Standard Procedures for Fatigue Evaluation of Bridges

Presentation for the

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by

Phil Sauser

Structural Engineer, Saint Paul District

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Fatigue Evaluation of Bridges

Topics

- ✓ Criteria
- ✓ Background
- ✓ Design Procedures
- ✓ Inspection Procedures
- ✓ Evaluation Procedures
- ✓ Results

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Fatigue Evaluation of Bridges

References

1. Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges (The Manual)
2. AASHTO LRFD Bridge Design Specifications
3. FHWA Bridge Inspector's Reference Manual
4. NCHRP Report 299, Fatigue Evaluation Procedures for Steel Bridges
5. Fracture and Fatigue Control in Structures, Barsom & Rolfe
6. 23 CFR Part 650 National Bridge Inspection Standards (NBIS)
7. ER 1110-2-111, Periodic Safety Inspection And Continuing Evaluation Of USACE Bridges

CRITERIA

NBIS

- ✓ Inspection Procedures
- ✓ Inspection Frequencies
- ✓ Inspector Qualifications
- ✓ References The Manual

The Manual

- ✓ Inspection Procedures
- ✓ Evaluation Criteria
- ✓ References the Bridge Design Specifications

CRITERIA

Bridge Design Specifications

- ✓ Fatigue Detail Categories
- ✓ Fatigue Strengths

CORPS, ER 1110-2-111

- ✓ Update Jan. 06
- ✓ Comply w/ Revised NBIS

BACKGROUND

Evaluation Methods

- ✓ Stress Life
- ✓ Strain Life
- ✓ Fracture Mechanics

Fatigue Types

- ✓ Load Induced
- ✓ Distortion Induced

Load Cycles

- ✓ Variable Amplitude
- ✓ Constant Amplitude

EVALUATION METHODS

Stress Life

- ✓ Strengths Based on Testing
- ✓ Fatigue strengths computed for a variety of components
- ✓ Strength is in terms of allowable stress vs. load cycles

Advantages

- ✓ Simple to Use
- ✓ Better Results for Long Life (Large N) & Constant Amplitude
- ✓ Large Amount of Data Available

Disadvantages

- ✓ Empirically Based, Limited to Testing Conducted
- ✓ Plastic Strains Ignored
- ✓ No Differentiation between Crack Initiation and Propagation

EVALUATION METHODS

Strain Life

- ✓ Strengths Based on Testing
- ✓ Fatigue strengths computed for a variety of components
- ✓ Accounts for Stress-Strain Response of Material

Advantages

- ✓ Accounts for Plastic Strain, Residual Stress
- ✓ Considers Cumulative Damage under Variable Amplitude
- ✓ Results can be Extrapolated to Complicated Geometries

Disadvantages

- ✓ More complicated (Numerical Integration Techniques)
- ✓ Accounts Only for Initiation Life

EVALUATION METHODS

Fracture Mechanics

- ✓ More Theory Oriented

Advantages

- ✓ Predicts Crack Growth, Failure
- ✓ Allows Monitoring of Cracks
- ✓ Gives Better Insight Into Behavior

Disadvantages

- ✓ Crack Size Must Be Known
- ✓ More Complex Analyses Required

BACKGROUND

FATIGUE TYPES

Load Induced

- ✓ In Plane Stresses
- ✓ Accounted For In Design
- ✓ Detail Sensitive

Distortion Induced

- ✓ Secondary Stresses
- ✓ Not Accounted For In Design
- ✓ Detail Sensitive

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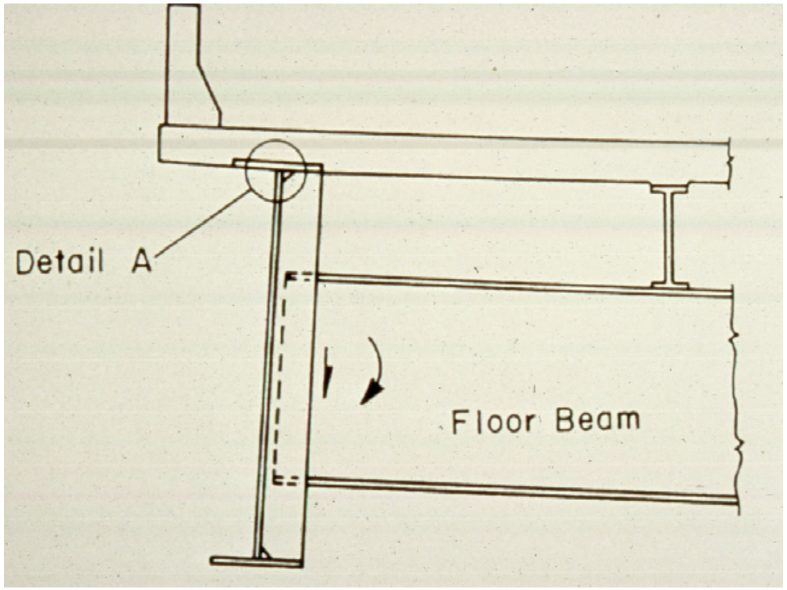
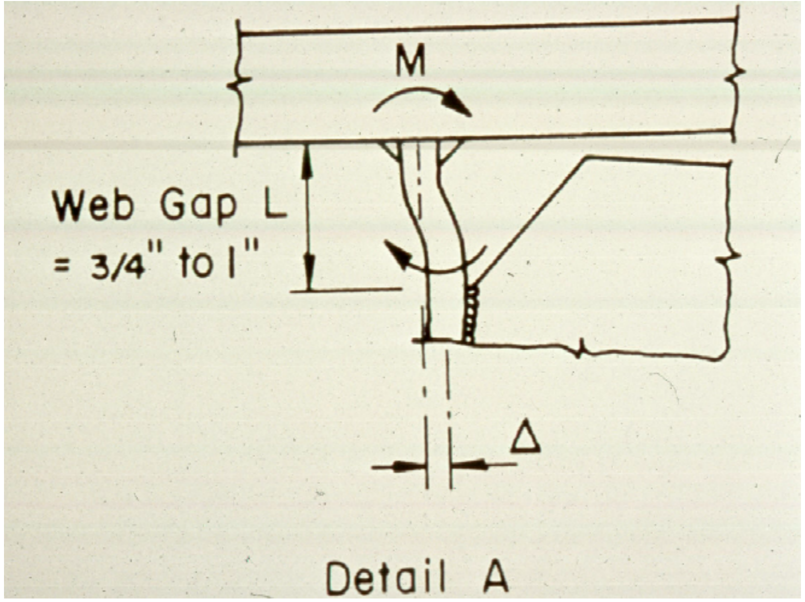
FATIGUE TYPES

Distortion Induced Examples





LOADING TYPES

LOADING TYPES

Constant Amplitude

- ✓ Stress Range Does Not Vary
- ✓ Test Applications

Variable Amplitude

- ✓ Random Sequence of Load History
- ✓ Realistic Behavior

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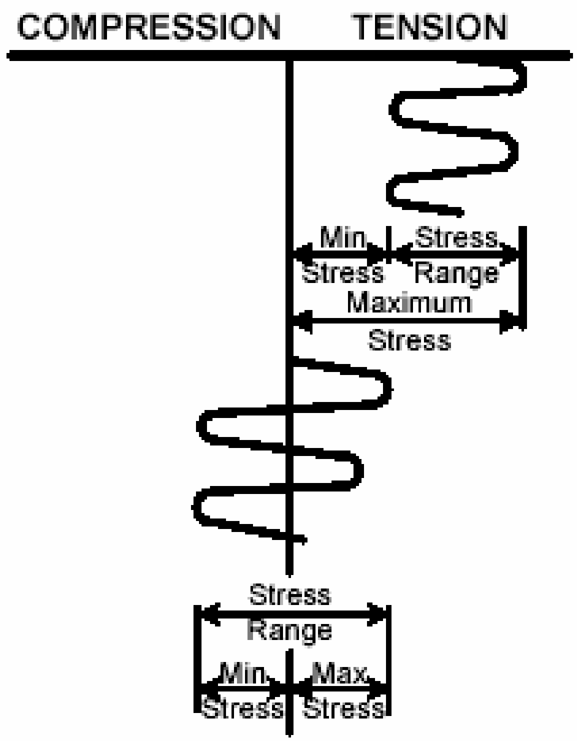
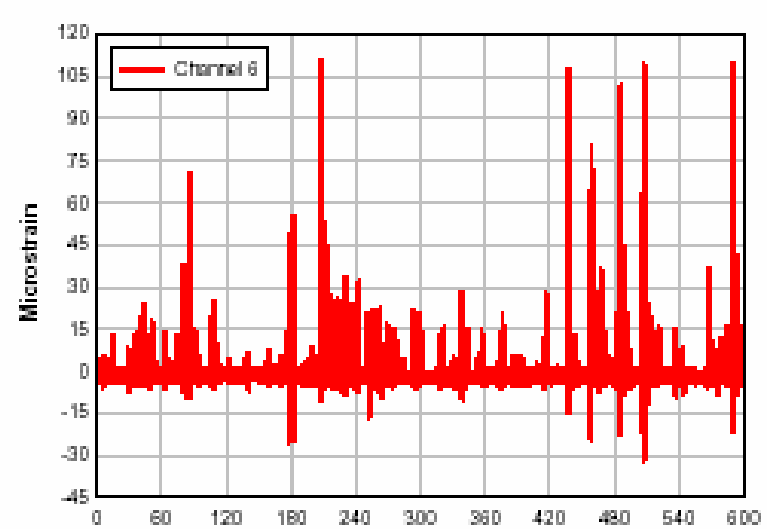
LOADING TYPES

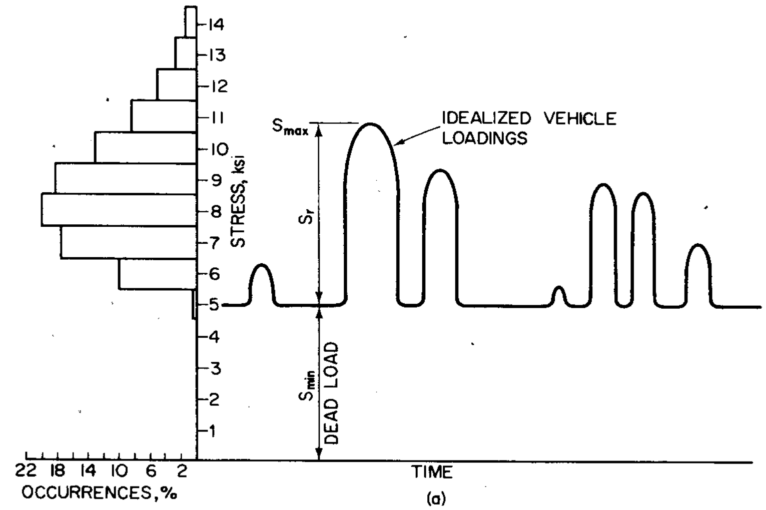
Constant Amplitude

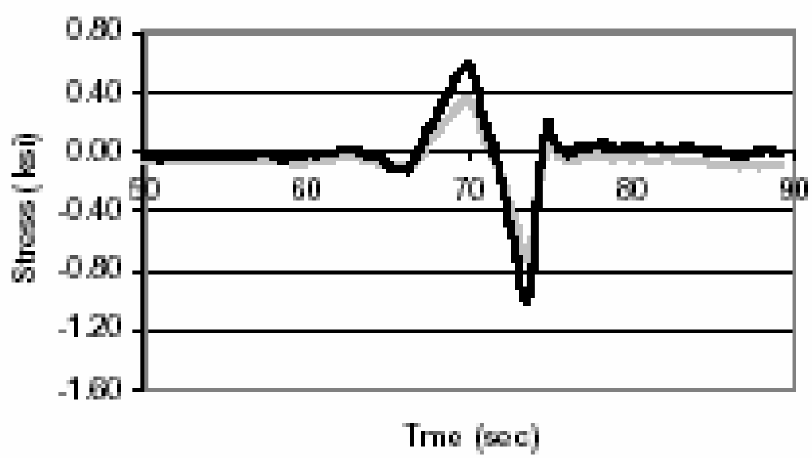


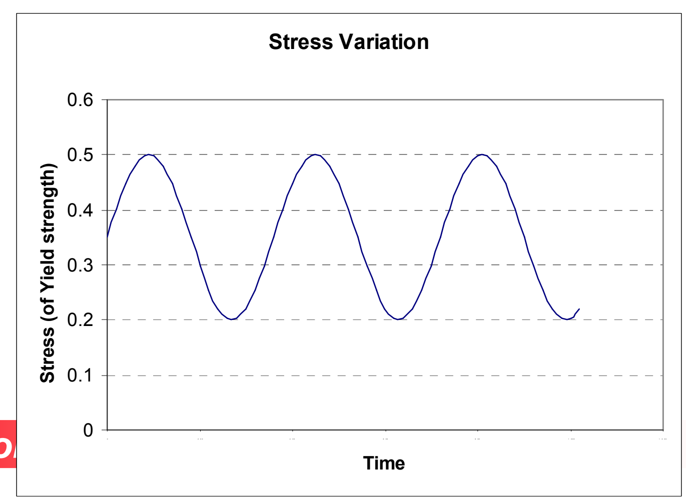
LOADING TYPES

Variable Amplitude







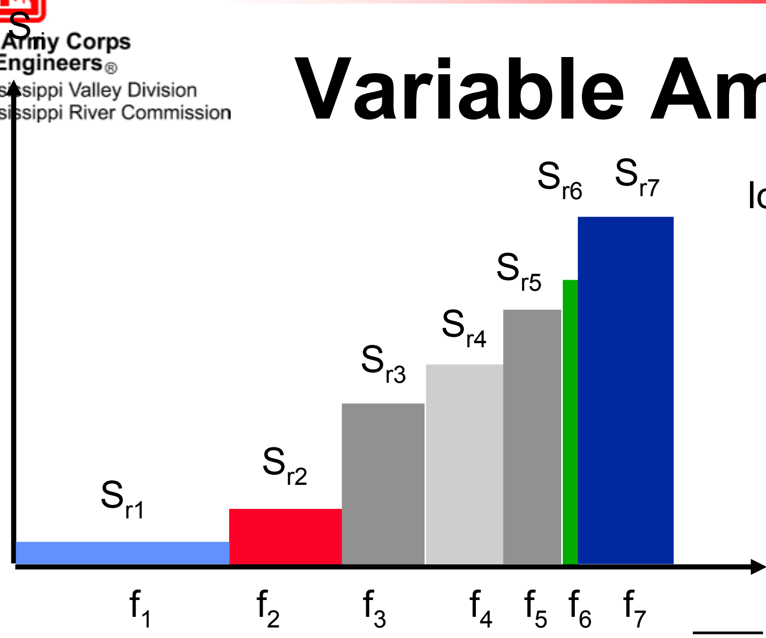


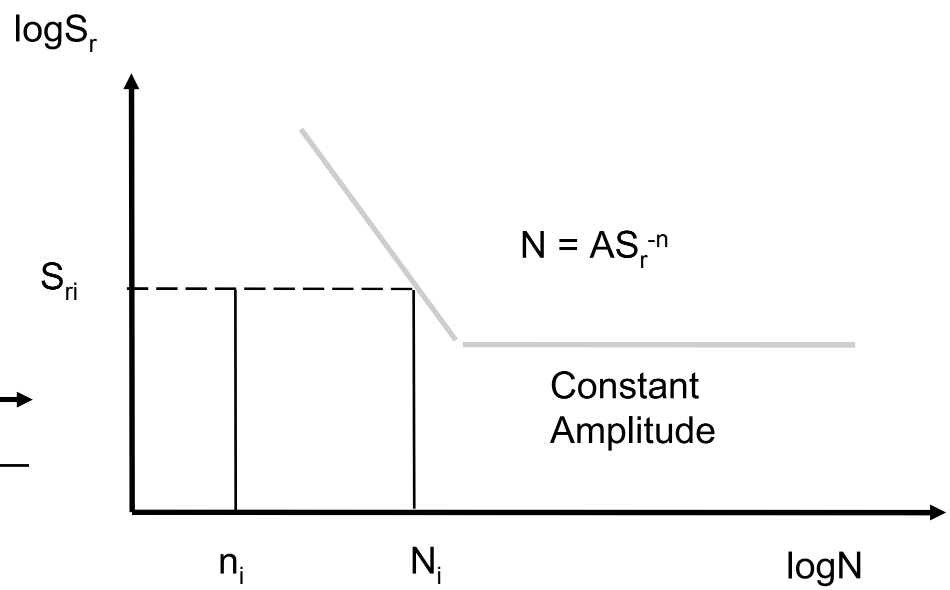
Variable Amplitude

Conversion to Constant Amplitude

- ✓ Compute Effective Stress
  - ✓ Equivalent constant amplitude stress range that produces the same fatigue damage as a variable amplitude spectrum
  - ✓ Effective stress range based on fatigue tests under simulated traffic
- ✓ Miner's Law
  - ✓ The fatigue damage caused by a given number of cycles of effective stress range (constant amplitude cycles) is the same damage caused by an equal number of variable stress ranges (variable amplitude).
  - ✓ Root Mean Cube (Log S vs. Log N fatigue curve)

Variable Amplitude Conversion





I	n_i	S_{ri}	f_i	$f_i S_{ri}^3$
1	4,500,000	0.1	0.792	0.001
2	800,000	0.6	0.141	0.030
3	140,000	5.6	0.025	4.390
4	232,000	7.8	0.041	19.457
5	3,900	10.2	0.0007	0.743
6	113	14.0	0.00002	0.055
7	2,300	15.0	0.0004	1.350
N_T= 5,678,313			1.0	26.026

$$S_{re} = \sqrt[3]{26.026} = 2.963..ksi$$

BACKGROUND

AASHTO METHOD

Load Induced Fatigue

- ✓ Uncracked, Unrepaired Members
- ✓ Does not consider distortion, corrosion, or other damage

Stress Life Approach

- ✓ S-N Curves
- ✓ Constant Amplitude Stress Ranges

Reliability Based Philosophy

- ✓ Statistics
- ✓ Data
- ✓ Variables

AASHTO METHOD

RELIABILITY

Random Variables

- ✓ Stress
  - ✓ Loads (truck weights, axle configurations, weight distribution, impact, multiple presence)
  - ✓ Load Distribution (analysis methods & assumptions, bridge behavior)
  - ✓ Section Properties
- ✓ Load Cycles
  - ✓ Traffic Volume
  - ✓ Stress Cycles
- ✓ Fatigue Strengths
  - ✓ Details (Real vs. Modeled)
  - ✓ Tests (Real vs. Laboratory)

AASHTO METHOD

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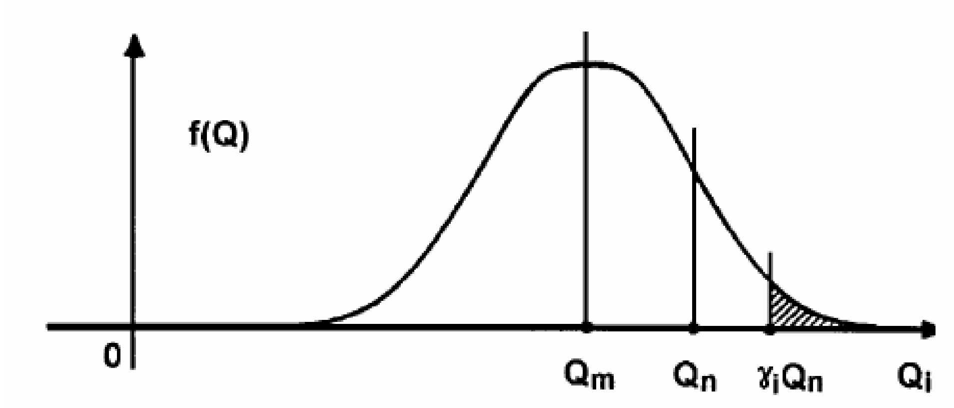
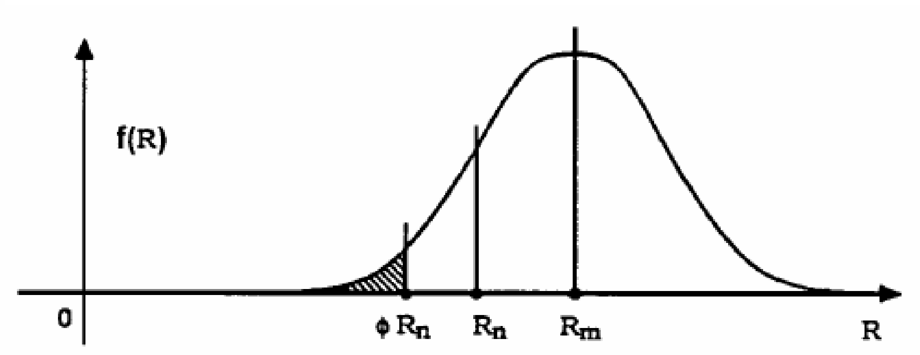
TARGET RELIABILITY



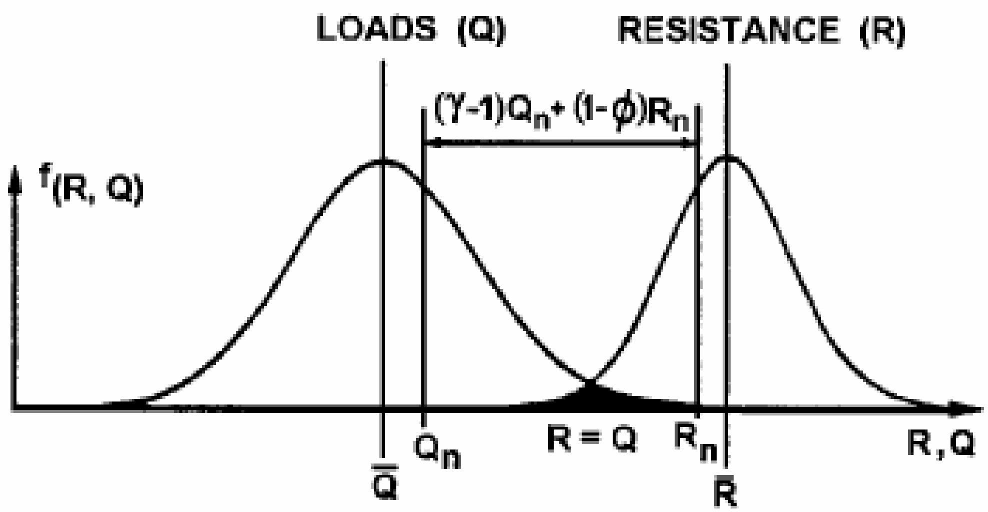


Loads **Resistance**

Probability Density Function

AASHTO METHOD

TARGET RELIABILITY



Loads Vs. Resistance

Probability Density Function

AASHTO METHOD

TRAFFIC LOADING

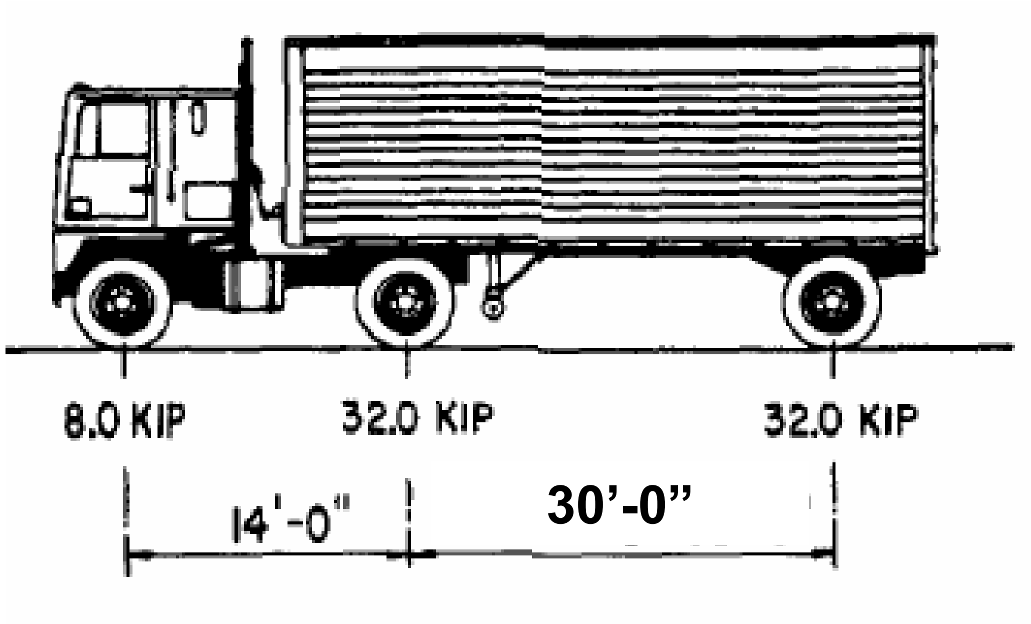
Fatigue Truck

- ✓ HS20 Truck with Constant 30' Spacing of Rear Axles
  - ✓ 0.75 Load Factor (54 kip)
  - ✓ Single Truck
  - ✓ Single Lane
  - ✓ Represent Typical Traffic

- ✓ WIM Studies
  - ✓ Effective Weight Calculated (Miner's Rule)
  - ✓ Used to Compute Constant Amplitude Loading Cycles

AASHTO METHOD

Fatigue Truck



AASHTO METHOD

FATIGUE STRENGTHS

S-N Curves

- ✓ Test identical details at different effective stress ranges
- ✓ Typical Relationship for Steel: $S_r = AN^b$
- ✓ b = -1/3
- ✓ Log-Log Plot
- ✓ Threshold Limit

Stress Limit Influences

- ✓ Stress Concentrations
- ✓ Residual Stress

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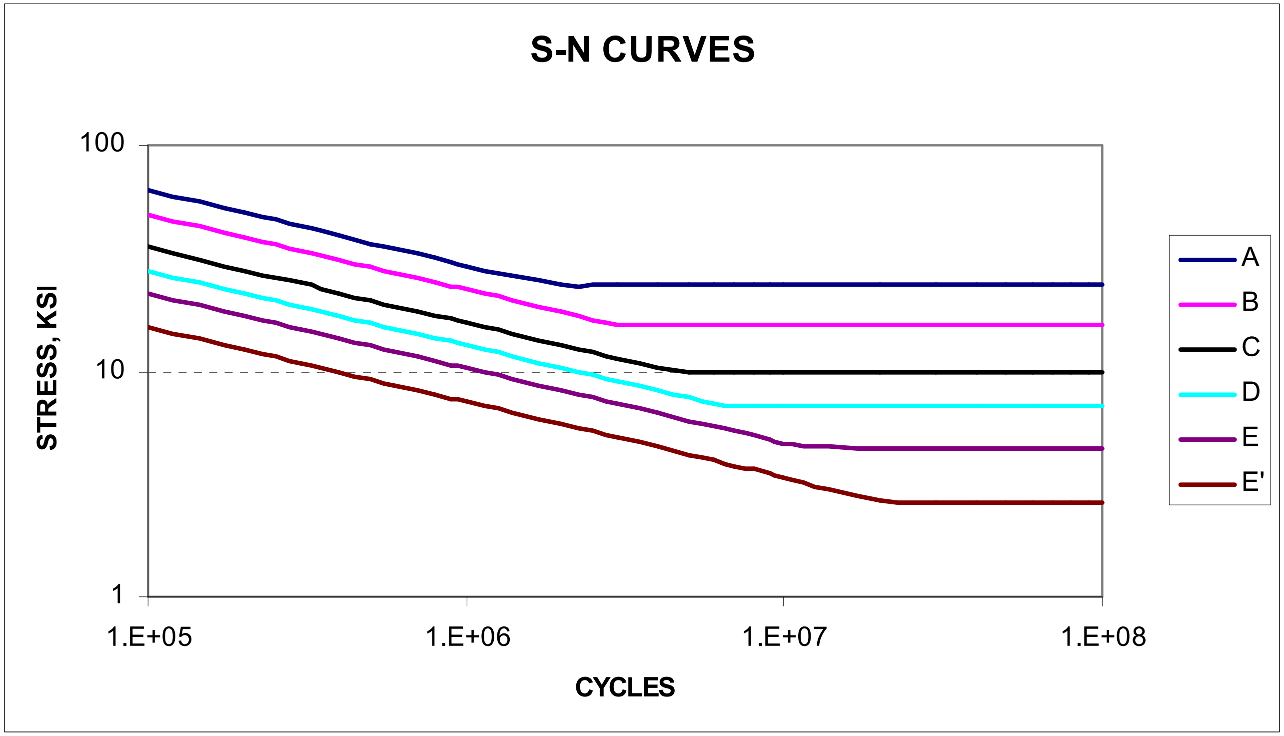
AASHTO METHOD

S-N Curves



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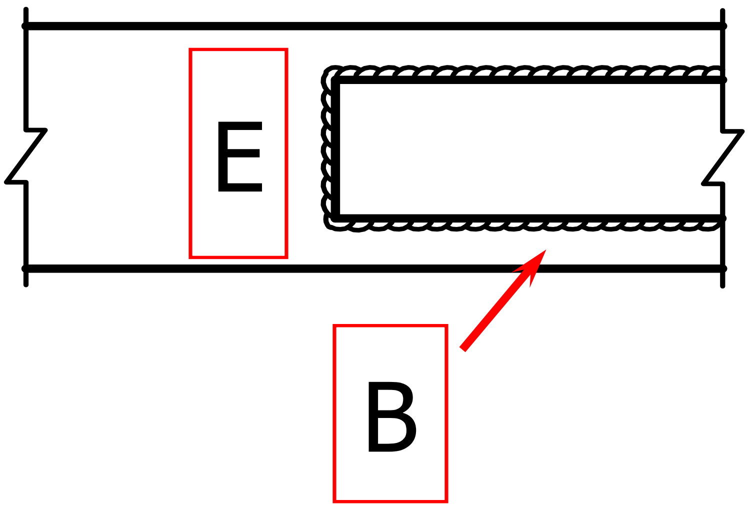
AASHTO METHOD

FATIGUE STRENGTHS

Fatigue Detail Categories

- ✓ 8 Categories (A-E')
- ✓ 11 General Conditions (Table 6.6.1.2.3-1)
  - ✓ Plain Members
  - ✓ Built-Up Members
  - ✓ Groove Welded Members
  - ✓ Fillet Welded Members

Fatigue Details



Builtup Member

B - Continuous fillet weld parallel to direction of applied stress

E – Base metal at ends of partial-length cover plates, narrower than flange, fl. Thickness < 0.8”

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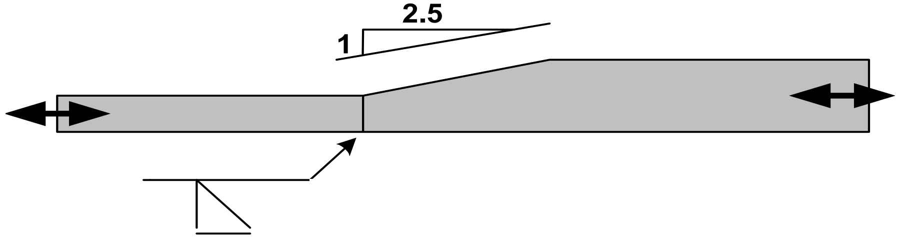
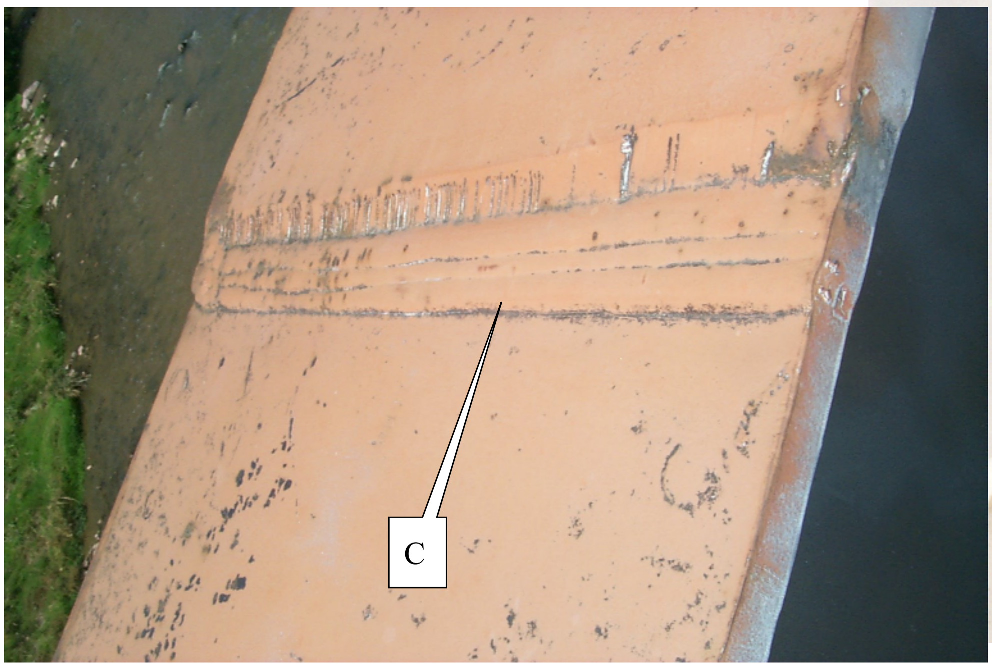
Fatigue Details

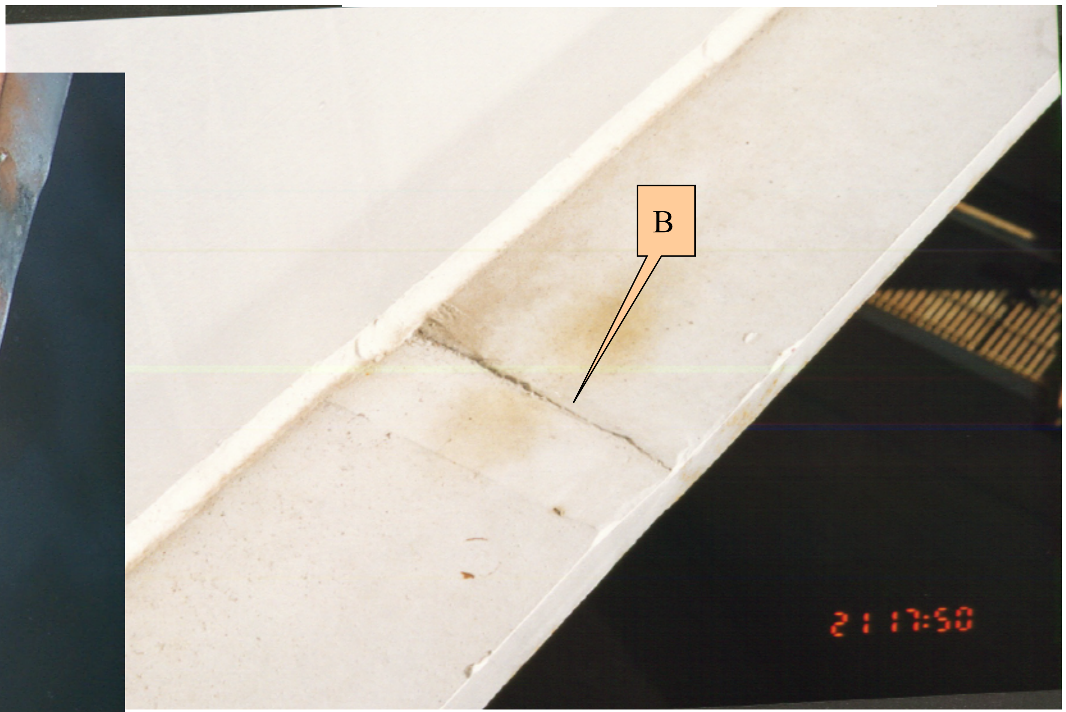
Groove Welded Splice (NDT)

B – Thickness transition 1:2.5 or shallower

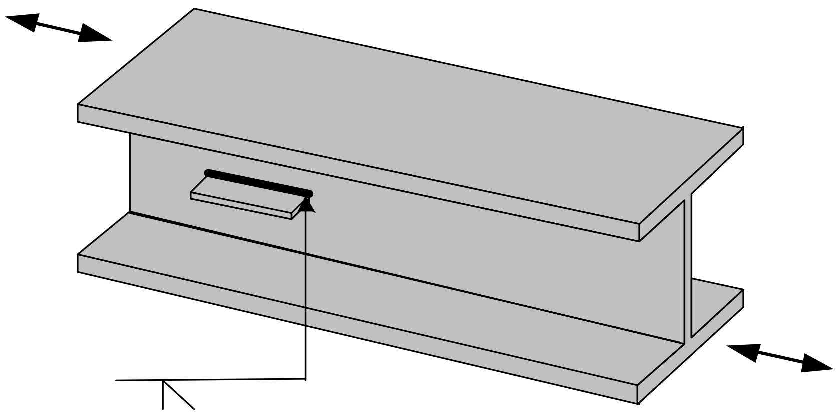
C – Weld Reinforcement not removed.

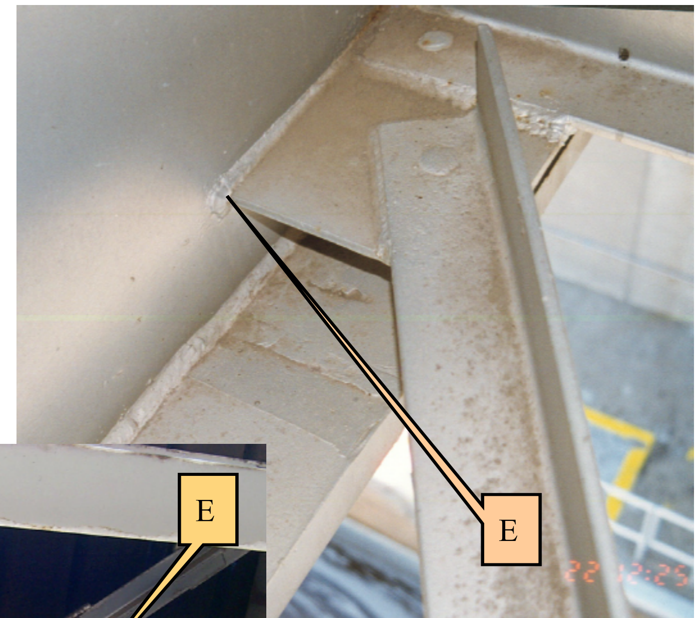


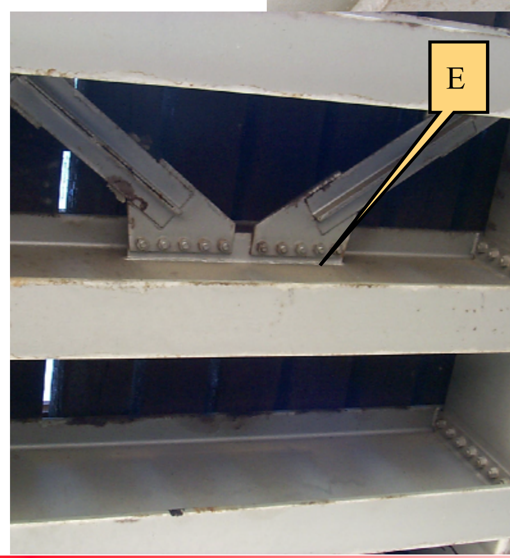




Fatigue Details





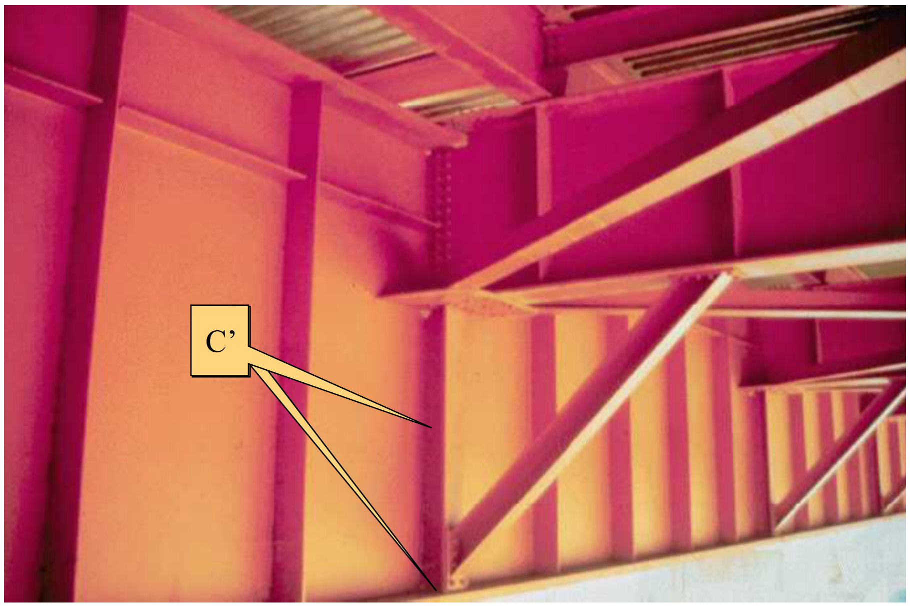


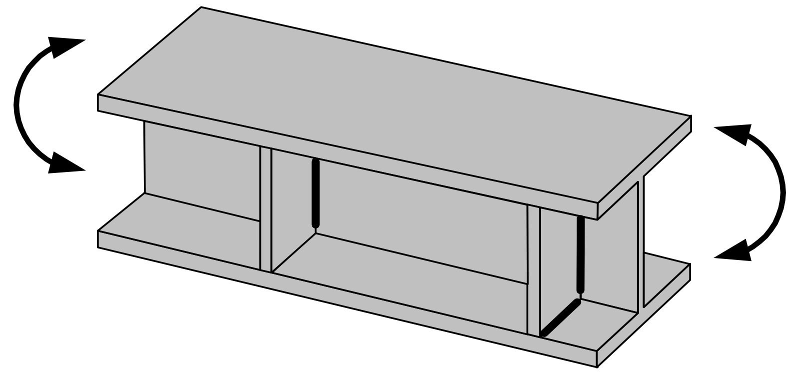
<u>Longitudinally Loaded Fillet Welds</u>

E – Detail Length > 12t or 4”

E –No transition radius

Fatigue Details



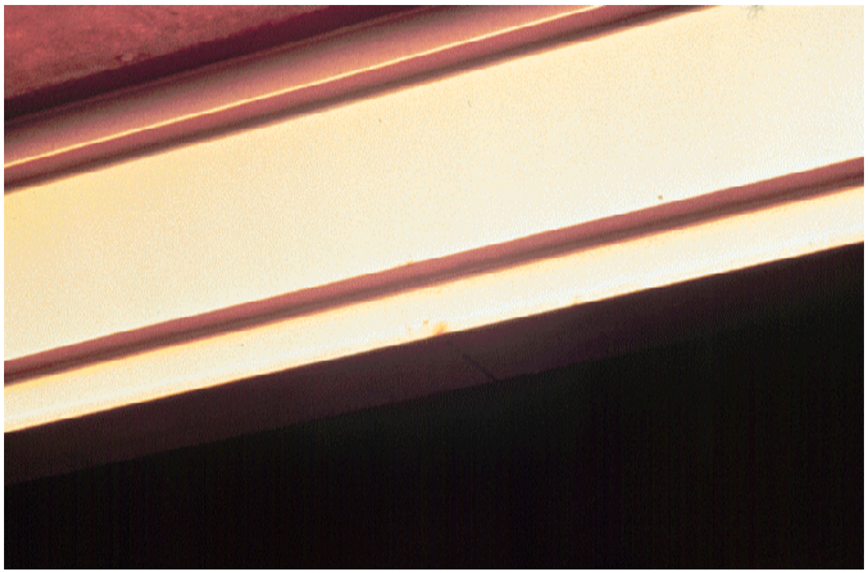


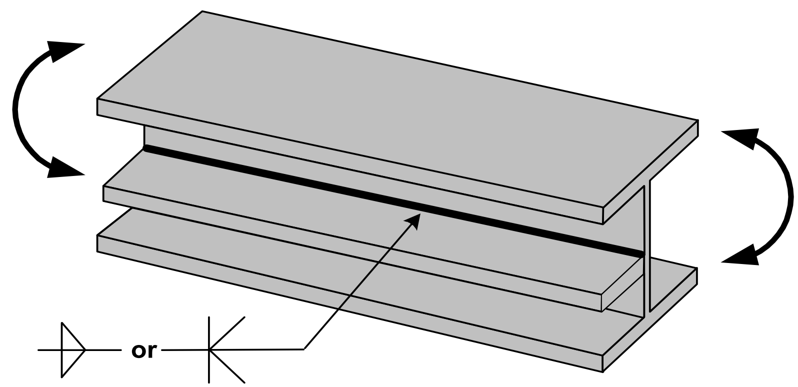
Category C'

<u>Fillet Weld Connections, Welds Normal to Direction of Stress</u>

C' – At toe of stiffener to flange or stiffener to web

Fatigue Details





Builtup Member

B - Continuous welds parallel to direction of applied stress

Category B

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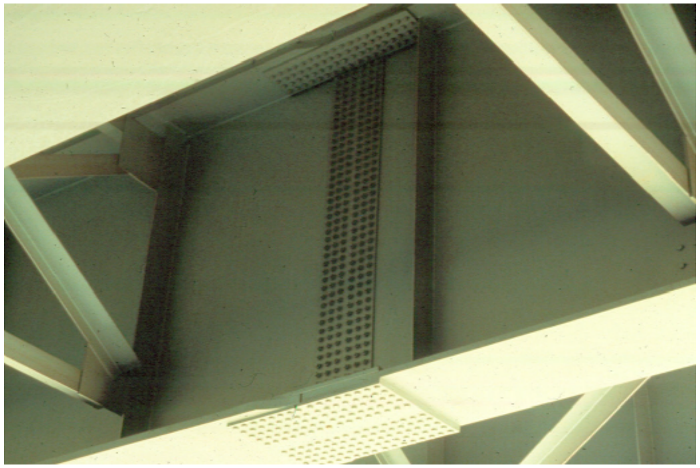
Fatigue Details

<u>Mechanical Connections</u>

B – Bolted

D – Riveted

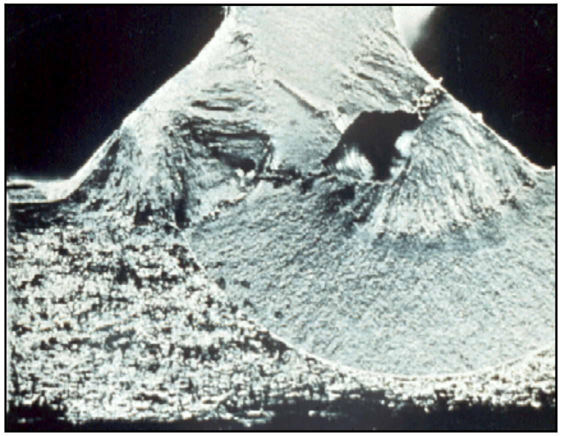


Category B

Category D

Fatigue Details

Category N (Not Allowed)

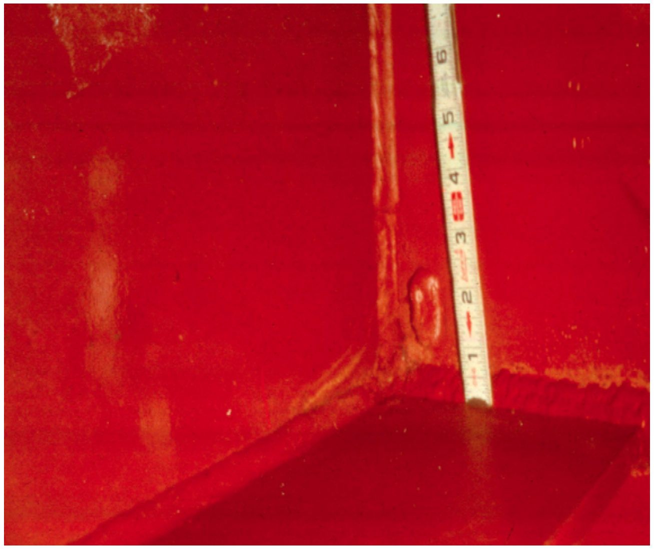


Noncompliant Weld

Cracked Weld

Fatigue Details

Category N (Not Allowed)

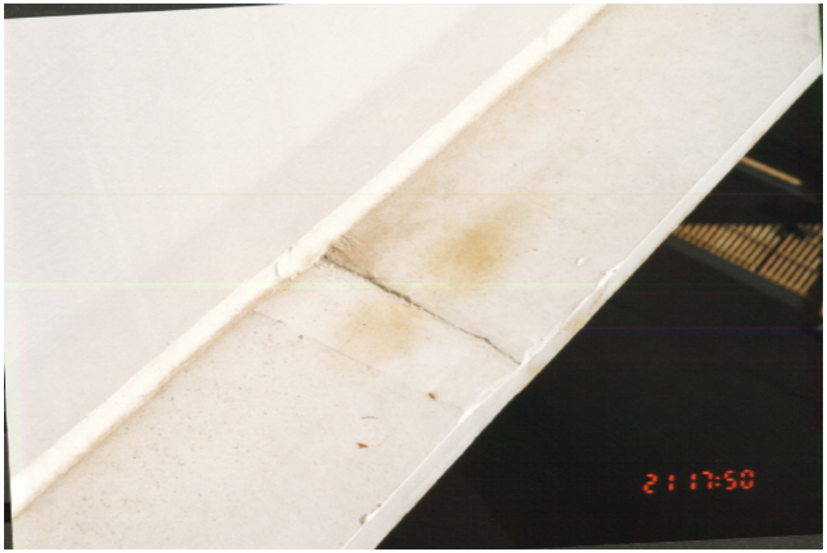


Triaxial Constraints

Excessive Corrosion

Fatigue Details

Category N (Not Allowed)



Transversely Loaded Partial
Penetration Groove Welds

DESIGN PROCEDURES

Design Equation $\lambda(\Delta f) \leq \varphi(\Delta F)_n$ $\lambda = 0.75$ $\varphi = 1.0$

(Δf) = Live Load Stress Range

$(\Delta F)_n$ = Nominal Fatigue Resistance

Design Procedures

1. Identify Fatigue Detail Category (C-E')
2. Apply Load – Single Truck, Single Lane, Max Effect
3. Distribute Load – Single Lane Load Distribution Factors
4. Apply Impact Factor (1.15)
5. Compute Section Properties – Short-Term Composite
6. Compute Stress at Detail – M/S, P/A
7. Compute Constant Amplitude Cycles – 75 year life
   - $N=365(75)n(ADTT)_{SL}$
8. Compute Nominal Strength (Fatigue Resistance)

DESIGN PROCEDURES

7. $N=365(75)n(ADTT)_{SL}$

- N = No. of Stress Range Cycles per Truck

Table 6.6.1.2.5-2
Cycles per Truck Passage, n

Longitudinal Members	> 40.0 ft.	< 40.0 ft.
Simple Span Girders	1.0	2.0
Continuous Girders		
1) near interior support	1.5	2.0
2) elswhere	1.0	2.0
Cantilever Girders	5.0	
Trusses	1.0	
Transverse Members	Spacing	
	> 20.0 ft.	< 20.0 ft.
	1.0	2.0

DESIGN PROCEDURES

7. $N=365(75)n(ADTT)_{SL}$

- $(ADTT)_{SL} = p \cdot ADTT$

Table 3.6.1.4.2-1 Fraction of Truck Traffic in a Sinple lane, p	
Number of Lanes Available to Trucks	p
1	1.00
2	0.85
3	0.80
>3	0.80

Table C3.6.1.4.2-1 ADTT	
Class of Highway	ADTT
Rural Interstate	0.20
Urban Interstate	0.15
Other Rural	0.15
Other Urban	0.10

DESIGN PROCEDURES

Design Procedures

8. Compute Nominal Strength (Fatigue Resistance)

$(\Delta F)_{TH}$ = Constant Amplitude Fatigue Threshold

$$(\Delta F)_n = \left(\frac{A}{N}\right)^{\frac{1}{3}} \geq \frac{1}{2}(\Delta F)_{TH}$$

Table 6.6.1.2.5-1
Detail Category Constant, A

DETAIL CATEGORY	A (10^8 ksi)
A	250.0
B	120.0
B'	61.0
C	44.0
C'	44.0
D	22.0
E	11.0
E"	3.9

Table 6.6.1.2.5-3
Constant-Amplitude Fatigue Thresholds

DETAIL CATEGORY	Threshold (ksi)
A	24.0
B	16.0
B'	12.0
C	10.0
C'	12.0
D	7.0
E	4.5
E"	2.6

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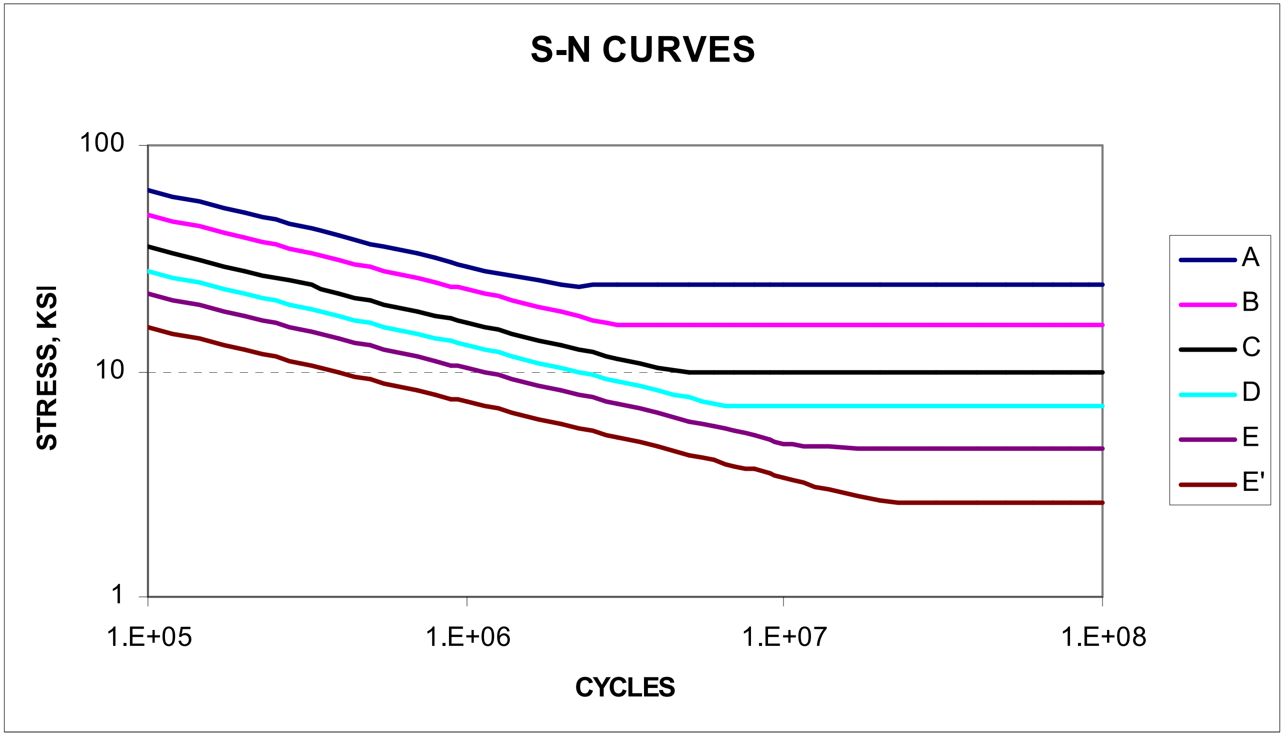
DESIGN PROCEDURES



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DESIGN PROCEDURES

$$\frac{1}{2}(\Delta F)_{TH}$$

- ✓ Assures the maximum applied stress range will always be less than the constant-amplitude fatigue threshold.
- ✓ This provides a theoretically infinite fatigue threshold.
- ✓ The maximum applied stress range is assumed to be twice that computed from a passage of the fatigue truck.

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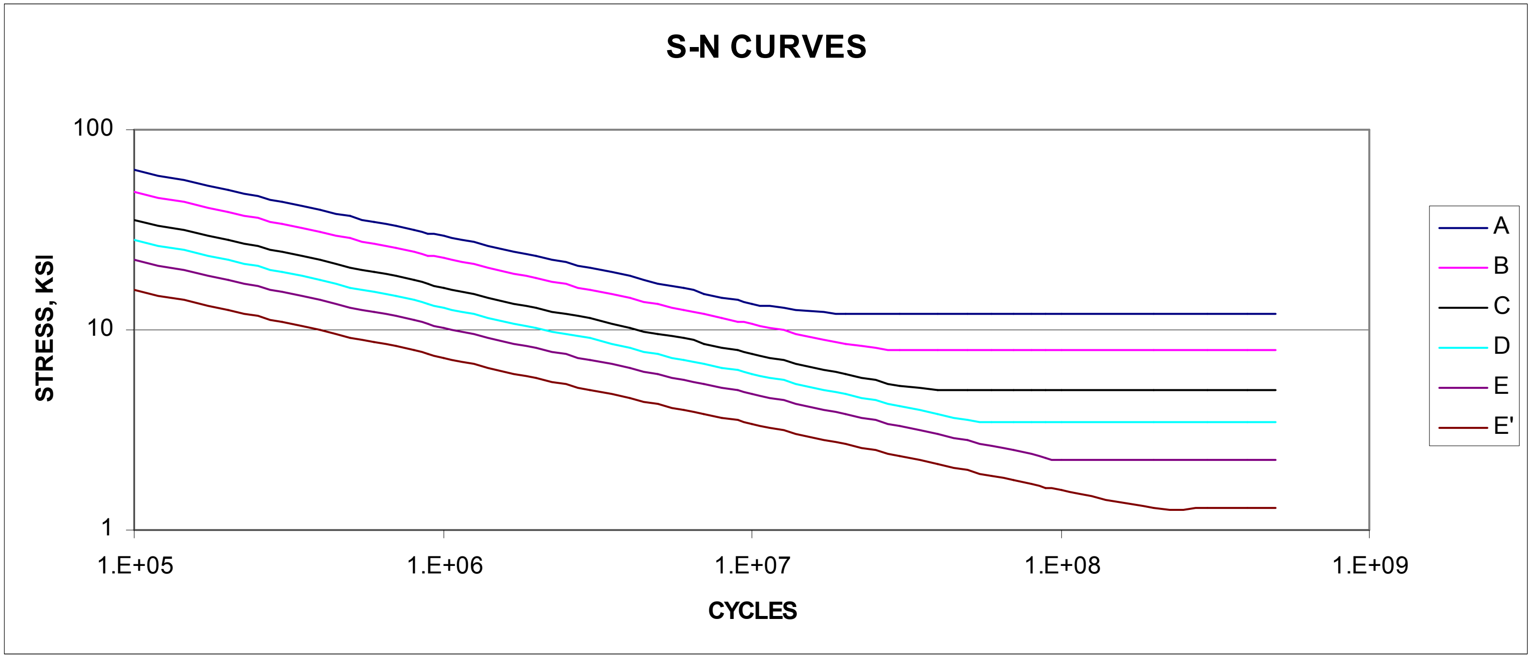
DESIGN PROCEDURES



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DESIGN PROCEDURES

Other Considerations

- ✓ Transversely Loaded Fillet Welds
  - ✓ See Additional Equation
- ✓ Members Under Dead Load Compression
  - ✓ Consider if Fatigue LL Tensile Stress > ½ DL Compressive Stress

INSPECTION PROCEDURES

Preparation

- ✓ Review As-Builts
- ✓ Identify Fatigue Details
- ✓ Identify FCMs
- ✓ Provide Proper Access

Inspection/Documentation

- ✓ Locate fatigue sensitive details and Identify category
- ✓ ***Inspect for cracks or signs of cracks***
- ✓ ***Inspect for noncompliant weld quality***
- ✓ ***Inspect for excessive corrosion***
- ✓ ***Inspect for other discontinuities (copes, nicks, gouges. Etc.)***
- ✓ ***Identify Intersecting welds***
- ✓ ***Identify Details (distortion, end restraints)***
- ✓ ***Emphasis on FCMs (NDT)***

INSPECTION PROCEDURES

End Restraint

EVALUATION PROCEDURES

Two Levels of Evaluation

- ✓ Infinite Life
- ✓ Finite Life

Fatigue Life Determinations

- ✓ Design Life
- ✓ Evaluation Life
- ✓ Mean Life

EVALUATION PROCEDURES

Stress Ranges

- ✓ AASHTO Fatigue Truck
- ✓ Truck Traffic Surveys
- ✓ Measured Effective Stresses

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EVALUATION PROCEDURES

Truck Traffic Surveys

- ✓ Weigh Stations
- ✓ Weigh In Motion (WIM) Studies

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

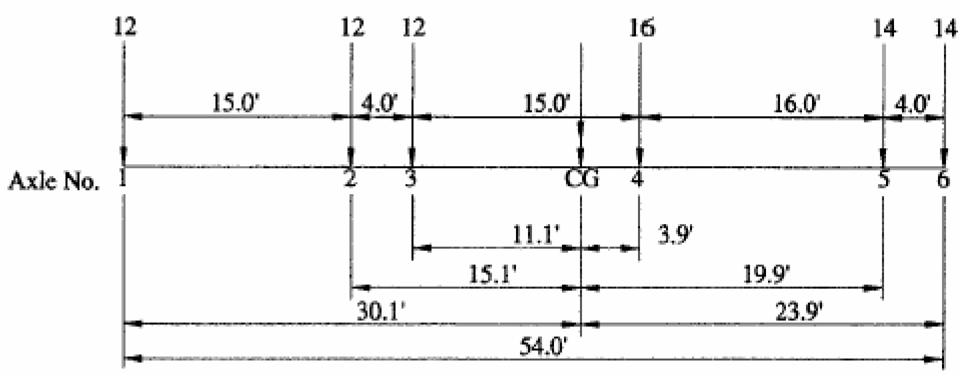

Figure B.6-4 Type 3-3 Unit WEIGHT = 80 kips (40 tons).

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EVALUATION PROCEDURES

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EVALUATION PROCEDURES

Weigh In Motion (WIM) Studies

- ✓ Bending Plates
- ✓ Load Cells
- ✓ Wire Loops

- ✓ Number of Trucks
- ✓ Axle Weights
- ✓ Axle Spacing

- ✓ Equivalent Fatigue Truck

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EVALUATION PROCEDURES

Weigh In Motion (WIM) Studies

EVALUATION PROCEDURES

Effective Stresses

$$(\Delta f)_{eff} = R_s \Delta f$$

Measured Effective Stresses

✓ Miner's Rule

$$(\Delta f)_{eff} = R_s \left(\Sigma \gamma_i \Delta f_i^{\,3} \right)^{\frac{1}{3}}$$

EVALUATION PROCEDURES

Partial Load Factors

$$R_s = R_{sa} R_{st}$$

- ✓ Uncertainty in Stress Range
- ✓ Uncertainty in Analysis Methods
- ✓ Uncertainty in Truck Weight

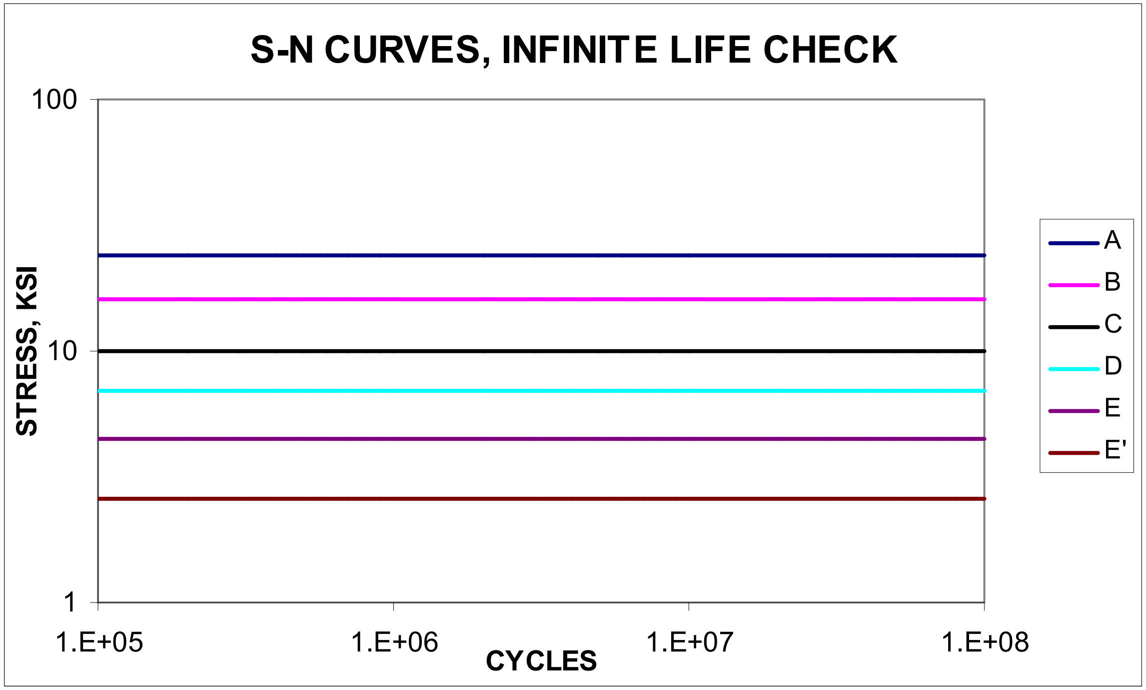
Table 7-1, Partial Load Factors: R_{sa}, R_{st}, and R_s

Evaluation Method	Analysis, R_{sa}	Truck Weight, R_{st}	Stress Range Estimate, R_s
Evaluation or Minimum Fatigue Life			
SR: Simplified Analysis TW: AASHTO Fatigue	1.0	1.0	1.0
SR: Simplified Analysis TW: WIM	1.0	0.95	0.95
SR: Refined Analysis TW: AASHTO Fatigue	0.95	1.0	1.0
SR: Refined Analysis TW: WIM	0.95	0.95	0.90
SR: Field Measurements	NA	NA	0.85
Mean Fatigue Life			
All Methods	NA	NA	1.0

EVALUATION PROCEDURES

Infinite Life Check

$$(\Delta f)_{max} \leq (\Delta F)_{TH} \qquad (\Delta f)_{max} = 2.0(\Delta f)_{eff}$$



EVALUATION PROCEDURES

Estimating Finite Fatigue Life

✓ Design (Minimum) Life	2σ	0.98
✓ Evaluation Life	1σ	0.85
✓ Mean Life	0σ	0.50

$$Y = \frac{R_R A}{365n(ADTT)_{SL}((\Delta f)_{eff})^3}$$

Y = Total Years

Remaining Life = Y-Present Age

EVALUATION PROCEDURES

Resistance Factors

Table 7-2, Resistance Factor, R_R			
Detail Category	Minimum (Design) Life	Evaluation Life	Mean Life
A	1.0	1.7	2.8
B	1.0	1.4	2.0
B'	1.0	1.5	2.4
C	1.0	1.2	1.3
C'	1.0	1.2	1.3
D	1.0	1.3	1.6
E	1.0	1.3	1.6
E'	1.0	1.6	2.5

EVALUATION PROCEDURES

Estimating Stress Cycles

- ✓ ADTT – Single Lane
  - ✓ Figure C7-1
- ✓ No. of Cycles per Truck
  - ✓ Same as Design
  - ✓ Influence Lines
  - ✓ Field Measurements

EVALUATION PROCEDURES

Influence Lines

EVALUATION PROCEDURES

Other Considerations

- ✓ Riveted Details
  - ✓ Category C instead of D (Design)
- ✓ Compressive Stresses
  - ✓ LL Tensile Stress must be at Least Twice DL Comp.
  - ✓ Consider Load used in the Evaluation

RESULTS

When to Evaluate:

- ✓ Detail Categories C-E'
- ✓ Consider Traffic
- ✓ Consider Stresses
- ✓ Consider Consequences
- ✓ ***Document***

If Results Are Unacceptable:

- ✓ Refine Analyses Parameters
  - ✓ Balance Costs vs. Savings
- ✓ Access Risk and Consequences
  - ✓ Increase Monitoring
- ✓ Retrofit