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Local stresses in webs of crane runway girders: Tests and numerical calculations

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ABSTRACT

The design of crane runway girders is strongly affected by the local stresses due to wheel loads (mainly fatigue design, but also web buckling). A realistic approach of these local stresses, particularly the vertical direct stresses σ_z at the web top, is very important for economic design.

In this paper firstly a summary of formulae in literature and in relevant international design standards is given. These formulae are based on very limited tests in the past, which are also mentioned.

In the main part of this paper new test results for local stresses in webs due to vertical wheel loads for crane runway girders with I-section and box section are given, also including different connections with the crane rails (with/without welds between rail and girder flange and cases with no rail). Centric loading was tested, but also eccentric loading with different eccentricities, leading to additional web bending out of plane.

For all tests, accompanying comprehensive Finite Element analyses were conducted. These FE-models are also presented and their results are compared with the test results and with the predictions of design formulae, used in practice. Finally, additional numerical investigations are presented, dealing with the effects of different contact properties between rail and girder flange.

1. Introduction

Vertical wheel loads on rails of crane runway girders will not only result in global stresses in the girder due to bi-axial bending and torsion. They will also cause local stresses in the girder's web that have to be superposed with the global stresses. While vertical loadings that act centrically on the girder (related to the centre plane of the web) induce membrane direct stresses in the web, eccentric vertical loadings will lead to membrane direct stresses plus plate bending of the web. A realistic approach of this local stresses at the top of the web is very important to get accurate predictions of the remaining fatigue life of crane runway girders and also for the verification of web buckling.

The theoretic background of the stresses due to centric wheel loading (see Eq. (1) in chapter 1.1) goes back to [1,2,3,4]. Apart from some minor differences in the simplifications of the local model, the resulting maximum local vertical direct stress is approximately the same for all these suggested solutions.

In [3] the author additionally presents three experimental test results, but is mainly focussing on the global direct stresses. So no results for the local vertical direct stresses are given.

In [4] another three experimental tests on IP 32 sections – that would approximately correspond to the European hot rolled section HEB 320 – are presented. Unfortunately, only one test specimen was equipped with strain gauges (five on each side of the web) to measure the local vertical strains. The results showed large differences between corresponding strain gauges at the two sides of the web. Therefore, it was concluded that the load introduction (that must have been eccentrically) induced local web bending. A comparison between experimental measurements and analytically calculated results showed that the calculated values for the membrane stresses would overestimate the measured values by over 40%. Note that the mean value of each two corresponding strain gauges has been used for the comparison.

In [5] the authors present several tests on a welded I-section specimen. A single wheel load was applied on four different configurations of rails (i.e. a flat steel rail 60 × 40 mm and a profile rail A 100, former KS 75. Each with and without elastic underlay). It is most likely that the flat steel rail (without underlay) has not been welded to the I-section as it would be common design practice nowadays. The comparison of analytic results with the measurements showed generally good agreement for the tests with the flat steel rail, while the calculated values overestimated the measured values for the tests with the profile rail. It should be noted that the authors in [5] made no comment whether and how the bending stiffness of the rails have been taken into account for their comparison.

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Further background on the local stresses in webs of crane runway girders and rails with elastic underlay can be found in [6,7,8].

In [9] a complete set of formulae is given for calculating the global and local direct stresses and the corresponding shear stresses due to centric loading. The formulae can be evaluated for every point in the web (not only the upper edge). The author additionally gives a comparison with a test result from literature that shows good agreement (differences less than 10%).

A good summary of the several formulae for the calculation of local vertical direct stresses due to centric wheel loads can be found in [10], where the authors also present the first finite element calculations upon that topic.

The theoretic background of the stresses due to eccentric wheel loading (see chapter 1.2) is based on the works of [11,12,13,14]. This derivation contains a rather rough assumption concerning the variation of the bending stiffness of the web out of plane (at its upper edge) along the length of the girder. Admittedly, this assumption allows for a drastic simplification of the formula. Furthermore, nearly no experimental tests on local stresses due to (intended) eccentric wheel loading are documented in literature. In [15] four centric tests and three eccentric tests on the ultimate buckling load of the web are presented, but no details on the local stresses are given.

Since suitable experimental tests from literature are rare, the present paper will show experimental tests of I-shaped and box-section girders with centric and eccentric wheel loading and focuses on comparing the test results with the theoretical formulae near the top of the web.

1.1. Centric vertical wheel loading

The maximum value of the local vertical direct stresses $\sigma_{oz,Ed}$ at the upper edge of the web with thickness t_w due to a centric wheel load $F_{z,Ed}$ can be calculated via the effective length l_{eff} according to EN 1993-6 [16]. Eqs. (1a), (1b) and (1c) show the corresponding formulae. A constant stress value $\sigma_{oz,Ed}$ is therefore assumed over the effective length l_{eff} in the design model, see Fig. 1. Certainly, the vertical direct stresses are accompanied by local horizontal direct stresses and local shear stresses, but these stresses are often neglected in design and therefore not the focus of the present paper.

$$\sigma_{oz,Ed} = \frac{F_{z,Ed}}{l_{eff} \cdot t_w} \tag{1a}$$

$$l_{eff} = 3.25\left(\frac{I_{rf}}{t_w}\right)^{1/3} \tag{1b}$$

$$l_{eff} = 3.25\left(\frac{I_r + I_{f,eff}}{t_w}\right)^{1/3} \tag{1c}$$

For rails that are rigidly connected to the flange (e.g. welded flat steel rails), l_{eff} can be calculated with Eq. (1b), where I_{rf} is the total moment of inertia of a single cross-section consisting of the rail and the effective part of the flange about the horizontal axis. For rails that are not rigidly connected to the flange (e.g. loose clamps for floating profile rails), l_{eff} can be calculated with Eq. (1c), where I_r and $I_{f,eff}$ are the separate moments of inertia of the rail and the effective part of the flange, respectively.

The effective part of the flange can be calculated via the flange thickness t_f and the effective flange width b_{eff}, the latter being the sum of the width of the rail at its bottom b_{fr}, the height of the rail h_r and the thickness of the flange t_f ($b_{eff} = t_f + b_{fr} + h_r$).

Note that the effective length l_{eff}, based on Eqs. (1b) and (1c), can be increased by approximately 30% if an elastic underlay with a minimum thickness of 6 mm is used. This takes into account the beneficial effect of a smoother load distribution through the underlay. It should also be mentioned that EN 1993-6 [16] defines certain values of wear-out that have to be taken into account for the calculation of the section properties of the rail. For example, the height of the rail h_r should be reduced by 25% of the head of the rail for the ultimate limit state (a reduction of only 12.5% is to be assumed for fatigue design checks). Further comments on EN 1993-6 can be found in [17,18].

Compared to other design codes EN 1993-6 gives the most sophisticated formula. Fig. 2 shows a comparison of the effective length l_{eff} for the former German design code for crane supporting structures DIN 4132 [19] (withdrawn), the European design code for cranes EN 13001-3-1 [20], the Canadian Guide for the design of crane supporting steel structures by CISC [21] and the Australian standard for crane runways AS 1418.18 [22].

All four procedures exhibit a linear (or bi-linear) increase of the effective length from the upper surface of the rail to the upper edge of the web. The two European codes [19,20] explicitly allow for a further extrapolation of the stresses for reference planes within the web (continued dashed lines in Fig. 2) while the effective lengths of the other two regulations is only given for the junction between the web and the upper flange. While the two European concepts start with a certain length at the top of the rail (that is 50 mm for most practical relevant cases), the Canadian and the Australian concept start with zero length. Within the rail all four procedures suggest a distribution angle of 45° (note that smaller values can be chosen for cranes in EN 13001-3-1). This angle is kept constant for DIN 4132 and EN 13001-3-1 also within the flange and web region, while a gradient of 2.5:1 (approx. 22°) is given in the CISC design guide and AS 1418.18 for the areas of the flange and the weld. From a practical point of view, the differences between these four recommendations are rather small for common configurations (i.e. not too thick flanges).

In that context it is worth noting that the so calculated effective lengths for all three European design codes ([16,19,20]) are also used for fatigue design checks, where elastically calculated stresses are to be considered. This is reasonable, since the assumed stress distributions are based on elastic concepts. The effective lengths of [21,22] that implicitly assume a plastic load distribution throughout the upper flange (gradient 2.5:1) are generally not used for any fatigue investigations. In fact, the CISC design guide explicitly states that if the top flange-to-web joint is done as a complete-joint-penetration groove weld with fillet reinforcement, the weld detail is known to provide satisfactorily service (and no detailed fatigue design check has to be done) [21]. This is very interesting, because exactly that fatigue design check often turns out to be the most decisive criteria for the verification of crane runway girders according to EN 1993-6. Therefore, the accuracy of the calculated local vertical direct stresses is crucial for a safe and economic design.

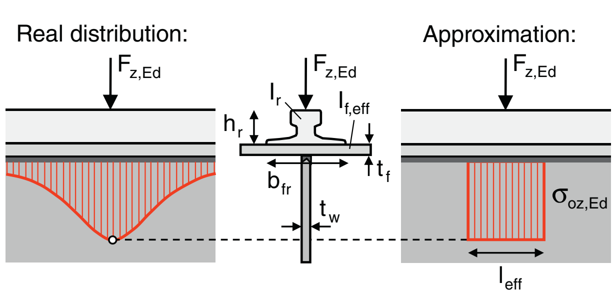

Fig. 1. Local vertical direct stresses in the web due to centric wheel loading and constant stress approximation.

1.2. Eccentric vertical wheel loading

In practice the wheel loading of an operating crane will hardly ever be introduced fully centrically. Therefore, also eccentric wheel loading has to be taken into account that leads to a rotation of the upper flange and thereby induced bending of the web out of plane. Fig. 3 shows the procedure of splitting the eccentric load case into a centric one (that