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LIMITATIONS IN FATIGUE STRENGTH EVALUATION OF THE WEB-FLANGE CONNECTION OF STEEL RUNWAY BEAMS - A REVIEW

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This study reviews the current state of research and limitations on the fatigue strength of web-flange connections in steel runway beams for overhead cranes. It evaluates key factors influencing fatigue strength, including stress-strain behavior, notch classifications, and various web-flange configurations (welded, rolled, combined). The research stresses the need for accurate fatigue life assessments, particularly for both new and older structures built with simplified standards. Key findings show the impact of notch classifications and stress interactions due to bending, tensile, and compressive forces. The study aims to improve calculation methods, offering recommendations for refining fatigue verification techniques, and assesses connection configurations' effectiveness in achieving desired fatigue life. The practical implications point to increased steel crane runway beams' durability through better fatigue life prediction and localized stress analysis.

Keywords: web-flange connection, runway beams, fatigue strength, stress-strain state, durability, crack formation

Introduction

Overhead cranes and their supporting structures, particularly steel runway beams, are critical components in many industries. A significant number of these structures, designed decades ago, remain in operation and are vital to the economy. The global overhead crane market is expected to grow by 5,5 % annually by 2031, according to extended market analysis (Transparency Market Research, 2021). Steel runway beams serve as primary supports for overhead cranes and are subjected to localized dynamic cyclic loads from crane wheels, leading to metal fatigue over time and increasing the risk of localized failures (Melchers & Beck, 2018). These failures often manifest as localized cracks at the web-flange connection of runway beams, as numerous inspection results have shown (Fig. 1). Therefore, accurately calculating fatigue strength in these zones is essential during both the design stage and over time, especially for structures designed many years ago, in order to accurately assess their remaining service life.

Fig. 1. Typical fatigue cracks in the web-flange connection area of steel runway beams

The web-flange connection can take various configurations (Fig. 2), such as welded plates, rolled sections, or combined configurations, e.g. as shown in Eurocode standard.

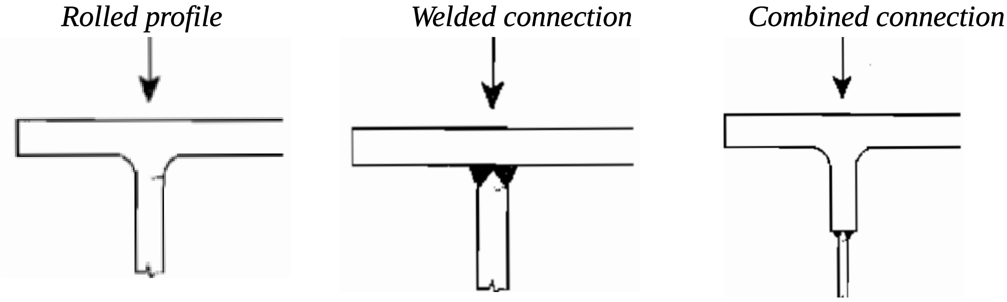


Fig. 2. Different types of web-flange connections in runway beams

The choice of different beam configurations not only impacts construction costs but also plays a crucial role in determining the fatigue strength of the web-flange connection, influenced by the type and quality of welds, which create localized stress concentrations. The web-flange connection in crane runway beams primarily endures compressive stresses from crane wheels, which are key in defining notch classes in national and international standards. However, fatigue strength calculations in this area are complex due to additional local tensile and bending stresses during crane operations, leading to a complex stress-strain state. The role of various loadings along with the crack initiation in the mentioned area are also briefly explained in the article (Rykaluk & Hotała, 2014). While existing standards provide general guidelines, they do not clearly address the benefits or drawbacks of different connection types or their impact on the structure's residual service life, instead offering simplified methods for stress and fatigue analysis described in EN 1993-6 (2007), NEN-EN 13001-3-1, EN 1993-1-9 (2005), EN 1991-3 (2006) and DBN V.2.6-198:2014 zi zminoiu №1.

To ensure the longevity of both new and existing crane runway structures, further research is needed to better understand the fatigue behavior of the web-flange connection and assess the effectiveness of different beam configurations.

Objective of this article

The purpose of this study is to conduct a literature review on the research related to the fatigue strength of the web-flange connection in steel runway beams. The focus will be on analyzing scientific sources that investigate the complex stress-strain state caused by the actual behavior of cranes and the fatigue strength of this connection. The aim is to identify the key challenges, limitations and opportunities in existing research, which will form the basis for further studies aimed at improving fatigue calculation methods and providing clear recommendations on the effectiveness of using crane runway beams in different configurations.

Histrorical development

The issue of calculating fatigue strength for steel runway beams under cyclic loading is becoming increasingly relevant due to many existing beams being designed decades ago using simplified fatigue calculation rules. August Wöhler's 19th-century tests on cyclic loading established the S-N curve (Fig. 3) and fatigue limit, foundational for today's fatigue analysis. Later, Palmgren and Miner improved the S-N approach by accounting for cumulative fatigue damage under variable loads, relevant for crane runway beams.

$$D_d = \sum_j^n \frac{n_{Ei}}{N_{Ri}} \tag{1}$$

Miner's rule states that failure occurs when the accumulated damage equals or exceeds a certain threshold, typically set at 1.

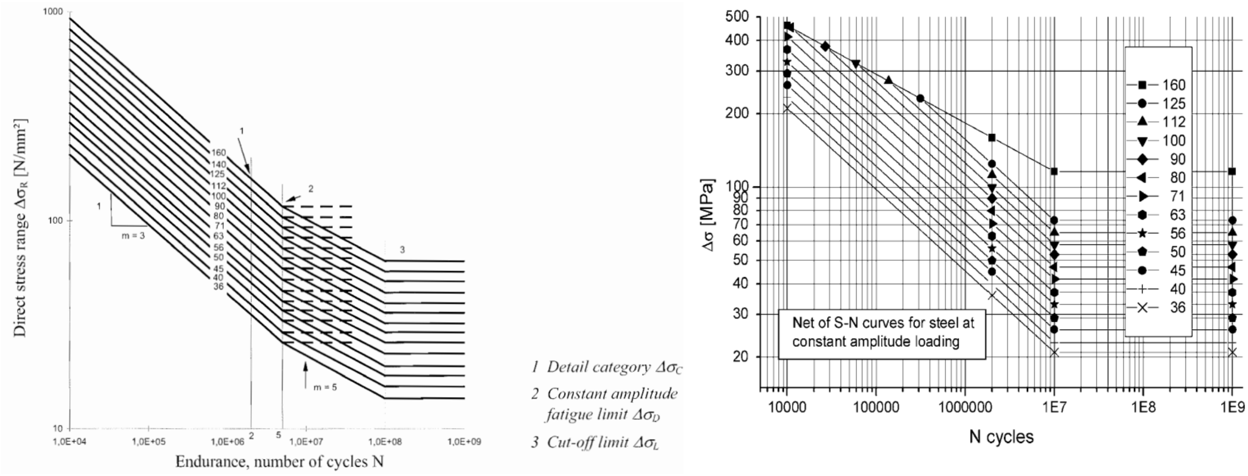


Fig. 3. Example of S-N curves according to Eurocode 3 and IIW

Before Eurocode, older national standards like DIN 15018, NEN 2019, and FEM 1.001 were widely used. With the formation of the European Union and the need for harmonized safety standards under the Machinery Directive (2006/42/EC), there was a push to develop unified standards across Europe. This led to the creation of the EN 13001 series and Eurocode, which replaced these national standards with consistent guidelines. Although FEM 1.001 served as a basis for EN 13001, a major difference was the introduction of the stress history parameter s_m, based on the Palmgren-Miner approach for cumulative fatigue damage:

$$s_m = \nu \times k_m, \tag{2}$$

$$k_m = \sum_i \left[\frac{\Delta\sigma_i}{\Delta\sigma}\right]^m \times \frac{n_i}{N_t}, \tag{3}$$

$$\nu = \frac{N_t}{N_{ref}}, \tag{4}$$

Final version of Eurocode was much more comprehensive than previous standards and included the calculation of stresses in welds using the Hot Spot Stress Method, more detailed notch class definitions for different crane runway beam configurations (albeit with more conservative values), and a more detailed methodology for calculating stresses in the web-flange connection of crane runway beams. These changes raised concerns about differences in fatigue strength predictions compared to older standards, leading to questions about the actual remaining lifetime. Despite differences in notch classes between EN 13001 and Eurocode, both recommend a simplified formula for calculating compressive stresses in the web-flange connection, which applies to both welded and non-welded connections (Fig. 4):

$$\sigma_{oz,Ed} = \frac{F_{z,Ed}}{l_{eff} t_w}, \tag{5}$$

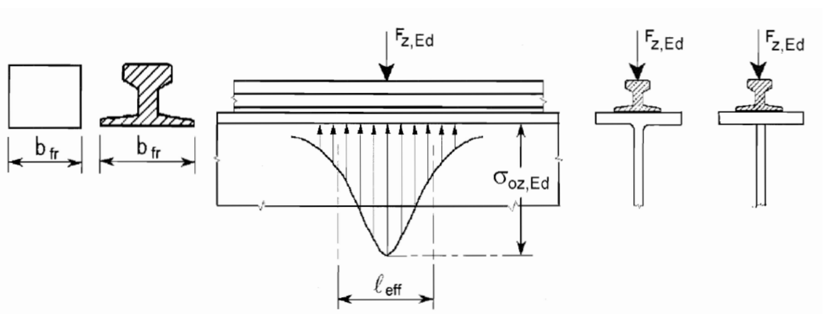


Fig. 4. Effective load length according to EN 1993-6 (2007)

The same formula is proposed by DBN V.2.6-198:2014 zi zminoiu №1 under section 9.2.2. However, the stress distribution for different types of welds and rounding (in the case of rolled profiles) will differ, often resulting in high stress concentrations in this area. On the other hand, Eurocode allows "ignoring stresses caused by horizontal forces from crane movement" (EN 1993-6, 2007, p. 34), despite the fact that these are caused by crane acceleration/braking, which are an integral part of its operational cycle, creating a risk of underestimated fatigue failures in runway beams. Meanwhile, the Ukrainian DBN V.2.6-198:2014 and DBN V.1.2-2:2006 standards allow omitting dynamic factors in fatigue stress amplitude calculations (DBN V.2.6-198:2014 zi zminoiu №1, p. 83; DBN V.1.2-2:2006, p. 19), whereas most European standards consider these impacts in crane loads. Most standards use the nominal stress method, ignoring local stress concentrations in welds. While more advanced methods like finite element analysis are allowed and partially described in the international IIW standard, these methodologies do not correlate with the generally accepted rules for stress calculations in crane runway beams described in Eurocode and EN13001, making the process quite complex.

Given the factors influencing fatigue strength according to existing standards, it can be concluded that further research in this area will help develop clearer recommendations for assessing the complex stress-strain state and fatigue strength of the web-flange connection in runway beams.

Experimental challenges

As described above, the actual operation of cranes creates a complex stress-strain state in the web-flange connection of runway beams, which is difficult to account for using simplified stress calculation methods according to standards. Notch classes also differ significantly between various standards. To better understand the actual structural behavior in this area under cyclic loading, several experimental studies have been conducted, highlighting various challenges and limitations as outlined below.

In a study (Citarelli & Feldmann, 2019), existing runway beams were tested under cyclic loading to evaluate fatigue failure in the web-flange connection. The analysis combined direct testing and numerical evaluation of notch classes, with results used to suggest amendments to current standards. The probabilistic model described in the article has been proved by the additional research on the basis of the maximum likelihood method (D'Angelo, 2015; Pollak & Palazotto, 2009; D'Angelo et al., 2014). The study found a characteristic fatigue strength of 116 MPa, much higher than the 71 MPa specified in Eurocode for fully welded connections. However, the effects of bending and different runway beam configurations, which can influence stress concentrations, were not fully addressed.

In the research (Polus et al., 2022), the effect of different connections between a 60x60mm square rail and the runway beam on compressive stresses in the web-flange connection area was studied using numerical and analytical methods. The study found that rigid rail attachment to the beam showed minimal error between Eurocode's analytical method and digital calculations (4-8 %). However, flexible connections resulted in significant deviations (22 %-27 %), and elastomeric bearing pads under the rail further increased the discrepancy by up to 59 % (Fig. 5). Similar research is done (Marcinczak, 2017) on resilient elastomeric bearing pad with the thickness of 6 mm. The study only considered central loading, neglecting additional bending stresses from crane braking forces and eccentricities

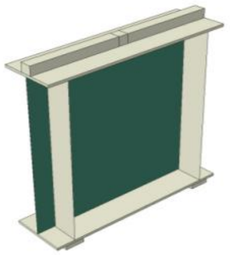
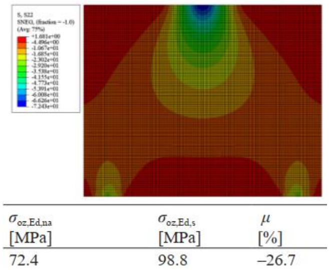
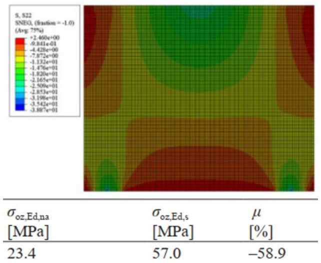
Model	***Continuous block rail flexibly fixed to the beam flange***	***Continuous block rail mounted on the elastomeric bearing pad***
	 $\sigma_{oz,Ed,na}$ [MPa] 72.4 $\sigma_{oz,Ed,s}$ [MPa] 98.8 μ [%] –26.7	 $\sigma_{oz,Ed,na}$ [MPa] 23.4 $\sigma_{oz,Ed,s}$ [MPa] 57.0 μ [%] –58.9

Fig. 5. Continuous block rail mounted on the elastomeric bearing pad

The study (Rykaluk, et al., 2018) examined fatigue failures in welded runway beams under cyclic loading, with a focus on the complex stress-strain state of the web, where cracks could initiate. They derived analytical formulas to calculate these stresses, with a deviation of less than 15 % between calculated and experimental values. However, the formulas did not account for variations in the web-flange connection type (welded, rolled, or combined), rail-to-flange attachment (rigid or on a pad), or horizontal forces from the crane, all of which influence stress in this zone. Additionally, various crane rail connection types were analyzed, showing increased compressive stresses compared to a continuous rail (Fig. 6).

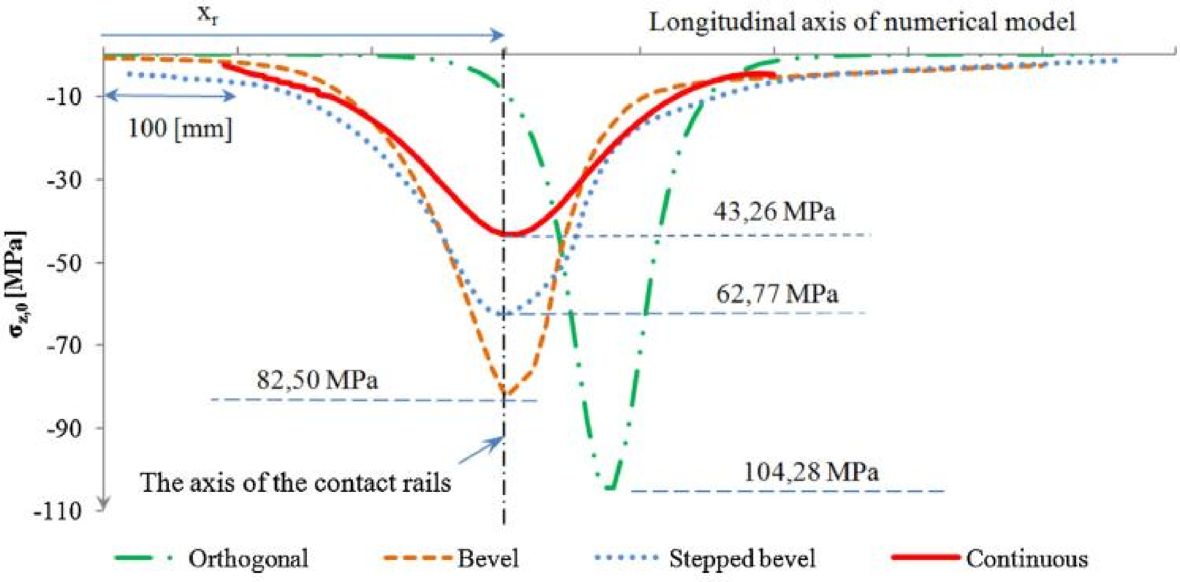


Fig. 6. Distribution of localized compressive stresses

The smallest stress increase occurred in stepped chamfered contact (50 %), and the largest in orthogonal contact (around 150 %), which is not considered by the standard and could serve as an additional topic for research aimed at determining clear recommendations, as noted by the authors.

In the work (Petrosian, 2002), the effect of eccentric loading on local stresses around the weld in the web-flange connection of crane runway beams was examined. The study found that in some cases, the eccentricity caused by incomplete rail support exceeded the normative eccentricity values, leading to underestimation of stresses in current standards. It was also shown that the distance between transverse stiffeners affects the size of tensile fibers in the beams, causing local twisting, but had little influence on compressive stresses at the beam's mid-span. The study did not consider different web-flange connection configurations, and the eccentricity analysis was based on a rigid foundation, excluding the stiffness of the pad between the rail and flange.

In the study (Caglayan, et al., 2010), it was found that the connection of transverse stiffeners to the top flange creates zones of increased fatigue damage, as confirmed by experimental tests. Another research (Tong, 2007) highlights the importance of stress concentrations and reduction with increasing cope radius and decreasing total depth. However, the study did not account for different rail-beam attachment types, which influence local stiffness and stress distribution.

Other researchers, (Kettler & Unterweger, 2020; Kettler et al., 2019; Kettler et al., 2017), highlighted the significant impact of crane loading eccentricity on fatigue damage. However, their study did not consider the effect of different beam configurations on stress levels at the web-flange connection.

These studies, along with others, reveal key challenges and potential improvements for fatigue calculation methods in steel runway beams. Most of them focus on isolated individual factors and do not consider the direct influence of different connection types on fatigue strength under a complex stress-strain state. Further research is needed to evaluate the effectiveness of crane runway beams in different configurations.

Conclusions and Prospects for further research

Based on the extensive literature review conducted on the research related to the fatigue strength of the web-flange connection in steel runway beams, the accurate verification of fatigue strength in this area is critical for ensuring the longevity and durability of crane-supporting structures. Existing research shows that key factors include the fatigue strength of the connection, which can vary depending on the standards, and the complex stress-strain state in this zone, which is challenging to capture with the simplified methods proposed in the standards. This is primarily due to compressive stresses from crane wheels, bending stresses from local twisting caused by eccentric loading, and horizontal crane forces, which are an integral part of the loading cycle. The situation can be further complicated by tensile stresses around stiffener attachments and at beam supports, making the analysis even more conservative. It's essential to consider how different connection types affect fatigue strength under such complex stress-strain conditions. Developing more detailed approaches, including the use of analytical methods and finite element analysis, would allow local stress concentrations from welds to be accounted for and the effectiveness of using different crane runway beam configurations to be assessed, ensuring the calculated service life of structural elements.

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ОБМЕЖЕННЯ В ОЦІНЦІ ВТОМНОЇ МІЦНОСТІ З’ЄДНАННЯ ПОЛИЧКИ ТА СТІНКИ СТАЛЕВИХ ПІДКРАНОВИХ БАЛОК – ОГЛЯД

Сталеві підкранові балки, які грають ключову роль в забезпеченні безперервної, безпечної роботи мостових кранів, постійно піддаються динамічним повторюваним навантаженям від коліс крана, що призводить до втоми металу та підвищує ризик місцевих пошкоджень. Наслідком таких пошкоджень є часто локальні тріщини в місці з’єднання полички та стінки підкранових балок, як видно з численних інспекцій цих конструктивних елементів. Ця стаття розглядає сучасний стан наукових досліджень та існуючі обмеження щодо оцінки втомної міцності з'єднання полички та стінки сталевих підкранових балок. Основною метою є оцінка ключових факторів, що впливають на втомну міцність цих з'єднань, таких як складний напружено-деформований стан при реальних умовах експлуатації, клас надрізів та різноманітні конфігурації з'єднань стінки та полички, включно зі зварними, прокатними та комбінованими з'єднаннями. Дослідження підкреслює необхідність точної оцінки втомної міцності та терміну служби як нових, так і старих конструкцій, збудованих за спрощеними стандартами. Основний фокус зроблений на аналізі існуючих праць та виявленні обмежень з метою рекомендацій щодо подальших досліджень. Виявлені результати підкреслюють значний вплив різних класів надрізів та складного напружено-деформованого стану у цій зоні, викликаного сукупним впливом згинальних, розтягуючих та стискаючих напружень, на втомну міцність підкранових балок. Дослідження сприяє вдосконаленню існуючих методів розрахунку та дає рекомендації для майбутніх досліджень, спрямованих на вдосконалення підходів перевірки втоми та визначення ефективності використання підкранових балок в різних конфігураціях для забезпечення необхідного ресурсу. Зрештою, практичні висновки допомагають підвищити довговічність сталевих підкранових балок через вдосконалене прогнозування втомного терміну служби, досягнутого за рахунок детальної оцінки різних конфігурацій з'єднань та локалізованих аналізів напружень.

Ключові слова: з’єднання полички та стінки, підкранові балки, втомна міцність, НДС, довговічність, тріщиноутворення.