces
- Adopted in 2008 as a “Guide Specification”
I-35W Collapse in Minneapolis
Gusset Plate Inspections
Gusset Plate Research NCHRP 12-84

Rating and Design Specs
Adopted 2012 Improved 2013

FEA Model
In Summary – Are There Other Limit States We Should Consider??

• Does current design address the real culprits?
• Where are owners spending maintenance $$?
• Do we know the impact of changes?
In Summary - Perfection is Still an Illusive Goal

Improvement is Possible and Demanded by Society - the Bar Keeps Rising!
Thank you!