Illustration of fatigue design of a crane runway beam

As indicated in the technical article[1] in the September 2018 issue of New Steel Construction Richard Henderson of the SCI discusses the fatigue design of crane runway beams with an illustrative design example.

Crane Loading

The loads on crane runway beams are determined in accordance with BS EN 1991-3[2]. This code sets out the groups of loads and dynamic factors to be considered as a single characteristic crane action. The relevant partial factors are set out in Table A.1 in Annex A of the code. At ultimate limit state for the design of the crane and its supporting structures, the characteristic crane action being considered is combined with simultaneously occurring actions (eg wind load) in accordance with BS EN 1990. The final ultimate design loads from the crane end carriage which are supported by the runway beam can thus be determined.

The groups of loads are identified in Table 2.2 of BS EN 1991-3 and include the actions listed in the table below. Several of the loads have a dynamic factor associated with them which depend on the class and function of the crane.

Item	Description of load	Dynamic factor
1	Self-weight of crane	φ_1 or φ_4
2	Hoist load	φ_2, φ_3 or φ_4
3	Acceleration of crane bridge	φ_5
4	Skewing of crane bridge	-
5	Acceleration or braking of crab or hoist block	-
6	In-service wind	-
7	Test load	φ_6
8	Buffer force	φ_7
9	Tilting force	-

Unfavourable crane actions have a γ_Q value of 1.35, not the usual value of 1.5. Fatigue assessment is regarded as a serviceability limit state with a partial factor of 1.0.

Fatigue Assessment

BS EN 1991-3 provides a simplified approach to designing crane runway beams (gantry girders) for fatigue loads to comply with incomplete information during the design stage, when full details of the crane may not be available. The crane fatigue loads are given in terms of fatigue damage equivalent loads Q_e that are taken as constant for all crane positions. The fatigue load may be specified as follows:

$$Q_e = \varphi_{fat} \lambda_i Q_{max,i}$$

where, as stated by the code, $Q_{max,i}$ is the maximum value of the characteristic vertical wheel load, i and $\lambda_i = \lambda_{1,i}\lambda_{2,i}$ is the damage equivalent factor to make allowance for the relevant standardized fatigue load spectrum and absolute number of load cycles in relation to N = 2.0 × 10^6 cycles. This concept was discussed in reference [1].

The damage equivalent dynamic impact factor φ_{fat} for normal conditions may be taken as:

$$\varphi_{fat,1} = \frac{1+\varphi_1}{2} \quad \text{and} \quad \varphi_{fat,2} = \frac{1+\varphi_2}{2}$$

The factors $\varphi_{fat,1}$ and $\varphi_{fat,2}$ apply to the self-weight of the crane and the hoist load respectively.

In BS EN 1991-3, Annex B Table B.1 gives recommendations for loading classes S in accordance with the type of crane and Table 2.12 gives a single value of λ for each of normal and shear stresses according to the crane classification. Overhead travelling cranes are in either S-class S6 or S7 so that, having selected an S class, the corresponding λ value is determined. (The classes S_i correspond to a stress history parameter s defined in BS EN 13001-1[3] but the details are not required for this example).

The method for carrying out the fatigue assessment is set out in section 9 of BS EN 1993-6[4]. Once the fatigue loads are determined, the stress ranges (denoted $\Delta\sigma_{E,2}$) for the critical details of the crane runway beam can be calculated. These are the damage equivalent stress ranges related to 2 million cycles. The fatigue stress range is multiplied by the partial factor for fatigue loads γ_{Ff} stated in BS EN 1993-6 section 9.2 which is equal to 1.0. The critical details must be categorized according to Tables 8.1 to 8.10 in BS EN 1993-1-9 and the detail category number noted. The category number (denoted $\Delta\sigma_C$) is the reference value of the fatigue strength at 2 million cycles. The partial factor for fatigue strength is γ_{Mf} and is given as 1.1 in the National Annex to BS EN 1993-1-9 for a safe-life fatigue assessment. The fatigue check involves showing that, for direct stresses:

$$\frac{\gamma_{Ff}\Delta\sigma_{E,2}}{\Delta\sigma_C/\gamma_{Mf}} \le 1.0$$

A similar check is required for fluctuating shear stresses:

$$\frac{\gamma_{Ff}\Delta\sigma_{E,2}}{\Delta\tau_C/\gamma_{Mf}} \le 1.0$$

If both direct and shear stresses are present, a further check is required.

Example

Consider an EO travelling crane of S-class 6 and hoisting class HC3 supported on 8.0m span runway beams in steel grade S355 which have laterally restrained compression flanges at 2.0 m centres. The crane is wholly inside a building and so there are no other simultaneously occurring actions. The relevant weights of the crane, the proportion of the weight applied to the end carriage in the worst case and the resulting maximum loads are:

▶28

▶26

Item	Load (kN)	Proportion of load	Load on end carriage (kN)
End carriage and bridge (Q_c)	164	50%	82
Crab (Q_c)	36	90%	33
Payload (Q_h)	300	90%	270

For the purpose of this example, consider load group 1 from Table 2.2 of BS EN 1991-3:

$$\varphi_1 Q_c + \varphi_2 Q_h + \varphi_5 (H_L + H_T)$$

where H_L and H_T are caused by acceleration or deceleration of the crane bridge and for simplicity will not be considered further. From Table 2.4 of BS EN 1991-3, the upper-bound value of $\varphi_1 = 1.1$ and the value of φ_2 is given by:

$$\varphi_2 = \varphi_{(2,min)} + \beta_2 v_h$$

where v_h is the steady hoisting speed and β_2 is a coefficient. According to Table 2.5 of BS EN 1991-3, for hoisting class HC3, $\varphi_{2,min} = 1.15$ and $\beta_2 = 0.51$. Taking the steady hoisting speed as $v_h = 1.0$ ms^{-1}, the value of φ_2 is 1.66. Applying the dynamic factors gives the following loads:

Item	Dynamic factor	Factored Load on end carriage (kN)
End carriage and bridge (Q_c)	1.1	90
Crab (Q_c)	1.1	36
Payload (Q_h)	1.66	448

The crane end carriage will be assumed to have wheels 2.0 m apart and the loads are distributed between them as indicated in the table below (the weight of the crane bridge is assumed not to be distributed evenly). The ultimate loads on each wheel are as indicated:

Item	Load Wheel 1 (kN)	Load Wheel 2 (kN)	Total (kN)
End carriage and bridge (Q_c)	50	40	90
Crab (Q_c)	18	18	36
Payload (Q_h)	224	224	448
Ultimate load (factor = 1.35)	393	381	774

The maximum moment in the beam occurs when the centre of the span bisects the distance between the resultant of the loads and a wheel load as shown in figure 1.

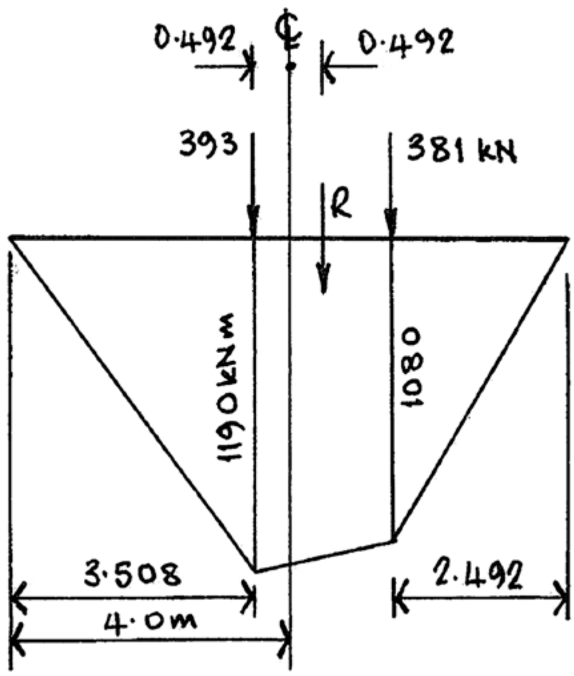

Figure 1: Ultimate bending moments

The maximum bending moment is 1190 kNm. Assuming a uniform bending moment between compression flange restraints, using the Blue Book, a 610 × 229 UB 125 with restraints at 2.0 m centres has a buckling resistance moment (with $C_1 = 1.0$) of 1230 kNm which is satisfactory for ultimate loads. The elastic modulus of the beam W_e is 3220 cm^3.

As indicated above, BS EN 1991-3 gives a simplified approach to calculating the fatigue damage equivalent load Q_e which may be expressed as follows:

$$Q_e = \varphi_{fat} \lambda Q_{max,i} = \lambda \left[\varphi_{fat,1}(Q_{max,i})_1 + \varphi_{fat,2}(Q_{max,i})_2 \right]$$

where $\varphi_{fat,j} = (1 + \varphi_j)/2$ and the index j refers to the dynamic factor. Substituting values for φ_1 and φ_2 gives $\varphi_{fat,1} = 1.05$ and $\varphi_{fat,2} = 1.33$. and calculating the characteristic and fatigue damage equivalent loads gives the following results:

Item	Load Wheel 1 (kN)	Load Wheel 2 (kN)	Total (kN)
Characteristic load $(Q_{max,i})_1$	62	53	115
Characteristic payload $(Q_{max,i})_2$	135	135	270
$\Sigma\, \varphi_{fat,j}\,(Q_{max,i})$	245	231	

The maximum bending moment in the beam is shown in Figure 2 and is equal to 734 kNm.

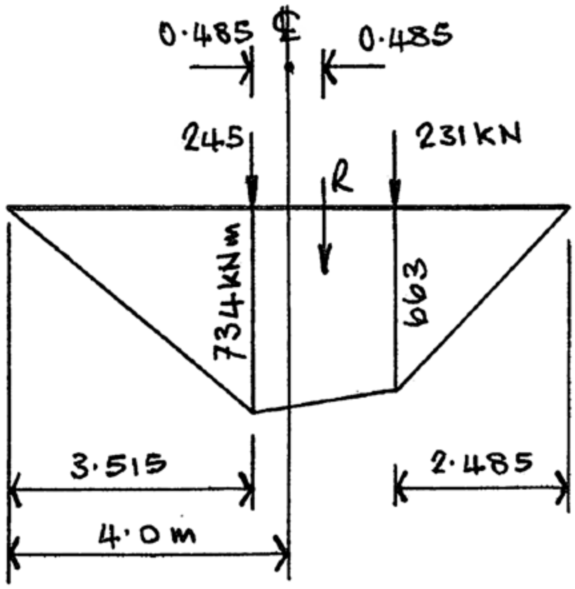

Figure 2: Bending moments from fatigue loads

The maximum direct stress due to fatigue loads is therefore 228 MPa. The self-weight bending moment at the same position is about 9.7 kNm which gives a stress of about 3.0 MPa. Table 2.12 of BS EN 1991-3 gives a single value of $\lambda = 0.794$ for direct stress for class S_6.

The fatigue stress range is therefore:

$$\Delta\sigma_{E,2} = (228 \times 0.794) - 3.0 = 178 \text{ MPa}$$

Consider the bottom flange first: the detail category is 160 which corresponds to a rolled section with as-rolled edges, fettled in accordance with the requirements stated in BS EN 1993-1-9 Table 8.1 for the relevant detail category, so $\Delta\sigma_C = 160$ MPa. For the fatigue verification, considering direct stress:

$$\frac{\gamma_{Ff}\Delta\sigma_{E,2}}{\Delta\sigma_C/\gamma_{Mf}} \leq 1.0$$

so, substituting values:

$$\frac{1.0 \times 178}{160 / 1.1} = 1.23 \text{ — fails!}$$

The fatigue load case is obviously more critical than the ultimate load case. Note that the highest fatigue class was chosen for the assessment. If the top flange is considered and the crane rail is fastened to the top flange with bolted cleats (a more onerous case), the relevant detail category is 90 (description: structural element with holes subject to bending and axial forces) and the factored fatigue stress is about 82 MPa. The stress $\Delta\sigma_{E,2}$ must be less than this value to satisfy the verification equation so a much larger beam is required. The elastic modulus must at least equal:

$$3220 \times \frac{178}{82} = 6990 \text{ cm}^3$$

A 914 x 305 UB 201 has an elastic modulus of 7200 cm³. This beam has a buckling resistance moment of 1310 kNm for a length of 8 m between lateral restraints so no intermediate restraints are required.

For a complete assessment, the axial and transverse forces which have been neglected increase the stresses in the beam and must be considered.

References

[1] Henderson R, Introduction to fatigue design to BS EN 1993-1-9, NSC, September 2018

[2] BS EN 1991-3: 2006 Eurocode 1 – Actions on structures Part 3: Actions induced by cranes and machinery

[3] BS EN 13001-1:2015 Cranes – General Design Part 1: General principles and requirements

[4] BS EN 1993-6: 2007 Eurocode 3 Design of steel structures – Part 6: Crane supporting structures

[5] BS EN 1993-1-9:2005 Eurocode 3 Design of steel structures – Part 1-9 Fatigue