DESIGN FOR FATIGUE

About Author:

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An IIT Roorkee Graduate, who belongs to the Indian Railway Service of Engineers (IRSE). He has expertise in Design and Construction of Rail/Road Bridges with more than 25 years of experience in Planning, Design, Construction and Maintenance of Rail/ Road Bridges, Metro network, Track & other Railway assets. He has received Prestigious National Award for Outstanding Service (Ministry of Railways) along with many others. He is member of IRC B2 & B5 code committees and published many papers.

UNDERSTANDING FATIGUE : DEFINITION

IRC: Fatigue - Damage caused by repeated fluctuations of stress, leading to progressive cracking of a structural element.

IRS: Fatigue - The phenomena of damage in a structural part through crack initiation and/or gradual crack propagation caused by repeated stress fluctuations.

Repeated stress fluctuations -> Cracking -> Damage

OVERVIEW OF FATIGUE DESIGN:

- Long term phenomenon – Important factor in durability
- Design -> Construction -> Service
- Cause and effect beyond Design and Construction phase
- Design is dependent on
  - Material Quality
  - Fabrication Practises
  - Erection Practises
  - Place – Cannot use Drawing for One Bridge for Another
  - In Service Periodic Inspections
- Codes updated in 2022
- No deviation from Drawing during fabrication/erection

FACTORS IN FATIGUE VERIFICATION

- **Load**
- Load stress range history – Calculated
- Volume of traffic – Given
- Service Temperature (Environmental Load)
- **Material**
- Member/Element Details – Detail category as per code
  - S-N Curve - As per code
- Material Quality – Fracture Toughness Requirement at Service Temperature
- Initial Surface Finish – As rolled, machine gas cut, hand gas cut, drag lines, stray arc, corrosion etc

FATIGUE PROVISIONS IN IRC:

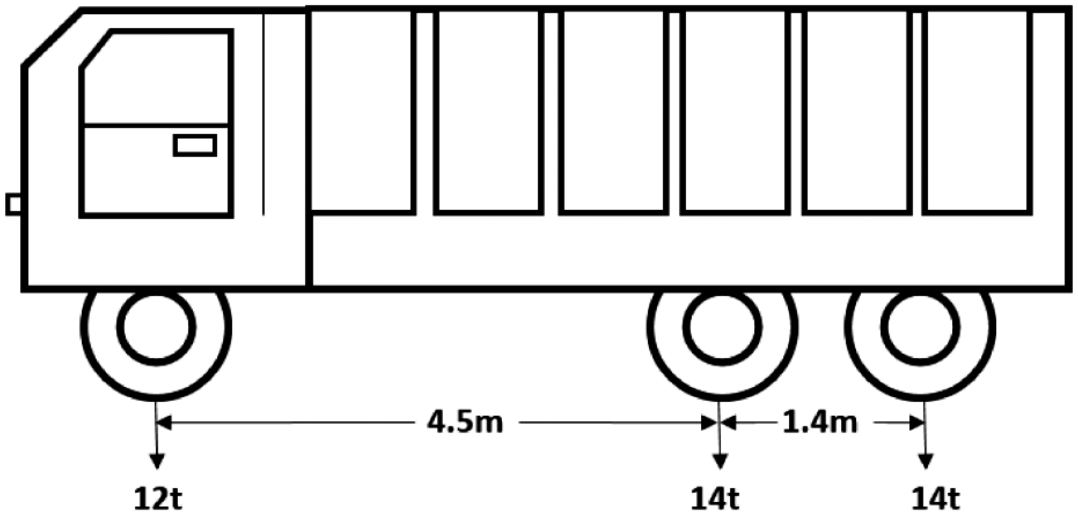
- May 2010 IRC-24 included fatigue provisions.
- Aug 2014 IRC-06 New Clause 204.6 on Fatigue Load added
- Nov 2017 IRC-24 Fracture Toughness Requirement added
- Oct 2022 IRC-6 Fatigue Load Model Revised in IRC 6 (204.6)
- Oct 2022 IRC-24 Fatigue design provisions amended

FATIGUE LOAD

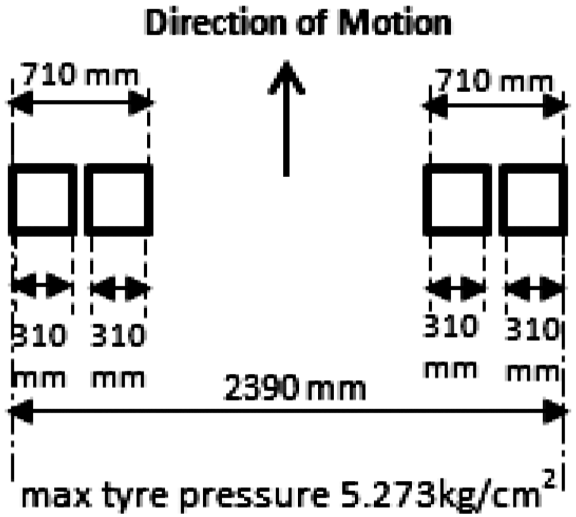
IRC-6

Basic fatigue Truck

- The 40t truck defined below shall be used for the fatigue life assessment of ROAD bridges. The transverse wheel spacing and tyre arrangement of this truck shall be as below.



FATIGUE TRUCK



LATERAL WHEEL PLACEMENT

DESIGN FOR FATIGUE : ROAD BRIDGES

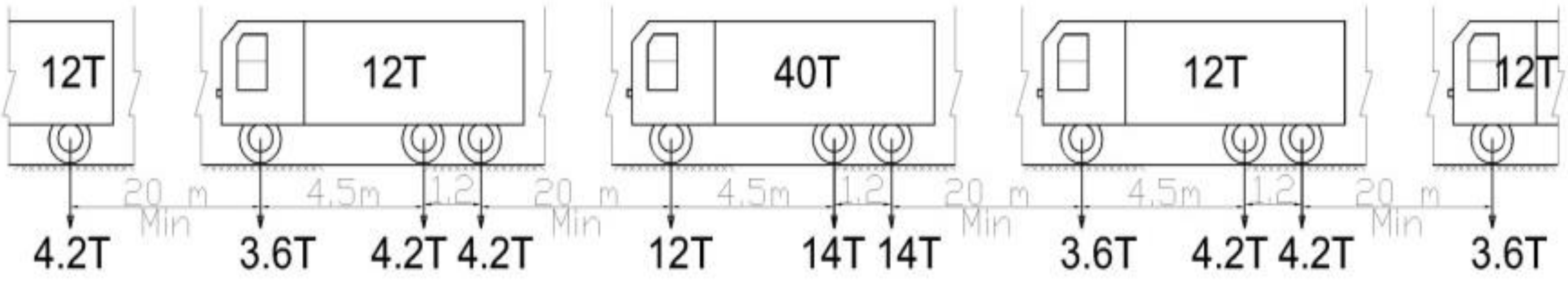


Fig. 7A : Fatigue Load Train

NOTE: 1. Fatigue truck of 40 T must be included in Fatigue Load Train

2. Only such number of additional 12 T trucks shall be included as can be accommodated in influence line of detail under consideration

- For super-structures supporting multiple lanes, fatigue load train need to be considered only in one lane at a time for each carriageway.
- 40% Impact shall be applied to the above fatigue load train for average surface riding quality.

DESIGN FOR FATIGUE : ROAD BRIDGES

- Stress range resulting from the single passage of the fatigue load train with min 150 mm clearance between outer edge of the wheel of the fatigue vehicle and roadway face of the kerb shall be used in design.

- Fatigue verification shall be carried out under frequent combination of Serviceability Limit State (SLS), with load factor equal to 1.0.

DYNAMIC AMPLIFICATION CLOSE TO EXPANSION JOINT

For sections/ details within 6.0 m of the expansion joint, the fatigue load arrived as above shall further be increased by a dynamic amplification factor, I_{ej} as given below:

$$I_{ej} = 1.3(1-x/26) > 1.0$$

where

x = distance of section/detail from nearest expansion joint.

NO OF VEHICLE PASSES

In absence of any specific provision in IRC 22, IRC 24 or IRC 112, number of cycles corresponding to following traffic may be considered for fatigue assessment, depending upon the location of the bridge and the category of roads:

1) The bridges on Expressway, National/ State Highways or other roads close to areas such as ports, heavy industries and mines and other areas, where generally heavy vehicles ply or bridges in other category of roads specifically identified by the Employer/Owner to carry high passage of heavy vehicles — 2.0×10^6 load/Yr.
2) Rural Roads — Fatigue not to checked
3) Other bridges — 0.5×10^6 load/Yr.

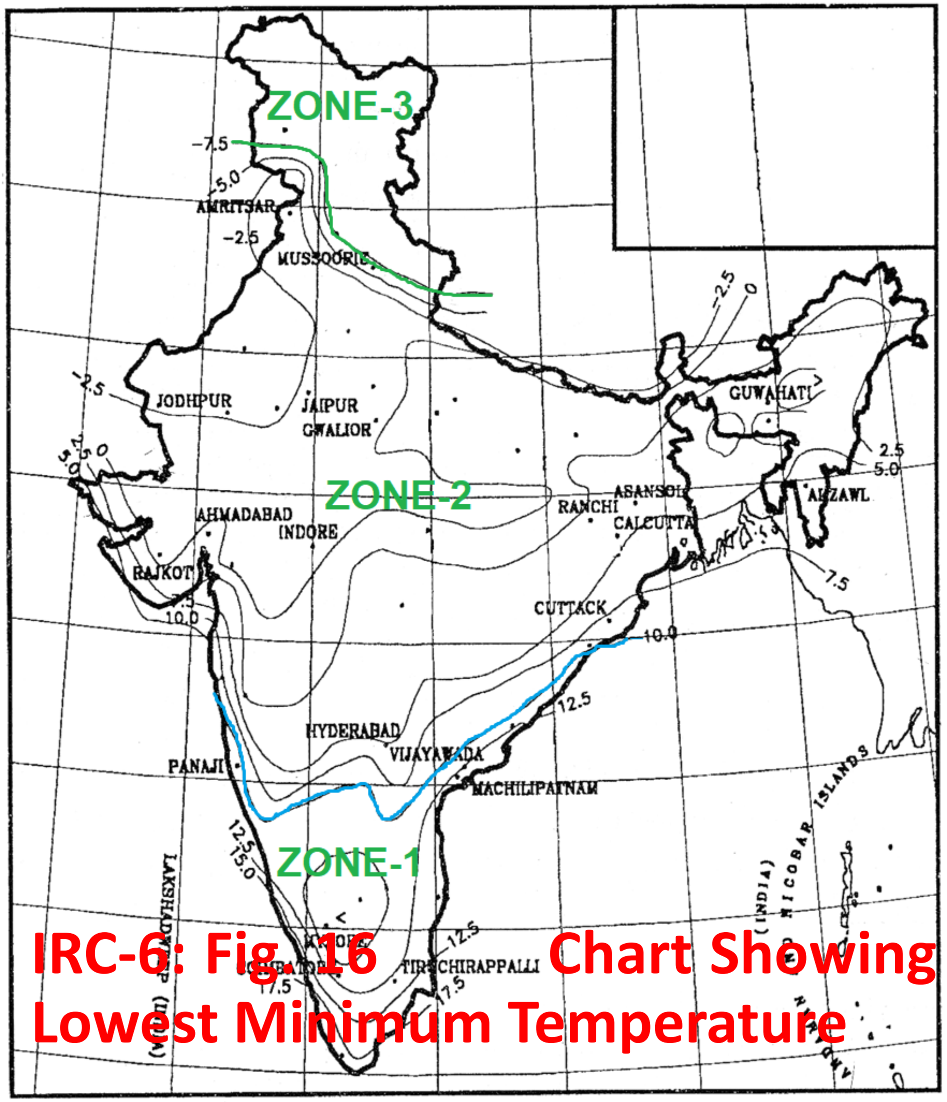
SERVICE TEMPERATURE:

- Steel proposed to be used in a part shall be able to sustain number of design cycles for design stress range at minimum service temperature of the part.
- Minimum service temperature

(i) -35ºC for snow bound areas and

(ii) minimum shed air temperature – 10ºC for other areas

- Zone -1 ST > 0;
- Zone-2 ST 0 oC to -17 °C
- Zone-3 ST < -18ºC



IRC-6: Fig. 16 Chart Showing Lowest Minimum Temperature

FRACTURE TOUGHNESS REQUIREMENT

IRC-22
IRC-24

Fracture toughness requirement :

In order to avoid brittle fracture, steel should have adequate fracture toughness taking into account the following:

- a) Design minimum service temperature of the part
- b) Fracture criticality of the member/part
- c) Type of the steel (Grade & quality) and construction detail used in the part
- d) Thickness of the stress carrying part

- Steel selected as per the guidelines given in clause 502.2.3.1 of IRC 24 shall be deemed to satisfy the requirement of this clause.
- Unless indicated otherwise in the contract plans, Charpy V-notch toughness requirement are not mandatory for the following items.
  - Intermediate transverse web stiffeners not serving as connecting plates,
  - Filler plates in bolted connection in double shear
  - Bearings, sole plates/ masonry plates/ Expansion plates, Drainage components

- The charpy V-notch toughness of different types of steel as per **IS: 2062:2011** are given below: (Test temperature for CVN values are 25 ^{o}C for BR, 0 ^{o}C for B0 and -20 ^{o}C for C grade)

Grade	Quality	Max. Yield stress (MPa)	CVN at test temperature
E 250	A, BR, B0, C	250	27
E 275	A, BR, B0, C	275	27
E 300	A, BR, B0, C	300	27
E 350	A, BR, B0, C	350	27
E 410	A, BR, B0, C	410	25
E 450	A, BR	450	20

Selection table for steel

GRADE	Thk (mm)	FRACTURE CRITICAL			NON-FRACTURE CRITICAL		
		ZONE 1	ZONE 2	ZONE 3	ZONE 1	ZONE 2	ZONE 3
E-250, E-275 & E-300	t ≤ 100	BR	B0	C	BR	BR	B0
E 350	t ≤ 50	BR	B0	C	BR	BR	B0
	50 ≤ t ≤ 100	B0	C	C	BR	B0	B0
E-410	t ≤ 100	C	NP	NP	B0	C	NP
E-450	t ≤ 100	C	NP	NP	B0	C	NP

Zone -1 ST > 0; Zone-2 ST 0 oC to -17 °C; Zone-2 ST < -18°C

FATIGUE ASSESSMENT

IRC-22
IRC-24

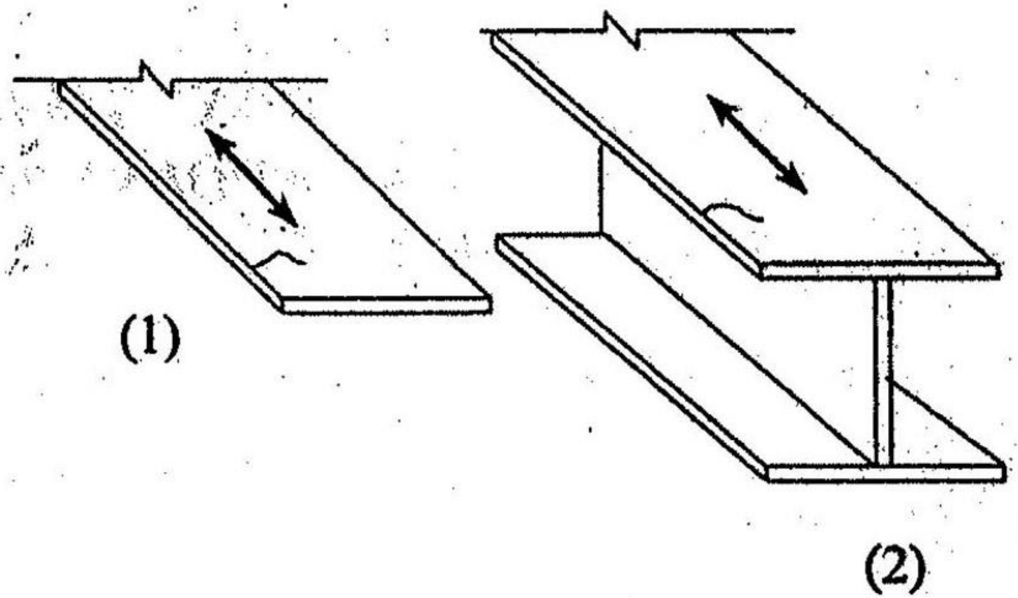
DEFINITIONS:

- **Stress Cycle Counting -** Counting of various stress range and their number of occurrence in a particular loading event history (Rainfall method or Reservoir method)
- **Stress range spectrum :** A histogram of different stress ranges and their frequency of occurrence for a particular loading event.
- **Design Spectra -** The combination of all stress range spectra applicable to the fatigue assessment.
- **Cut off limit :** The stress range, corresponding to the particular detail, below which cyclic loading need not be considered in cumulative fatigue damage evaluation (corresponds to 100 M cycles in most cases).

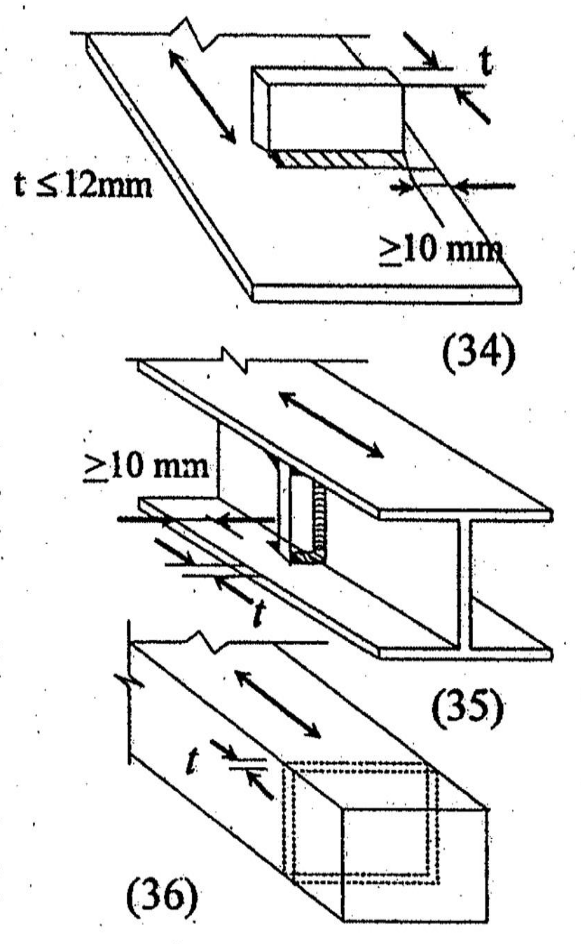
DEFINITIONS:

- **S-N curve** - The curve defining the relationship between the number of stress cycles to failure (N_{sc}) *and constant stress range* (S_c)
- **Detail Category** - Designation given to a particular detail to indicate the S-N curve to be used in fatigue assessment. (Value given in IRC-24 & IRC-25 corresponding to **5 M** Cycles)
- **Fatigue Strength:** Stress range for a category of detail depending upon the number of cycles it is required to withstand during its design life
- **Damage :** For a specific stress range, the ratio of the actual number of cycles a detail is subjected to the number of cycles to failure.
- **Cumulative damage :** (Palmgren – Miner's rule) The linear combination of the damage corresponding to each stress range in a stress spectrum

Fatigue Strength (Detail Category)

Detail Category	Constructional Details	
	Illustration (See Note)	Description
118		***ROLLED AND EXTRUDED PRODUCTS*** (1) Plates and flats (2) Rolled sections Sharp edges, surface and rolling flaws to be removed by grinding in the direction of applied stress.

Fatigue Strength (Detail Category)

Detail Category	Constructional Details: Illustration (See Note)		Constructional Details: Description
59	$t \leq 12mm$		*TRANSVERSE WELDS* (34) Transverse fillet welds with end of the weld ≥10 mm from edge of the plate. (35) Vertical stiffeners welded t beam or plate girder flange or v by continuous or intermittent wel In the case of webs carryi combined bending and shear des actions, the fatigue strength shall determined using the stress range the principal stresses. (36) Diaphragms of box gird welded to the flange or web continuous or intermittent welds.
52	$t > 12mm$		

Fatigue Assessment : SN CURVE

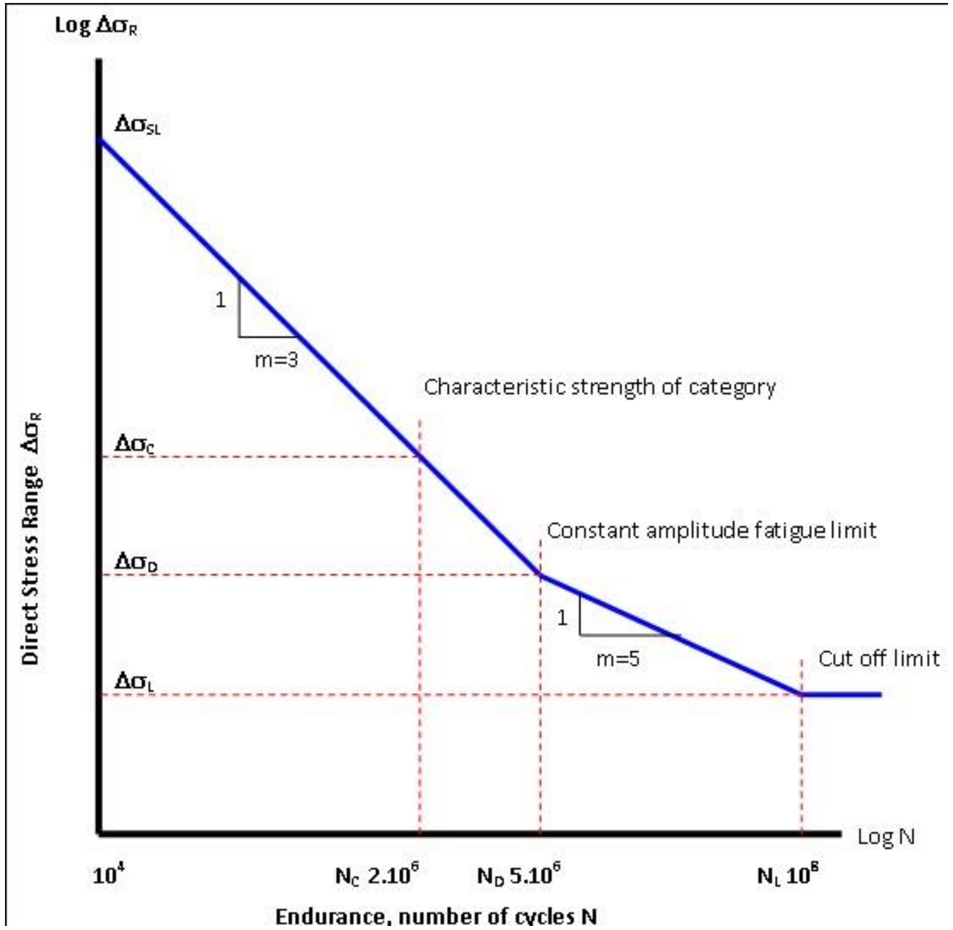
For nominal stress ranges $\Delta\sigma_i$, Ni may be calculated as follows :

(a) if $\gamma_{Ff} \cdot \Delta\sigma_i \geq \Delta\sigma_D / \gamma_{Mf}$

$$N_i = 5 * 10^6 * \left[\frac{\Delta\sigma_D / \gamma_{Mf}}{\gamma_{Ff} * \Delta\sigma_i} \right]^3$$

(b) if $\Delta\sigma_D / \gamma_{Mf} \geq \gamma_{Ff} \cdot \Delta\sigma_i \geq \Delta\sigma_L / \gamma_{Mf}$

$$N_i = 5 * 10^6 * \left[\frac{\Delta\sigma_D / \gamma_{Mf}}{\gamma_{Ff} * \Delta\sigma_i} \right]^5$$



(c) if $\Delta\sigma_L / \gamma_{Mf} \geq \gamma_{Ff} * \Delta\sigma_i$ then N_i may be taken as infinite

PERIODIC INSPECTION:

PARTIAL SAFETY FACTORS FOR FATIGUE ASSESSMENT

γ_{fft} **= 1.00** (:Loads & Stresses)

Table-18: Partial safety factors for Fatigue Strength (γ_{mft})

Inspection and Access	Consequence of Failure	
	Fail-safe	Non-fail-safe
Periodic inspection and maintenance, Accessibility to detail is good	1.00	1.25
Periodic inspection and maintenance, poor accessibility for detail	1.15	1.35

Cycle Counting Methods

- **For fatigue design, Design Spectra is required**
- **Design Spectra :** The combination of stress range spectra for all load sets
- **Stress range spectrum :** A histogram of stress ranges and their frequency
- **Run a fatigue load set - > Get Stress history for a detail**

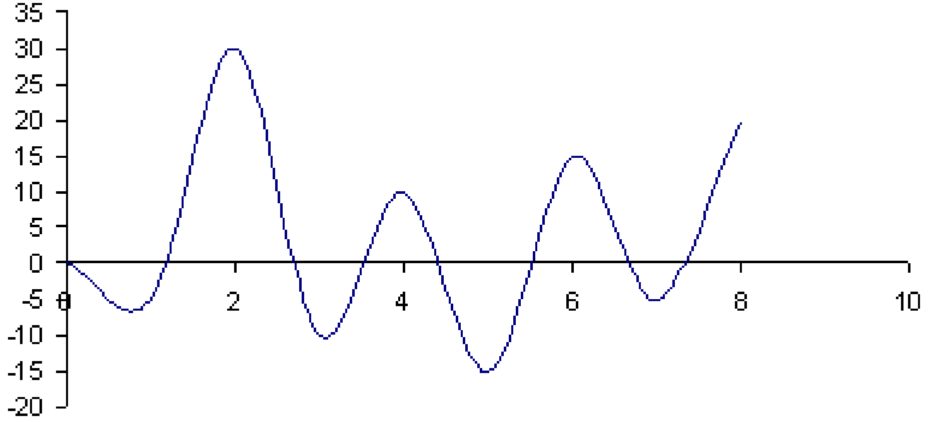


Figure A.1 Typical segment of a stress history

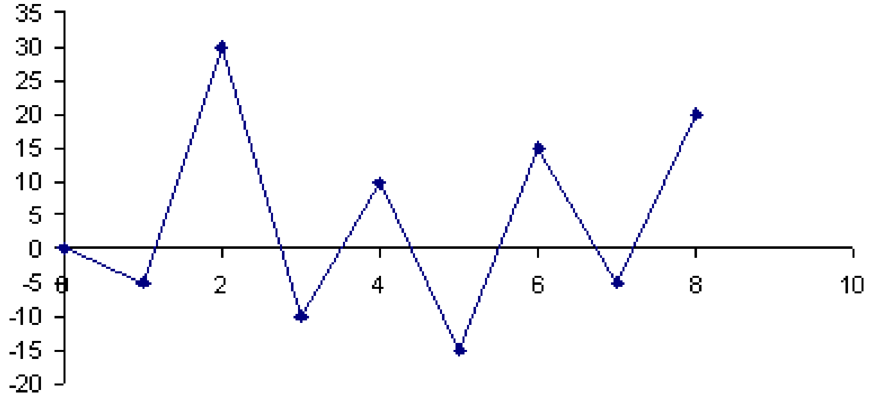
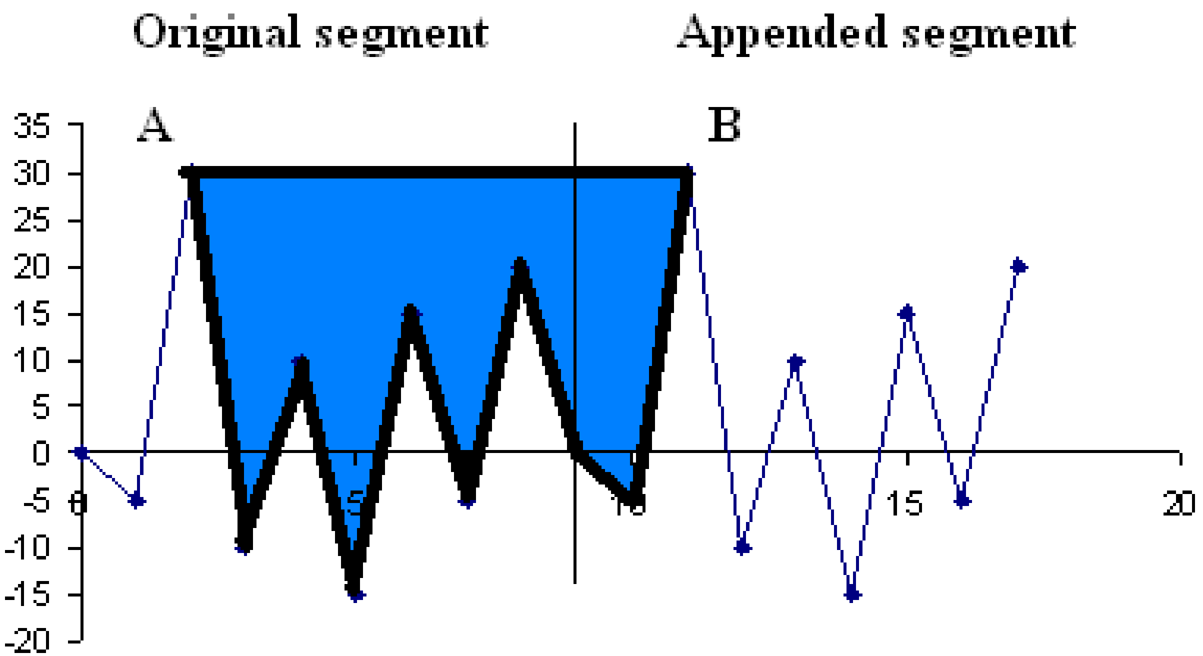


Figure A.2 Stress history segment showing peaks and valleys

Cycle Counting Method

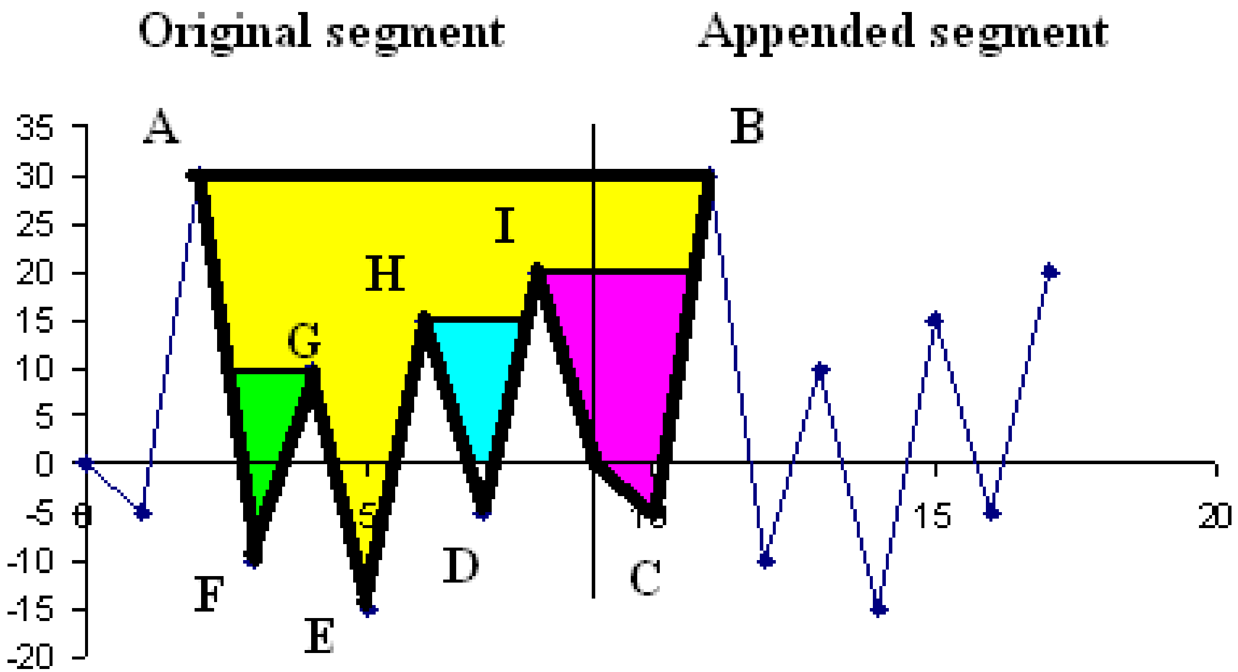
- **Repeat stress history**



- **Join two highest ridges – AB is usable stress history**

Cycle Counting Method

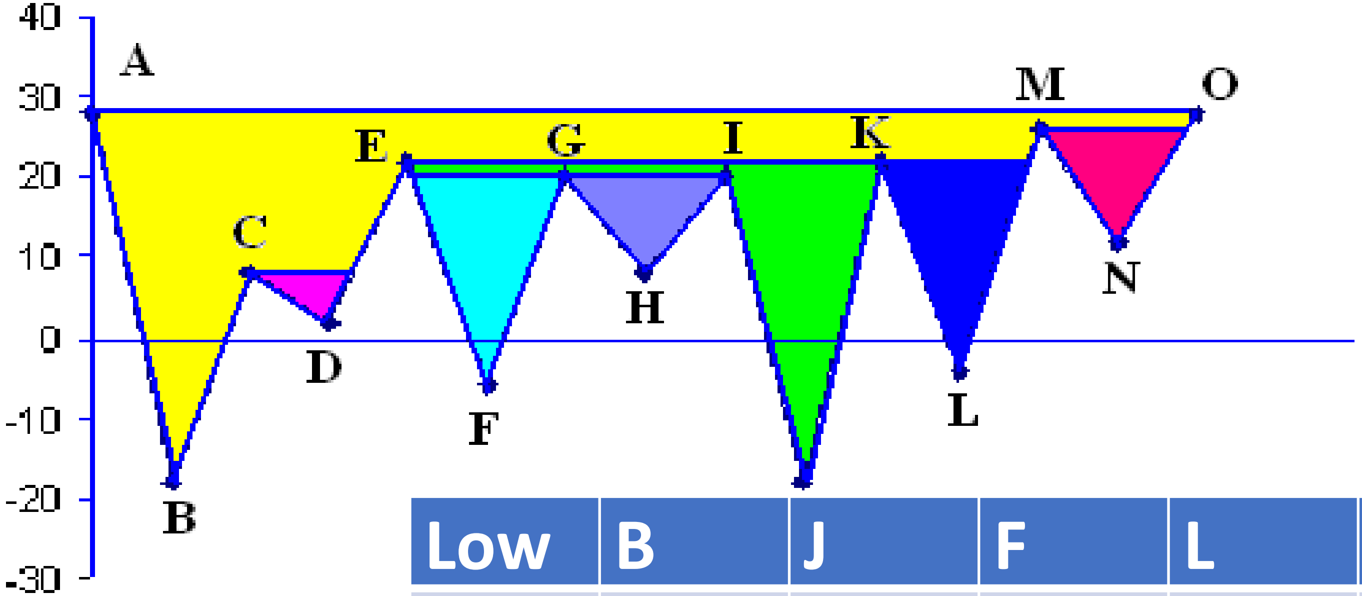
- Cycle counting by the rainflow method or by **the reservoir method**



- **Drain the reservoir successively starting from deepest trough**

Cycle Counting Method

- Example
- Time 1 2 3 4 5 6 7 8 9 10 11 12 13 14
- Stress 28 -18 8 2 22 -6 20 8 20 -18 22 -4 26 12



Low	B	J	F	L	D	H	N
High	A	K	G	K	C	G	M
S R	46	40	26	26	6	12	14

Cycle Counting Method

- Prepare Histogram

SN	1	2	3	4	5	6
SR	46	40	26	14	12	6
f	1	1	2	1	1	1

- Calculate load set pass in life – 0.5M/Yr x 100 Yr = 50 M
- Update for life of bridge

SN	1	2	3	4	5	6
SR	46	40	26	14	12	6
f (M)	50	50	100	50	50	50

- Similarly calculate for other load sets and combine for Design Spectrum

Palmgren-Miners' law

For variable amplitude loading defined by a design spectrum, the fatigue assessment shall be based on Palmgren-Miner rule of cumulative damage.

A cumulative damage assessment may be made using

$D_d = \Sigma(n_i/N_i) \leq 1$

where

n_i = number of cycles of stress range $\Delta\sigma_i$ during the required design life and

N_i = number of cycles of stress range $\gamma_{Ff} \cdot \gamma_{Mf} \cdot \Delta\sigma_i$ to cause failure for the relevant detail category.

Design stress:

$f_{fd} = \mu_r \, f_f / \gamma_{mft}$

$\tau_{fd} = \mu_r \, \tau_f / \gamma_{mft}$

$\mu_r = (25/t_p)^{0.25} \leq 1$ (Factor for plate thickness)

t_p = plate thickness

f_f , τ_f = Detail category value

γ_{mft} = Partial safety factor (1.0, 1.15, 1.25, 1.35)

FLOW CHART FOR FATIGUE VERIFICATION

- Select Detail & Force Resultant (BM, SF, AF)
- Draw ILD for selected force resultant
- Place fatigue vehicles so as to have worst effect as per ILD
- Calculate force & stress history by Moving Load Analysis
- Use Reservoir or Rainfall Method for cycle counting associated stress range
- Modify stresses by Load/Stress factors

FLOW CHART FOR FATIGUE VERIFICATION

- Chose appropriate detail category (Numerical value in Mpa) applicable at section under check. Different categories for same members may need to be adopted based on different section and their connections and attachments

- Apply SN Curve for applicable detail category to calculate Endurance cycles for each stress range

- Apply eqv. constant amplitude stress range method or Palmgren-Minor's Rule to check accumulated damage

- Document Fabrication Details & Process considered during verification in Drawings

FATIGUE RESULTS IN MICROCRACKING

MICROCRACKING LEADS TO FRACTURE

IT CAN BE PREVENTED BY PROPER DESIGN AND FOLLOWING DUE PROCEDURES

Thank You