

Guidance on the verification of crane systems using the allowable stress method

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**Guidance on the Verification of Crane Systems using the Allowable Stress Method
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1.0 Introduction

Predominantly in the UK, cranes were designed to BS 2573^[1] which uses the maximum allowable stress principle for design. This standard is to be withdrawn and superseded by the 13001-standard series, this series encourages you to use the limit state method.

SME's have relatively low production volumes and as such, the advantage of saving money on materials by over-engineering is nominal compared to the cost associated with investing resources in using the ultimate state method. The cost associated with changing to this method and designing to the ultimate limit states is cause of great concern for some SME's because of the complicated nature of this standard. These concerns, however, are misguided because EN 13001-1^[2] does allow for the maximum allowable stress method to be used, the guidance herein seeks to ease some of these concerns and guides the SME's to the relevant clause of EN 13001-1 which allows them to use this method.

It is recommended this document is read alongside the relevant Eurocodes, particularly EN 13001-3-1^[3] and that all relevant forces are considered.

1.1 Maximum Allowable Stress Method

[§4.2.7.2 of EN 13001-1]

The maximum allowable stress method is a special case of the limit state method which is applicable for the proof of competence calculation where cranes or portions of the cranes mass act only unfavourably and have a linear relationship between load actions and the load effects.

Individual specified loads f_i shall be calculated and amplified where necessary using the factors ϕ_i and shall be combined according to the load combinations under consideration. The combined load \bar{F}_j shall be used to determine the resulting load effects \bar{S}_k , i.e the inner forces in structural and mechanical components or the forces in articulations and supports.

For proof that yielding and elastic instability do not occur, the nominal stress $\bar{\sigma}_{1l}$ due to the action of the load effects on a particular element or component shall be calculated and combined with any stresses $\bar{\sigma}_{2l}$ resulting from local effects. The resulting stress $\bar{\sigma}_1$ shall be compared with the maximum allowable stress adm σ . In this guidance document, you will see the maximum allowable stress expressed as $f_{Rd\sigma}$ and $f_{Rd\tau}$ for normal stresses and shear stresses respectively.

One of the advantages of this method is that we can obtain the maximum allowable stress at the beginning stages of the process, this in turn allows the engineer to design their system so that the area of the components is large enough that it can support the load and keep the resultant stress below the maximum allowable stress.

1.2 The Method

1. Calculate \bar{F}_j

Guidance on obtaining the dynamic factors appears in BS EN 13001-2: Load Actions. ^[4]

Where:

ϕ_i : Dynamic factors

f_i : Individual loads

$$\phi_i f_i = \bar{F}_j$$

LEE A has a worked example which shows how individual loads can be calculated and amplified with dynamic factors, for more information refer to LEEA 075 – Guidance to the verification of runway beams. Annex A. Worked example for the verification of a runway beam with an underslung hoist. ^[5]

2. Determine \bar{S}_k (Shear Force & Bending Moments)

The combined load \bar{F}_j shall be used to determine the resulting load effects through structural and dynamic analysis. These are typically the bending moments and shear forces resulting from the combined load \bar{F}_j .

Where:

\bar{F}_j : Combined Load accounting for dynamic uncertainties.

\bar{S}_k : Resulting load effects (Inner forces in components or articulations).

$$\bar{F}_j \rightarrow \bar{S}_k$$

3. Calculate nominal stresses $\bar{\sigma}_{1|}$.

Through an appropriate elasto-kinetic model the resulting load effects \bar{S}_k shall be applied to their respective connections and components, from these the nominal stresses $\bar{\sigma}_{1|}$ should be obtained. \bar{S}_k : Resulting from load effects (Inner forces in components or articulations)

$\bar{\sigma}_{1|}$: Stress due to load effects on an element

$$\bar{S}_k \xrightarrow{\text{Through component}} \bar{\sigma}_{1|}$$

4. Combined stresses

Combine stresses due to load effects on a component $\bar{\sigma}_{1|}$ with the stresses resulting from local effects $\bar{\sigma}_{2|}$.

$$\bar{\sigma}_{1|} + \bar{\sigma}_{2|} = \sigma_1$$

5. Compare stresses

The resulting stress σ_1 must be less than the maximum allowable stress.

$$\sigma_1 \leq \sigma_{adm}$$

The maximum allowable stress is derived from the specific strength of the material in question with a 95% probability of survival divided by the overall safety factor.

$$f_{Rd\sigma} = \frac{f_y}{\gamma_n \times \gamma_{Rm}}$$

$$f_{Rd\tau} = \frac{f_y}{\gamma_n \times \gamma_{Rm} \times \sqrt{3}}$$

Where:

$\gamma_{Rm} = \gamma_f \times \gamma_{sm}$ for the allowable stress method.

$\gamma_{sm} = 0.95$.

γ_f is the overall safety factor for the allowable stress method.

γ_n is the risk coefficient and it shall be applied where applicable.

2.0 Actions Induced by Cranes and Machinery

We have established that when the allowable stress method is used, the bridge of the crane should be verified in accordance with EN 15011 [6], EN 13001-2 and EN 13001-3-1.

Once this is done, we must ensure that the supporting structure can handle the resultant stresses, Annex G of EN 15011 provides you with a format that enables designers of crane supporting structures to create relevant load combinations in accordance with EN 1991-3 [7] and EN 1993-6 [8].

The forces due to load effects described in Table G.1 of EN 15011 shall be given. Unlike the bridge of the crane, these forces shall be calculated without applying the dynamic factors and partial safety factors. The load positions shall be selected so as to give the maximum loads for each end carriage. The simultaneous lighter loads in the other shall also be given where relevant.

3.0 Design example for the allowable stress method

The sections below offer a simplified example of the allowable stress method.

For more information on the use of the Eurocodes BSI has produced comprehensive guidance on the subject. Please refer to Worked example for Eurocodes 3: Design of steel structures. [9]

For simplicity, we will assume that the load effects applicable to the bridge of the crane have been correctly obtained by amplifying the loads with the corresponding dynamic factors, the inner forces and moments resulting from this load combination must be calculated.

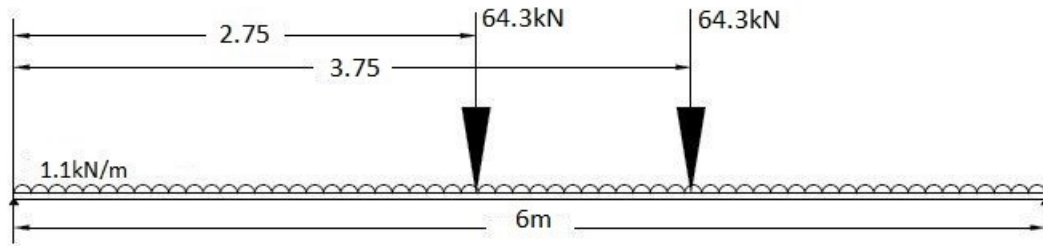


Figure 1: Design example

3.1 Calculate the point of maximum stress

We are looking to obtain the maximum bending moments arising from the crane loads, therefore we must figure out the points along the beam at which these occur.

$$P_{max, stress} = 0.5 \left(L - \frac{a}{2} \right) = 0.5 \left(6 - \frac{1}{2} \right) = 2.75m$$

To obtain the maximum shear force, the wheel forces must be applied at the supports, the reactions are shown in section 7.10.

3.1.2 Wheel load positions for maximum stress

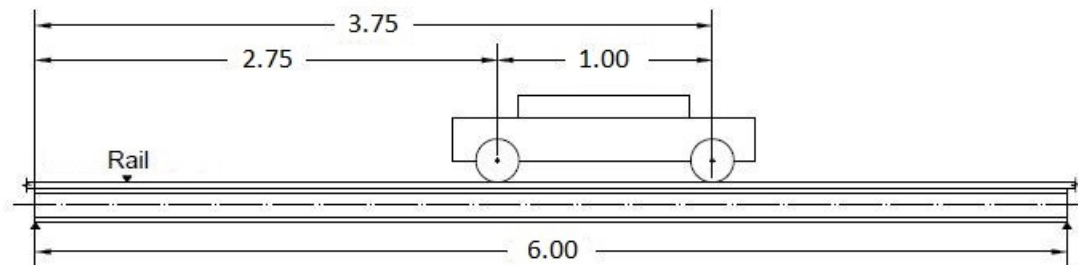


Figure 2: Wheels located at the point of maximum stress

3.2 Calculate reactions

Where the left-hand support will produce a reaction force R_A and the right-hand support will produce R_B .

We find that:

$$R_A + R_B = 64.3 + 64.3 = 128.6kN$$

$$6R_B - 2.75(64.3) - 3.75(64.3) = 0$$

$$6R_B = 176.825 + 241.125$$

$$6R_B = 417.95$$

$$R_B = 69.658kN$$

$$R_A = 128.6 - 69.658 = 58.942kN$$

3.3 Resultant shear force and bending moments from point loads

$$V = 58.942kN$$

$$\text{Maximum Bending Moment} = V \times x_1$$

$$\text{Maximum Bending Moment} = 58.942 \times 2.75 = 162.089kNm$$

3.4 Shear force and bending moments arising from uniformly distributed load

$$UDL = 1.1 \text{ kN/m}$$

$$V = \frac{UDL \times L}{2} = \frac{1.1 \times 12}{2} = 6.6kN$$

$$\text{Maximum Bending Moment} = \frac{UDL \times L^2}{8}$$

$$\text{Maximum Bending Moment} = \frac{1.1 \times 12^2}{8} = 19.8kNm$$

3.5 Total forces arising from point loads and the uniformly distributed load

$$M_y = 162.089 + 19.8 = 181.889kNm$$

$$V_{Ed} = 58.942 + 6.6 = 65.542kN$$

3.6 Wheel loads adjacent to supports

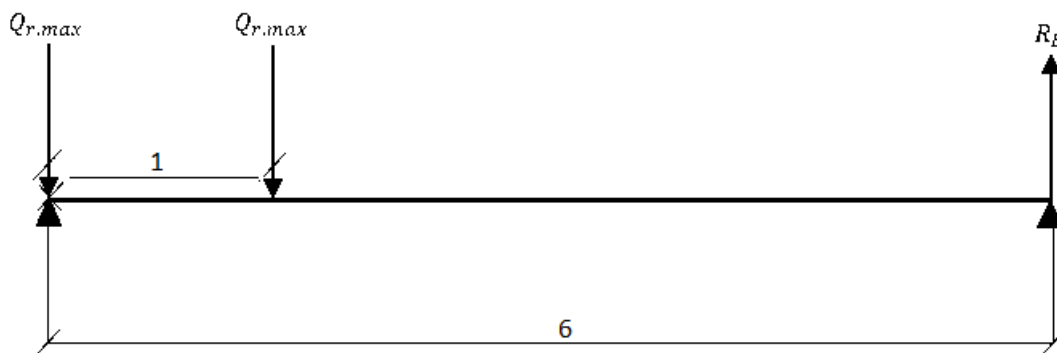


Figure 3: Wheel load position for maximum shear force on runway beam

$$V_{max} = 117.884kN$$

3.7 Summary of resulting forces and moments \bar{S}_k

When the wheel loads are positioned at the points of maximum stress, we find that:

Bending moment arising from point loads and UDL: $M_y = 181.889kNm$;

Shear force arising from points loads and UDL: $V_{Ed} = 58.942 + 6.6 = 65.542kN$;

When the left-hand wheel is adjacent to the supports, we find that:

Shear force arising from point loads and UDL; $V_{max} = 117.884k$

3.8 Stresses

3.8.1 Nominal stresses due to load effects $\bar{\sigma}_1$

$$\sigma_{max,Bending} = \frac{My}{I} = \frac{181889 \times 0.270}{0.000291} = 168762989.7 = 168.7MPa$$

$$\tau_{Max} = \frac{VQ}{It}$$

Figure 13: Nomenclature for obtaining first moment of area Q

$$Q = A_{flange}(\bar{y}'_1) + 2 \times A_{web}(\bar{y}'_2) + A_{rail}(\bar{y}'_3)$$

$$Q = 1.128775 \times 10^{-3}m^3$$

When the left-hand wheel load is adjacent to the left support:

$$\tau_{Max} = \frac{75.96 \times 10^3(1.128775 \times 10^{-3})}{0.000291 \times 0.0125} = 36MPa$$

3.8.2 Shear Stresses due to torsion

Closed sections are very resistant torsion, this is why the local shear stress due to torsion is assumed to be negligible when these sections are used. However, the following section provides an example of how these stresses can be calculated.

For closed thin walled sections we know that the shear stress is defined by:

$$\tau_{max} = \frac{T}{2A_m t}$$

Where:

T is the torque acting on the section;

A_m is the area enclosed by the median line of the section.

First, we must calculate A_m .

The area enclosed by the whole box is given by $A_2 = 0.4m \times 0.2m = 0.08m^2$

The area of the section is $A = 0.0142m^2$

$A_m = A_2 - 0.5A = 0.08 - 0.5(0.0142) = 0.0729m^2$

$T = 64300N \times 0.270m = 17361Nm$

$$\tau_{max} = \frac{17361}{2 \times 0.0729 \times 0.0125} = 9525925.9 = 9MPa$$

Rail properties A

$b = 12.5mm$

$h = 70mm$

$f_y = 355 N/mm^2$

$UDL = 1.1kN/m$

3.9 Combined stresses σ_1, τ_1

In accordance with the maximum allowable stress method the local stresses must be combined with the nominal stresses, for simplicity we have neglected some of the applicable local stresses. However, please note all of these must be considered and included in the calculations for the allowable stress method, guidance on local stresses arising from wheel loads is provided for in Annex E of EN 15011.

3.9.1 Combined bending stress

If web stiffeners are fitted, then the resulting maximum bending stress can be defined by:

$$\sigma_1 = \sigma_{max,Bending}$$

$$\sigma_1 = 169MPa$$

3.9.2 Combined shear stress

$$\tau_1 = \tau_{max} + \tau_{torsion} = 36 + 9 = 45MPa$$

3.10 Calculating the maximum allowable stress

The details of the maximum allowable stress are given in BS EN 13001-2, the method requires the use of 'special safety factors γ_f ', instead of the partial safety factor γ_m which is required for the limit state method. These special safety factors can be found on table 12a of EN 13001-2. However, further guidance for the limit design stress is given in BS EN 13001-3-1 Cranes – General Design. Limit States and Proof of Competence of a Steel Structure. [8]

The maximum allowable stress shall be calculated in accordance with BS EN 13001-3-1 with the relevant special safety factors given in BS EN 13001-2 instead of the general resistance factor γ_m suggested in the former standard.

For example, the maximum stress shall be calculated using the following expressions:

$$f_{Rd\sigma} = \frac{f_y}{\gamma_n \times \gamma_{Rm}} \text{ for normal stresses.}$$

$$f_{Rd\tau} = \frac{f_y}{\gamma_n \times \gamma_{Rm} \times \sqrt{3}} \text{ for shear stresses.}$$

Where:

$\gamma_{Rm} = \gamma_m \times \gamma_{sm}$ for the limit state method.

$\gamma_{Rm} = \gamma_f \times \gamma_{sm}$ for the allowable stress method.

γ_{sm} is the specific resistance factor for material, refer to 5.2.2 of EN 13001-3-1.

$\gamma_{sm} = 0.95$ for rolled materials.

γ_n is the risk coefficient and it shall be applied where applicable.

Therefore, for load combination type A, we find that the maximum allowable stress can be defined by:

$$f_{Rd\sigma} = \frac{f_y}{\gamma_{Rm}}$$

For bending stresses:

$$f_{Rd\sigma} = \frac{355}{1.48 \times 0.95} = 252.5MPa$$

For shear stresses:

$$f_{Rd\tau} = \frac{355}{(1.48 \times 0.95)\sqrt{3}} = 145.8MPa$$

For load combination type B, we find that the maximum allowable stress can be defined by:

For bending stresses:

$$f_{Rd\sigma} = \frac{355}{1.34 \times 0.95} = 278.9MPa$$

For shear stresses:

$$f_{Rd\tau} = \frac{355}{(1.34 \times 0.95)\sqrt{3}} = 161MPa$$

For load combination type C, we find that the maximum allowable stress can be defined by:

For bending stresses:

$$f_{Rd\sigma} = \frac{355}{1.22 \times 0.95} = 306.3Pa$$

For shear stresses:

$$f_{Rd\tau} = \frac{355}{(1.22 \times 0.95)\sqrt{3}} = 176.8MPa$$

3.11 Compare stresses

The resulting stress must be less than the allowable stress, so for load case A, the following applies:

Shear stress

$$\sigma_1 \leq f_{Rd\tau}$$

$$45 < 145.8 \checkmark \text{ this is satisfactory.}$$

Bending stress

$$\sigma_1 \leq f_{Rd\sigma}$$

$$169 \leq 252.5 \checkmark \text{ this is satisfactory.}$$

4.0 Conclusion

This guidance directs the crane designer to the relevant standards that must be considered for the use of the allowable stress method. It also provides a simplified example to the allowable stress method.

The designer of the crane bridge must ensure that the resultant combined stresses from load cases A, B and C are compared to the appropriate admissible stress for each of its corresponding load cases. Once this is done, the designer of the bridge must provide the designer of the supporting structure with all the relevant forces acting on the structure, the forces should be provided in the format laid out in Annex G of EN 15011 and the structure should then be verified in accordance with the relevant parts of EN 1991-3 & EN 1993-6.

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