# Structural Design

design issues for structural engineers

# *Survival of a Crane Truss in a Waterfront Project*

*Part 1*

*By Vitaly Feygin, P.E.*

Modern container terminals are often built on sites with existing infrastructure like tunnels, sewers and pipelines. Sometimes the relocation of these obstructions is not feasible. These conditions often require the engineering of long-span trusses for container cranes. Nowadays, availability of suitable waterfront industrial sites dictates the direction of development of new port facilities. This article gives some insight into the most critical issues of the design of waterfront crane trusses and discusses fatigue, dynamic impact allowance, torsional resistance, effect of dynamic impact on fatigue, fracture critical connections and buckling analysis of built up box elements. Other important issues discussed include the impact of the environment on corrosion fatigue, methods of corrosion protection within ice fluctuation zones, and proposed deflection and camber criteria for long-span crane ways.

## Background

Cyclical movements of long-span crane girders and crane trusses have been identified as the cause of many structural failures in the past. Repeated fluctuating loads can result in fractures at stress magnitudes well below elastic failure in monotonically loaded elements and connections. Failure due to accumulation of plastic deformation is known as fatigue. Normal fatigue can be described as a process of cumulative plastic damage in a non-aggressive environment. Fatigue aggravated by a corrosive environment is known as corrosion fatigue. Fatigue normally develops at connections or discontinuities where local stresses exceed the steel yield stress. Accumulated plastic damage initiates a crack, which in turn aggravates the discontinuity and increases stress in the remaining part of the connection, causing crack propagation and ultimately structural failure. Geometry of the detail, material and weldment quality is described by stress category. The AISC 13th Edition and AASHTO LRFD 4th Edition define eight such categories, each described by a reliability constant ($C_f$) and an endurance limit, called the stress threshold ($F_{TH}$). The temperature and aggressiveness of the medium also affect fatigue resistance.

Among the most effective methods of increasing the fatigue lifespan of a connection are:

- Upgrading the stress category.
- Reducing the stress range.
- Decreasing the severity of stress concentrations.
- Implementing corrosion protection.

Stress concentrations can be reduced by incorporating smooth transitions with large radii and avoiding sharp geometrical discontinuities in welds.

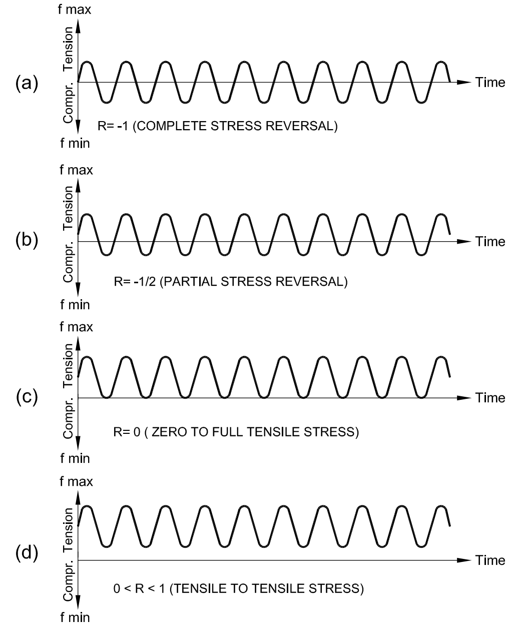


*Figure 1: Constant amplitude cycle loading.*

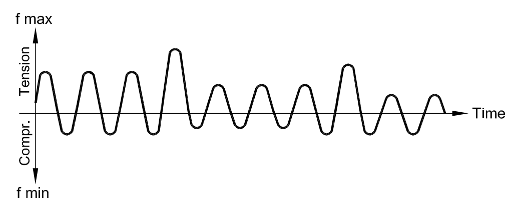


*Figure 2: Variable amplitude cycle loading.*

Corrosion fatigue behavior is affected by the same parameters as normal fatigue. However, in a corrosive environment, the fatigue threshold limit is lower and crack propagation is faster at all stress intensity levels. Common corrosion types – particularly crevice, pitting and inter-granular corrosion – affect crack propagation. Pitting corrosion is the most damaging type. How much should the threshold limit be lowered in a corrosive environment? There is no definitive answer, but it would be reasonable to reduce it by 10-15% unless a protective coating can provide reliable protection. Frequently the weld becomes the source of stress concentration, which itself leads to accelerated corrosion, which in turn increases the chances of fatigue. The whole process can be described by a simple sequence of events:

> Corrosion → Stress Concentration → Accelerated Fatigue, or Stress Concentration → Corrosion → Growing Stress Concentration → Accelerated Fatigue

On many occasions, corrosion is initiated in transition welds, at weld discontinuities and at sharp transition angles.

## Stresses Affecting Long-Span Crane Trusses

Crane trusses undergo a complex, fluctuating loading cycle. An overview of fluctuating load terminology can be seen in *Figure 1* and *Figure 2*.

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Stress cycles shown in *Figure 1* represent ideal constant-amplitude fatigue stresses. However, actual stress fluctuation is much more complex; a graph would show several short-term load cycles. Each cycle can be described by three operations:

- Load pick-up (maximum load on crane wheels).
- Load carry-over into the loading bay.
- Unloading (minimum load on crane wheels).

A new short-term load cycle starts when a crane moves into a new stationary position. There are also sub-cycles, characterized by crane travel between stationary positions. Sub-cycles are the least frequent events. The type of load fluctuation described by the curve shown in *Figure 2* is known as variable-amplitude loading. The cycle with the largest stress range is called a primary cycle. Crane relocation and operation from other stationary positions along the truss creates a series of secondary cycles, with much smaller stress range magnitudes. Therefore, the estimated fatigue life of the connection should be based on an equivalent constant-amplitude fatigue stress range, rather than the maximum stress range.

## Engineering for Fatigue

Stresses during the cyclic load are described by several parameters (*Figure 1*), including the maximum stress ($f_{max}$), the minimum stress ($f_{min}$), and the stress range ($f_{sr} = f_{max} – f_{min}$). Another important parameter, called the stress ratio ($R = f_{min}/f_{max}$), is strangely missing from the AASHTO LRFD 4th Edition and AISC 13th Edition. *Figure 1a* shows idealized cyclic stresses with complete stress reversal, $R = {}^{-}f_{min} / {}^{+}f_{max} = -1$. *Figure 1b* shows compression to tensile stress reversal with compression stress ${}^{-}f_{min} = –(0.5\ {}^{+}f_{max})$, R = – 0.5. *Figure 1c* shows cyclic stresses with zero to full tensile stress, $R = 0 / {}^{+}f_{max} = 0$. *Figure 1d* shows a tensile to tensile stress cycle, 0 < R < 1. Both $f_{max}$ and $f_{min}$ have positive signs.

*Figure 3* shows the fatigue limit correlation for different stress ratios, R = -1, R = 0 and R = 1. The fatigue strength was compared at 2,000,000 cycles and significantly decreases as the stress ratio decreases from R = 0 to R = -1. The fatigue limit with stress ratio 0 < R < -1 can be analytically interpolated from S-N stress curves shown in the *USS Steel Design Manual* for A36 and A50 steels. The threshold stresses shown in Table A-3.1 of AISC 13th Edition and Table 6.6.1.2.5-3 of AASHTO LRFD 4th Edition were referenced to a complete stress reversal cycle (R = -1). Comparison of the data streams indicates that threshold limits, referenced by both manuals, lead to overly conservative results. *Table 1* will help the designer to justify a constant-amplitude fatigue threshold ($F_{TH}$) based on the stress ratio (R).

### *Load Combinations and Dynamic Impact*

The dynamic vertical load is a random event. The main cause of impact is a combination of crane rail vertical misalignment and crane loading – e.g., unloading operations. Crane rail vertical misalignment affects impact during crane sub-cycles, and therefore should not be combined with impact due to loading-unloading operations. AISE Technical Report No 13 sets crane rail vertical misalignment criteria at ¼-inch. In the absence of any better references, designers of waterfront crane railways should indicate a ¼-inch vertical misalignment as a practical design limit. Presently, documents used for the design of crane ways, notably AISC 13th Edition and UFC 4-152-01, *Design: Piers and Wharves*, prescribe a 25% impact factor applied to the maximum listed wheel loads of the crane bogie.

A paper presented by P. H. Griggs (1976) indicated that measured vertical impact typically does not exceed 7% of the vertical static load on a crane wheel. The summary of suggested vertical impacts referenced by different sources is illustrated in *Table 2 (page 24)*.

The impact produced by a crane lift is explained by the ramped impulse equation described by S. P. Timoshenko (1974):

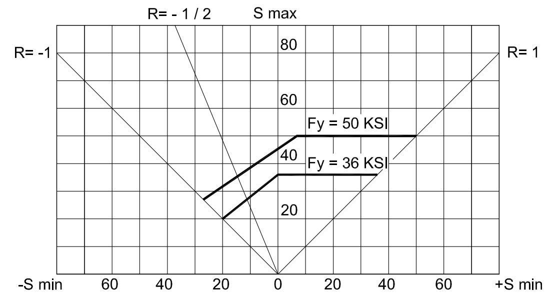


*Figure 3: Comparison of fatigue strength of as received structural steel plates at 2,000,000 stress cycles.*

$\delta_{max} = \delta_{st}\ (1+ T/\pi\tau\ {*}\sin(\pi\tau/T))$ (*Equation 1*)

where,

$(1+ T/\pi\tau\ {*}\sin(\pi\tau/T))$ = the dynamic amplification factor;

$\tau$ = is the duration of the impulse; and,

T = is the period of the first mode, known as the fundamental natural period.

Reverse analysis of *Equation 1* presented in *Table 3 (page 24)* shows the ($\tau$/T) influence on impact results. *Table 3* explains why measured impacts were never larger than 7% of that predicted by *Equation 1*. Weaver provides the following explanation for measured impact phenomena: "Actual tests have shown that impact on the crane girders rarely exceeds 5 to 7% of static load, even for relatively fast hoist speeds, due to cushioning effect resulting from torsion-spring action of the ropes (cables) and leaf-spring

*Table 1: Fatigue threshold limits.*

| Stress Category | Reliability Factor, Cf | Stress Ratio, R | Threshold Limit, FTH (ksi) |
|---|---|---|---|
| A | $250{*}10^8$ | 0 | 33 ( 0 to tensile) |
| | $250{*}10^8$ | -1/2 | 33 (partial reversal) |
| | $250{*}10^8$ | -1 | **24 (full reversal)** |
| B | $120{*}10^8$ | 0 | 26 (0 to tensile) |
| | $120{*}10^8$ | -1/2 | 21 (partial reversal) |
| | $120{*}10^8$ | -1 | **16 (full reversal)** |
| B' | $61{*}10^8$ | 0 | 20 (0 to tensile) |
| | $61{*}10^8$ | -1/2 | 16 (partial reversal) |
| | $61{*}10^8$ | -1 | **12 (full reversal)** |
| C | $44{*}10^8$ | 0 | 16 (0 to tensile) |
| | $44{*}10^8$ | -1/2 | 13 (partial reversal) |
| | $44{*}10^8$ | -1 | **10 (full reversal)** |
| D | $22{*}10^8$ | 0 | 11 (0 to tensile) |
| | $22{*}10^8$ | -1/2 | 9 (partial reversal) |
| | $22{*}10^8$ | -1 | **7 (full reversal)** |
| E | $11{*}10^8$ | 0 | 7 (0 to tensile) |
| | $11{*}10^8$ | -1/2 | 6 (partial reversal) |
| | $11{*}10^8$ | -1 | **4.5 (full reversal)** |

*Table 2: Vertical impact on crane railway.*

| Reference | Description |
|---|---|
| Griggs | ≤ 7% of the crane static load |
| Whiting Crane Handbook. | 5% to 7% from sum of hoist lifted load and weight of grappling device. |
| Russian Standard, SNIP 2.01.7-85 for Container Cranes (GOST 25546-82) | 10% of the crane static load on the crane bogie wheel. |

*Table 3: Theoretical impact.*

| $\tau/T$ | $\delta_{max} == \delta_{st}$ * *$[(1+T/\pi\tau*\sin(\pi\tau/T)]$ |
|---|---|
| 1.000 | $1.00\delta_{st}$ |
| 0.500 | $1.63\delta_{st}$ |
| 0.250 | $1.90\delta_{st}$ |
| 0.125 | $1.97\delta_{st}$ |
| 0.000 | $2.00\delta_{st}$ |

action of the girders." The boom of the container crane compliments leaf-spring action of the crane girder. A more gradual rise of the impulse duration reduces the effect of dynamic amplification. Since 1991, many crane girders used for support of heavy 300- to 400-ton steel mill cranes were successfully designed using a 10% impact factor applied to the maximum listed wheel load. Russian SNIP 2.01.7-85 has prescribed a 10% impact allowance applied to crane wheel loads since 1975. The majority of sources that have done independent research on impact agree that a 25% impact factor is overly conservative and highly unrealistic. *Tables 4* and *5* present load combinations suggested for crane way analysis. Notice that impact in these load combinations is taken as 10% of the static wheel load.

Very similar load combinations were suggested by Bhimani and Soderberg (2006). The impact suggested by Bhimani and Soderberg was included in load combinations WOP1 and WOP2 with 50% of the AISC 13th Edition and UFC 4-152-01 recommended value, virtually restricting the effect of vertical impact to 12.5% of the static load acting on the crane wheel. The author strongly believes that a 10% vertical dynamic impact allowance for crane runway design is a reasonable and sufficiently conservative assumption.

### Crane History

UFC 4-152-01 and the AISC 13th Edition have no provisions for fatigue design based on variable-amplitude loading. Design based on a maximum stress range coupled with the maximum number of load cycles is beyond reasonable conservatism. A properly designed long-span crane truss is always based on the anticipated future loads. "Future history" can be created by the facility operator, using data from the assumed ship sizes and scheduled arrivals. The ship data helps to locate the crane stationary positions for loading-unloading operations. Crane positions predetermine primary and secondary short-term load cycles for each critical location along the truss span. For fatigue analysis, all short-term load cycles are compiled into one variable-amplitude loading case. Fatigue analysis of all tension elements and connections of the structure is based on statistical formulas known as Miner's Rules and fatigue resistance curves.

### Miner's Rules

Fatigue analysis based on maximum stress levels and the maximum number of cycles yields ultra-conservative results. Shilling et al. (1979) expanded the Miner's Rule for the case of variable-amplitude loading. The first rule of that analysis states that the stress response of each joint is based on a fatigue damage ratio, which should not exceed unity:

$D = \Sigma\ (n / N)$ (*Equation 2*)

where,

n = number of cycles applied at a given stress range.

N = number of cycles for which the given stress range would be allowed by the appropriate S-N curve.

The second rule implies that the effective stress range is equal to the cube root of the mean cube of the stress range.

$S_{eff} = (\Sigma(n_i/N_{total}) * S^3_{ri})^{0.333}$ (*Equation 3*)

### S-N Curves

Fatigue resistance is derived from exponential curves, called the S-N relationship, where N is the number of cycles to failure and $S_r$ is the stress range.

$N = C_f / S^n_r$ (*Equation 4*)

n = 3 for all stress categories except F.

*Table 4: Suggested service load combinations.*

| Mode | Operating | | | Stowed |
|---|---|---|---|---|
| | WOP1 * | WOP2** | WOP3*** | |
| Crane Dead Load, **DL** | 1.0 | 1.0 | 0.66 | 1.0 /(0.66) |
| Lift System, **LS** | 1.0 | 1.0 | 0.66 | 1.0 /(0.66) |
| Lifted Load, **LL** | 1.0 | 1.0 | | |
| Impact Load, **IL** | 0.1(LS+LL) | 0.1(DL+LS+LL) | | |
| Operational Wind, **OWL** | 1.0 / (0) | 1.0 / (0) | | |
| Storm Wind Load, **SWL** | | | | 1.0 |
| Earthquake Load, **EQ** | | | | |
| Collision Load, **CL** | | | 0.66(DL+LS) | |

*Table 5: Suggested factored load combinations.*

| Mode | Operating | | | Stowed |
|---|---|---|---|---|
| | WOP1 * | WOP2** | WOP3*** | |
| Crane Dead Load, **DL** | 1.2 | 1.2 | 1.0 | 1.2 /(1.0) |
| Lift System, **LS** | 1.2 | 1.2 | 1.0 | 1.2 /(1.0) |
| Lifted Load, **LL** | 1.6 | 1.6 | | |
| Impact Load, **IL** | 0.1*1.6(LS+LL) | 0.1*1.6(DL+LS+LL) | | |
| Operational Wind, **OWL** | 1.6 / (0) | 1.6 / (0) | | |
| Storm Wind Load, **SWL** | | | | 1.6 |
| Earthquake Load, **EQ** | | | | |
| Collision Load, **CL** | | | 1.0(DL+LS) | |

*NOTES:*

* *Load Combination for load pick up*

** *Load Combination for load carried by crane along the crane way within the crane loading bay.*

*** *Factors shown in parenthesis / ( ) are given for load cases when wind load causes uplift.*

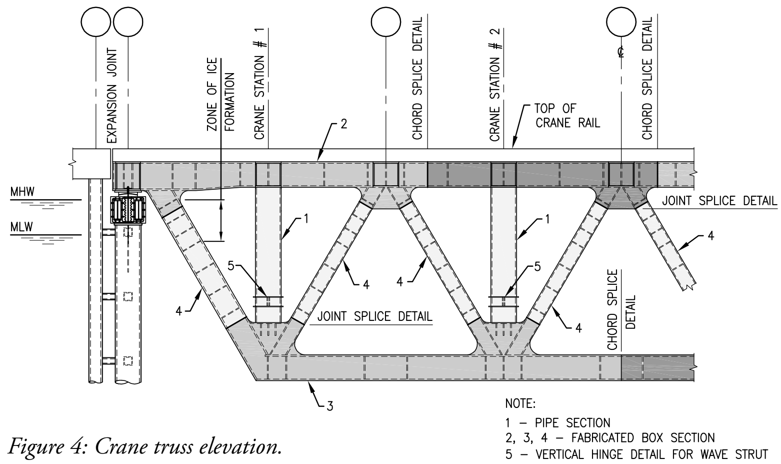


*Figure 4: Crane truss elevation.*

$C_f$ = stress category reliability coefficient.
$S_r$ = design service load stress range.

The S-N curves were developed for different stress categories and are presented in the AISC 13th Edition and AASHTO LRFD Specifications Tables (based on constant-amplitude, full-stress-reversal loading). The following example provides step-by-step direction on how to determine the service life of a connection detail, converting variable-amplitude stress ranges into an equivalent effective stress range.

### Example 1

Assume four short-term load cycles. *Figure 4* shows a crane truss with four stationary positions. Obviously, the designer can select stations at 1 foot o.c. However, experienced designers should select strategic stations, allowing for a more efficient analysis. Load cycle #1 denotes the primary load cycle. Load cycles from #2 to #4 are secondary load cycles for investigated stationary positions of the crane. Thus, each crane stationary position denotes the cycle number. Service load stresses imposed by each load cycle at the connection are shown in column $S_{ri}$. The number of stress ranges for each cycle is shown in column $n_i$. *Table 6* gives the number of cycles per day; the ideal time history will be based on a longer term. The longer the time history, the greater the analysis precision. Analyses of the effective stress range and fatigue damage ratio are presented in *Tables 6* and *7*. The result of the analysis compiled in *Table 6* shows that the effective constant-amplitude stress range $S_{eff,}$ = 14.12 ksi.

Using the S-N relationship formula (*Equation 4*), the designer can calculate the equivalent number of cycles, or fatigue life, of the connection.

$N = C_f / S^n_r$ for stress category B, (n = 3)

$N_B = 1.20*10^{10} / 14.12^3$ = 4,262,625 cycles

If the stress category is changed to B', the number of load cycles will become significantly lower:

$N_{B'} = 0.61*10^{10} / 14.12^3$ = 2,166,835 cycles.

Knowing the estimated number of annual cycles, the designer can estimate the lifespan of the structure. Assuming 160 cycles per day or 160 x 365 = 58,400 per year, the life span of the connection,

$N_{B'years}$ = 2,166,835 / 58,400 = 37.10 years for Stress Category B'.

$N_{B\ years}$ = 4,159,059 / 58,400 = 71.21 years for Stress Category B.

Fatigue life of the structure is determined from the lowest number of cycles attributed to each joint. Similar checks should be made for each connection detail subjected to tensile stresses. In general, the design fatigue life of each joint and member should be at least 25% longer than the intended service life of the structure. In other words, all elements have to be designed with a safety factor of 1.25.

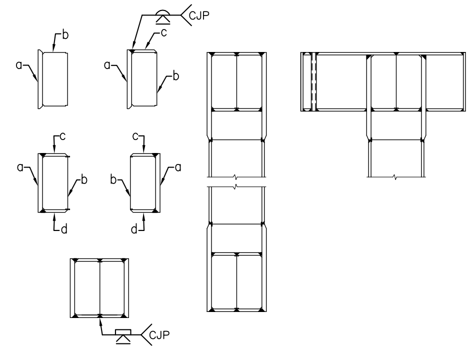


*Figure 5: Fatigue resistant box section for truss fabrication.*

The lifespan of the structure can be derived from the limit imposed on the fatigue damage ratio, D < 1.0 (*Equation 2*). An analysis of the Fatigue Damage Ratio is compiled in *Table 7*.

$N_{B'\ years}$ = 1.0 /0.02 = 50 years for Stress Category B'.

The estimated service life of the truss derived from *Equations 3* and *4*.

N service = 37.10 / 1.25 = 30 years

All connections and joints of the crane truss should be specified with prequalified full-penetration welds. Weldments prone to lamellar tear must be excluded. Weldment details recommended for the best fatigue resistance performance are shown in *Figure 5*.

Connections designed with the highest stress category and lowest stress range, $S_r$, will have the best fatigue resistance.▪

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Part 2 of this article will appear in an upcoming issue of STRUCTURE.

*Table 6: Analysis of effective stress range, connection 1, miner rules, equation 4.*

$N_{total}$ =160

| | Stress Category B’ | | | | | |
|---|---|---|---|---|---|---|
| Cycle # | $C_f$ | $S_{ri}$, ksi | $n_i$ number of stress ranges $S_{ri}$ | $n_i / N_{total}$ | $(n_i / N_{total})*S^3_{ri}$ | S eff, ksi |
| 1 | 0.61*1010 | 18 | 40 | 0.25 | 1458.0 | |
| 2 | | 16 | 40 | 0.25 | 1024.2 | |
| 3 | | 10 | 40 | 0.25 | 250.0 | |
| 4 | | 7 | 40 | 0.25 | 85.75 | 14.12 |

$\Sigma(n_i / N_{total})*S^3_{ri})$
$= S^3_{eff}$ = 2,817.9

*Table 7: Analysis of fatigue damage ratio, connection 1, miner rules, equation 3.*

| | Stress Range | | Stress Category B’ (n=3) | | |
|---|---|---|---|---|---|
| Cycle # | $S_r$ | n | $C_f$ | $N=C_f / S^n_r$ | n / N |
| 1 | 18 | 40*365 | 0.61*1010 | 1,045,953 | 0.0104 |
| 2 | 16 | 40*365 | | 1,489,258 | 0.007 |
| 3 | 10 | 40*365 | | 6,100,000 | 0.0018 |
| 4 | 7 | 40*365 | | 17,784,256 | 0.0006 |

$D = 0.02N_{years} < 1.0$

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