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The impact of corrosion on the fatigue strength of steel used in bridge structures

Wpływ korozji na wytrzymałość zmęczeniową stali stosowanej w konstrukcjach mostowych

The phenomenon of corrosion, its processes and dependence on the physicochemical properties of the corroded material and the environment in which it occurs, as well as issues related to corrosion protection, are the subject of numerous research papers. Despite the preliminary recognition of the impact of corrosion pitting on the fatigue of structural steel elements, in particular, the impact of notches on the reduction of fatigue strength, appropriate coefficients have not yet been introduced in most of the standards for the design of steel bridges in the world, including Poland. The paper will present the results of the author's research work on the estimation of the effect of corrosion on the fatigue capacity of rail and road steel bridge structures in service. The study was performed on two types of bridge steel commonly used in existing, in-service bridge structures. In order to determine the magnitude of the title phenomenon, an atmospheric corrosion simulation facility was set up for the tests. The experimental results unequivocally showed a significant decrease in the fatigue limit for both bridge steels and up to 50% of the initial condition.

Keywords: corrosion, fatigue, steel structures, bridges

Zjawisko korozji, jej procesy oraz zależności od właściwości fizykochemicznych korodowanego materiału i środowiska, w jakim zachodzi, a także zagadnienia związane z ochroną antykorozyjną są tematem licznych prac badawczych. Pomimo wstępnego rozpoznania w zakresie wpływu wżerów korozyjnych na zmęczenie stali konstrukcyjnych, w szczególności wpływu karbów na obniżenie wytrzymałości zmęczeniowej, nie wprowadzono dotychczas odpowiednich współczynników w większości światowych, także polskich normatywów dotyczących projektowania mostów stalowych. Artykuł przedstawia wyniki autorskich prac badawczych nad oszacowaniem wpływu korozji na nośność zmęczeniową eksploatowanych stalowych konstrukcji mostowych – kolejowych i drogowych. Badania przeprowadzono na dwóch rodzajach stali mostowej powszechnie stosowanej w konstrukcjach eksploatowanych obiektów mostowych. W celu określenia skali wpływu korozji na wytrzymałość zmęczeniową stali stosowanej w konstrukcjach mostowych na potrzeby badań wykonano stanowisko do symulacji korozji w warunkach atmosferycznych. Wyniki badań jednoznacznie wykazały znaczny spadek granicy wytrzymałości zmęczeniowej w wypadku obu stali mostowych, i to nawet na poziomie 50% stanu wyjściowego.

Słowa kluczowe: korozja, zmęczenie, konstrukcje stalowe, mosty

1. Introduction

The corrosion of steel is a complex process that can be divided into different types depending on the characteristics of its development. The three main types of corrosion commonly found on steel bridges are point corrosion, spot corrosion and pitting corrosion. They all have their own specific mechanisms and factors influencing their development. The formation of such phenomena clearly affects the fatigue strength of structural components, as described later in this article. The microcracks formed as a result of the corrosion process (particularly pitting corrosion) reduce the fatigue strength of components and frequently become the foci of fatigue cracking [1].

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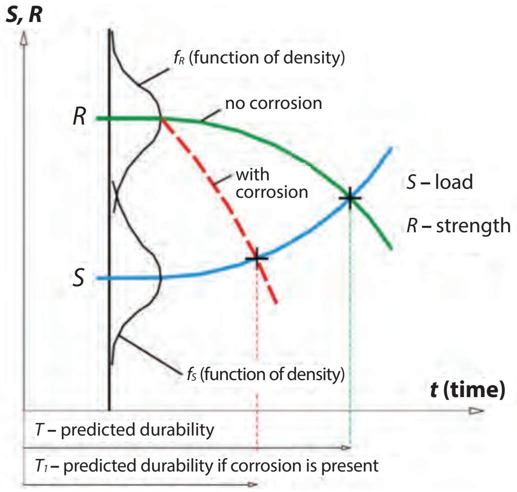

Fig. 1. Graphic illustration of the effect of corrosion on the load-bearing limit state and durability of the component

Source: [5, p. 429].

Rys. 1. Wpływ korozji na stan graniczny nośności i trwałość elementu

Źródło: [5, s. 429].

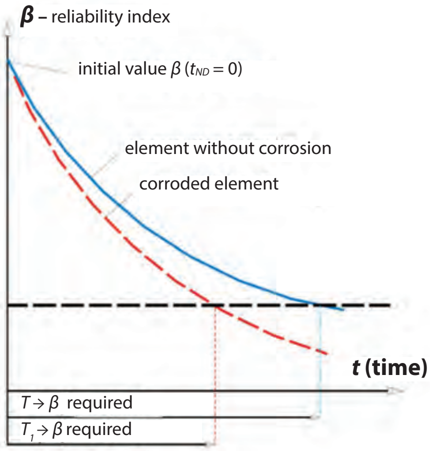

Fig. 2. Graphic illustration of the effect of corrosion on the reliability index of the structure and its durability

Source: [5, p. 429].

Rys. 2. Wpływ korozji na wskaźnik niezawodności konstrukcji i jej trwałość

Źródło: [5, s. 429].

Electrochemical corrosion is common in steel bridge structures. The process involves an electrochemical reaction between a metallic material (steel) and chemical agents, moisture and oxygen in the environment. The steel acts as an anode and cathode in this process, resulting in material loss and the formation of corrosion foci points. It is therefore important for the safe operation of these structures to provide suitable protective conditions, such as protective coatings, which limit the access of moisture and oxygen to the surface of steel structural elements.

The development of corrosion on bridges is the result of the interaction of many factors, such as the degree of aggressiveness of the environment, the type and chemical composition of the steel, the nature of the loads, the quality of maintenance and repair work. In addition, and particularly in the case of electrically powered railway bridges, the influence of stray currents must be taken into account. These can affect the electrochemical activity in areas (structural elements) where the current flow is concentrated. This leads to disturbances in the electrochemical balance, which favours the corrosion processes that develop.

In addition, the damaging effects of corrosion are greatly enhanced when variable stresses are applied, and corrosion generally facilitates the fatigue process. The phenomenon of fatigue is therefore closely related to the corrosion process, its forms and its evolution [2]. Therefore, when assessing the durability of steel bridges, the influence of corrosion should be considered together with the influence of fatigue strength, as shown by the few studies to date [3, 4], which highlight the significant influence of corrosion on the fatigue capacity of steel structures. This influence is clearly illustrated in Fig. 1.

In addition, corrosion fatigue significantly increases the probability of failure compared to fatigue alone. Fatigue reliability can be estimated probabilistically using the Hosofer-Lind method, in which statistical quantities change over time, which is also associated with a change in the β reliability index. The correlations related to corrosion are included in Fig. 2.

A reduction in the fatigue capacity of steel bridges due to corrosion occurs in two main aspects. The first aspect, as in the case of ad hoc load carrying capacity, is the effect of corrosion on the overall section loss of the steel elements and hence the overall increase in stresses in the section. The second aspect relates to the effect of corrosion pitting, which locally increases the stress amplitude in the bridge steel elements at these points in the section [5, 6] under simultaneous cyclic loading. The effect of corrosion on the fatigue strength of steel is observed in all steel elements of bridge structures. It is of particular importance in the case of load-bearing (primary) elements subjected to long-term cyclically varying actions. It should be noted that the structural elements of steel bridges have significant spans due to the "continuous" nature of these structures. This applies not only to the main girders themselves, but also to the cross girders, stringers and braces. The formation of pitting in these components is therefore particularly dangerous in terms of fatigue phenomena.

Photo 1. Example of a steel girder of an in-service steel bridge with locally damaged paint coating resulting in pitting corrosion of the structural steel

Fot. 1. Przykład dźwigara stalowego eksploatowanego mostu stalowego z uszkodzoną punktowo powłoką malarską, co powoduje powstawanie korozji wżerowej stali konstrukcyjnej

The technical and practical significance of the described phenomenon of the effect of corrosion pitting on fatigue resistance is illustrated by the example of a steel girder of an operational steel

Photo 2. View of the support zone on the bearing of the bottom flange of the main girder of the road bridge – total perforation of the bottom flange due to pitting corrosion can be seen

Fot. 2. Widok strefy oparcia na łożysku pasa dolnego blachownicowego dźwigara głównego mostu drogowego – widoczna całkowita perforacja półki dolnej na skutek korozji wżerowej

Photo 3. View of the connection zone between the web and the bottom flange of the sheet metal girder of a main railroad bridge – a clearly visible example of the occurrence of pitting corrosion of structural elements, due to the presence of rainwater moisture

Fot. 3. Widok strefy połączenia środnika z pasem dolnym blachownicowego dźwigara głównego mostu kolejowego – dobrze widoczny przykład korozji wżerowej w strefie połączenia elementów konstrukcyjnych dźwigara na skutek zawilgocenia wodą opadową

Photo 4. View of the bottom flange of a truss girder of a railroad bridge – visible cracking of the roll-formed section caused by advanced pitting corrosion

Fot. 4. Widok pasa dolnego dźwigara kratownicowego mostu kolejowego – widoczne pęknięcie kształtownika walcowanego wywołane zaawansowaną korozją wżerową

Photo 5. View of the web of a plate girder of a main road bridge – visible fatigue cracking within the welded joint as a result of additional corrosion weakening of the section in the contact zone of the elements

Fot. 5. Widok środnika blachownicowego dźwigara głównego mostu drogowego – widoczne pęknięcie zmęczeniowe w obrębie połączenia spawanego, powstałe w wyniku dodatkowego osłabienia korozyjnego przekroju w strefie styku elementów

bridge with a locally damaged coating, as shown in Photo 1. Photos 2 and 3 show examples of typical pitting corrosion on the main load-bearing elements of in-service rail and road steel bridges.

A study in [7] showed that corrosion affects the fatigue strength in a similar way to components where the edges of steel plates are cut with a torch (i.e. with intense notches). Based on numerous studies and analyses of corrosion phenomena, it has been found that fatigue cracks start "at the bottom" of corrosion pits. In addition, it has been found that corrosion pits form in the weakest parts of the passive layer of structural steel, most often in areas of minor mechanical damage, in areas of member joints, or in areas of structural changes in the steel, such as non-metallic inclusions.

The mechanism of corrosion cracking itself is not fully understood, despite much experimental work and theoretical consideration [8, 9]. However, given the development of research in the field of electrochemistry, it must be concluded that the primary factor in the development of a crack is the accelerated structural degradation of the material directly in the crack of the corrosion pit.

2. Methods for estimating the degree of corrosion and corrosion pitting

The crack propagation is fully dependent on the value of the tensile stresses and the frequency of these stresses. For further analy-

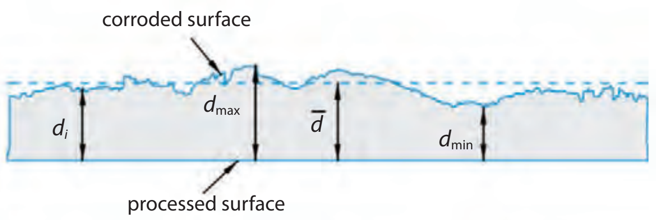

Fig. 3. Thickness measurements of a corroded specimen for determining geometric characteristics

Source: [11, p. 885].

Rys. 3. Schemat pomiarów grubości skorodowanej próbki, przeprowadzanych w celu określenia jej charakterystyki geometrycznej

Źródło: [11, s. 885].

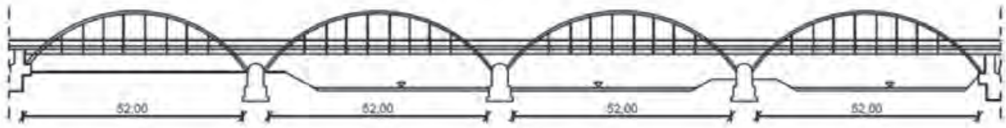

Fig. 4. Side view of the Trzebnica North Bridge over the Oder River in Wrocław – M1

Rys. 4. Widok z boku mostu Trzebnickiego Północnego nad Odrą we Wrocławiu – M1

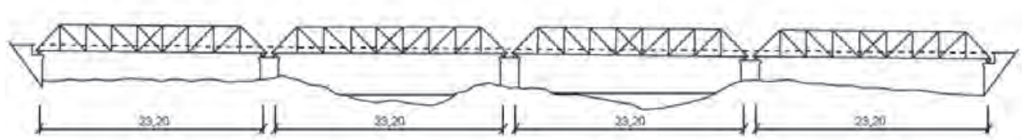

Fig. 5. Side view of the railroad bridge over the Bystrzyca River in Pracze Odrzańskie

Rys. 5. Widok z boku mostu kolejowego przez rzekę Bystrzycę w Praczach Odrzańskich

sis of the phenomenon described, it should also be borne in mind that the characteristics of fatigue cracks due to corrosion, in plastic materials, are of a brittle fracture nature [10]. Photos 4 and 5 show examples of cracks in structural elements caused by corrosion fatigue in steel bridges.

Field tests are usually carried out to determine the degree of corrosion of steel components in service. On this basis, it is possible to analyse the degree of corrosion loss of the primary structural members and, consequently, to estimate their degree of wear and fatigue strength.

In order to correctly determine the geometrical design parameters of a corroded section, it is necessary to carry out appropriate calculation procedures. These procedures mainly consist of a comparative analysis of the results of microstructural measurements of the corrosion damage pattern on the surface of the steel element. Figure 3 shows a typical diagram of a corroded section specimen for determining its geometrical parameters [11].

On the basis of detailed, microstructural thickness measurements, it is possible to determine the main parameters of the steel samples [11]:

– the maximum roughness is determined from the formula:

$$R_{max} = d_{max} - d_{min}, \quad (1)$$

where: d_{max} – maximum measured section thickness, d_{min} – minimum measured section thickness;

– average roughness is determined from the formula:

$$R_m = \frac{1}{n}\sum_{i=1}^{n}\left|d_i - \bar{d}\right|, \quad (2)$$

where: $\bar{d}$ – average thickness, d_i – i-th thickness reading, n – total number of measurements;

– the standard deviation of roughness S_d is determined from the formula:

$$S_d = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(d_i - \bar{d})^2}. \quad (3)$$

When determining the basic parameters of the cross-section, the accuracy of the corrosion notch measurements must be continuously adjusted. The corrosion pits on the surface of the steel structure are characterised by a variable cross-section (irregularity), therefore it is necessary to change the measurement base (reference length of the specimen under the microscope) when carrying out the identification of corrosion damage.

According to the tests carried out on bridge steels described later in this paper, the most important factor determining the fatigue strength of a given structural element is precisely the described influence of the cross-sectional loss caused by general corrosion and the influence of the corrosion pits that occur.

3. Evaluation of the influence of corrosion on fatigue based on tests of real bridge structures

<u>3.1. Introduction and research description</u>

According to the author, a good example of the influence of corrosion on steel fatigue and its magnitude described in the paper is provided by the laboratory tests that have been carried out. The aim of this research was to determine the influence of real corrosion processes on steel bridge components on the fatigue strength of two commonly used bridge steels. In order to adequately represent corrosion, samples of steel components were taken from actual road and railway bridges. These analyses were used to detail the extent of corrosion damage for laboratory testing. On this basis, typical forms of corrosion were modelled on the surface of bridge steel specimens for fatigue testing, taking into account three different stages of corrosion. The tests were carried out on two types of bridge steel commonly used in existing in-service bridge structures, with yield strengths of 240 MPa and 335 MPa.

a) b) c)

Fig. 6. The microstructure of the element samples near the corroded surface (at 100 times magnification): a) sample M1-A, b) sample M1-B, c) sample M1-C

Rys. 6. Mikrostruktura próbek elementów przy skorodowanej powierzchni (w 100-krotnym powiększeniu): a) próbka M1-A, b) próbka M1-B, c) próbka M1-C

a) b)

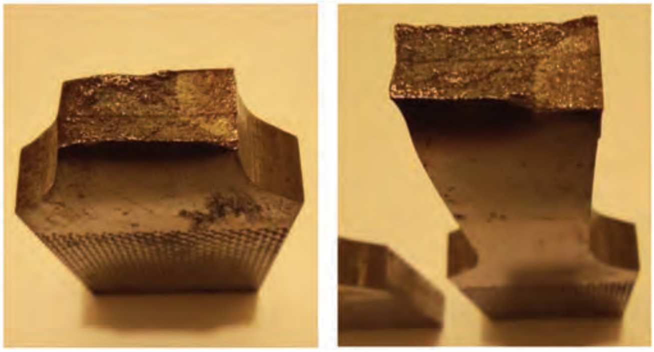

Photo 6. View of steel sample fracture with a characteristic fatigue area: a) first part of the sample b) second part of the sample

Fot. 6. Widok pęknięcia z charakterystycznym obszarem zmęczeniowym stalowej próbki: a) pierwsza część próbki b) druga część próbki

Table 1. Characteristics of the corrosion states of the specimens
Tabela 1. Charakterystyka stanów korozyjnych próbek

Designation	Condition of the samples
COR 0	initial condition without corrosion: steel specimens in as-delivered condition with working section size of 5 × 10 mm
COR 1	medium condition with a depth of up to 1.0 mm: corroded steel specimens with a working section size of 4.7 × 9.75 mm or 4.5 × 9.70 mm
COR 2	extreme condition with a loss depth of up to 2.0 mm: corroded steel specimens with a working section size of 4.3 × 9.3 mm

Two bridges were selected to assess the corrosion processes: the Trzebnica road bridge in Wroclaw (M1; Fig. 4) and the railway bridge over the Bystrzyca river in Pracze Odrzańskie (M2; Fig. 5) on the Wrocław–Szczecin trunk line. The actual degree of corrosion was determined by laboratory analyses of steel samples taken from bridges M1 and M2.

3.2. Identification of the degree of corrosion of bridge steels

Microscopic examinations were carried out using a Neophot 2 light microscope on samples selected from the macroscopic examinations in areas with the highest intensity of corrosion processes. A magnification range of 50 to 500 times was used.

Three samples of fragments of steel main girder hangers were taken from the M1 bridge, which showed a variety of corrosion changes. The samples were identified as M1-A, M1-B and M1-C. Localised pitting, ranging from 5 mm to 20 mm in diameter and 0.5 mm to 2.0 mm in depth, and in extreme cases causing local perforation of the component, was found in the areas of greatest intensity of corrosion.

Four samples of severely corroded sections of the B2 railway bridge structure were also taken for testing, designated as: M2-A – transverse beam fragment, M2-B – transverse beam fragment, M2-C – fragment of the lower chord of a truss, M2-D – wind bracing fragment. Local pitting with a diameter of 1.0 mm to 6.0 mm and a depth of 0.5 mm to 4.0 mm was found in the areas of the highest intensity of corrosion processes. Figure 6 shows photographic documentation of samples M1-A, M1-B and M1-C being evaluated.

The results obtained allowed a detailed plan to be adopted for further fatigue testing of the steel in as-delivered condition and in two model corrosion states. The test programme included the testing of specimens of two types of steel used in bridge construction: low carbon steel (steel designated A^{240}) and high strength steel (steel designated B^{335}). The specimens were subjected to a corrosion process under laboratory conditions after comparative testing to obtain a form of corrosion similar to that found in real bridges (M1, M2) [12].

3.3. Results of tests to determine the effect of corrosion on bridge steel fatigue

An accelerated sample rusting bench was designed, consisting of a chamber to simulate corrosion under atmospheric conditions.

Table 2. Strain amplitude values for different degrees of corrosion of steel A^{240}
Tabela 2. Wartości amplitudy odkształceń dla różnych stopni korozji stali A^{240}

Corrosion degree	Assumed number of load cycles							
	$36 \cdot 10^3$	$72 \cdot 10^3$	$108 \cdot 10^3$	$144 \cdot 10^3$	$180 \cdot 10^3$	$216 \cdot 10^3$	$252 \cdot 10^3$	$288 \cdot 10^3$
COR 0	0.00090	0.00095	0.00105	0.00110	0.00115	0.00120	0.00125	0.00130
COR 1	0.00060	0.00065	0.00070	0.00080	0.00090	0.00100	–	–
COR 2	0.00040	0.00050	0.00060	0.00070	0.00080	0.00090	0.00100	–

Table 3. Strain amplitude values for different degrees of corrosion of steel B^{335}
Tabela 3. Wartości amplitudy odkształceń dla różnych stopni skorodowania stali B^{335}

Corrosion degree	Assumed number of load cycles							
	$90 \cdot 10^3$	$180 \cdot 10^3$	$270 \cdot 10^3$	$360 \cdot 10^3$	$450 \cdot 10^3$	$540 \cdot 10^3$	$630 \cdot 10^3$	$720 \cdot 10^3$
COR 0	0.00100	0.00120	0.00140	0.00160	0.00180	0.00200	0.00220	–
COR 1	0.00060	0.00070	0.00080	0.00090	0.00100	0.00110	0.00130	–
COR 2	0.00050	0.00060	0.00070	0.00080	0.00090	–	–	–

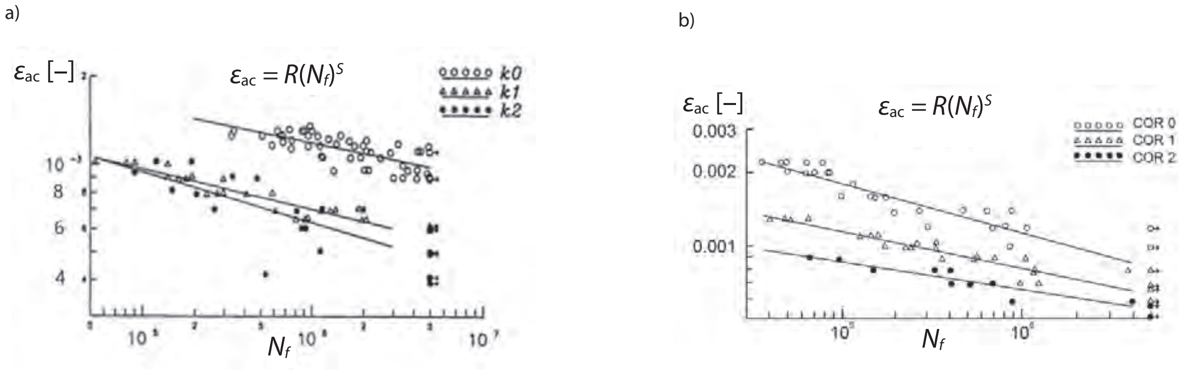

Fig. 7. Relation $\ln\varepsilon_{ac}$ - $\ln(N_f)$ in three degrees of corrosion: a) steel A^{240}, b) steel B^{355}

Rys. 7. Zależności $\ln\varepsilon_{ac}$ - $\ln(N_f)$ stali A^{240} (po lewej) i B^{355} (po prawej) w trzech stopniach korozji

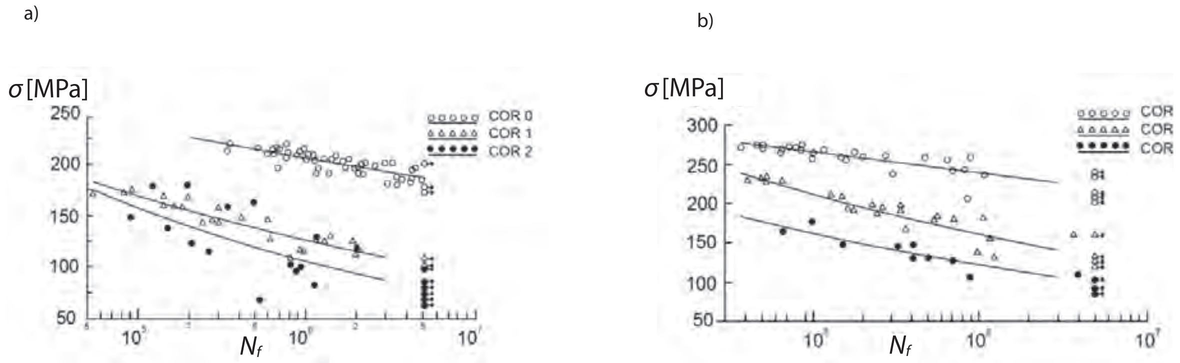

Fig. 8. Relation $\ln\sigma_a$ - $\ln(N_f)$ in three degrees of corrosion: a) steel A^{240}, b) steel B^{355}

Rys. 8. Zależności $\ln\sigma_a$ - $\ln(N_f)$ w trzech stopniach korozji: a) stal A^{240}, b) stal B^{355}

During the simulation, the samples were subjected to periodic wetting to simulate precipitation. The corrosion simulation also included dry cycles corresponding to periods of sunny and dry weather conditions that occur during normal operation.

The test programme included three types of specimens with different corrosion states. The characteristics of the corrosion states are shown in Table 1. There were 40 samples prepared for each corrosion condition (COR 0, COR 1, COR 2). A total of 120 specimens were made from A^{240} steel and 120 from B^{335} steel [12].

After preparing a set of specimens for cyclic loading tests with different degrees of surface corrosion (COR 0, COR 1, COR 2), the actual tests were started. Fatigue tests were performed with a controlled total strain amplitude e_{ac} (constant and incremental). Photo 6 shows an example specimen after fatigue testing [12].

During the study an attempt was made to identify cyclic strain curves using the Ramberg-Osgood model. A cyclic strain curve is defined as a function of stress amplitude σ and strain amplitude ε. It is a graphical representation of the peaks of the hysteresis loop obtained during dynamic loading of the specimen.

The fatigue loading was in the form of pendulum uniaxial tension-compression. The loading spectrum had a sinusoidal frequency of f = 25 Hz for A^{240} steel specimens and f = 40 Hz for B^{335} steel specimens. It was assumed that the measurement was performed in real time for the load cycles.

Each ascending cycle load measurement was performed for 36,000 cycles for A^{240} steel and 90,000 cycles for B^{335} steel. Zeroing of the electrical phase shift angle was performed in the elastic strain region ($\varepsilon_{ac} = 0.7 \cdot 10^{-3}$), corresponding to a stress of 150 MPa. The strain amplitude values for the tested bridge steels in different corrosion states are summarised in Tables 2 and 3.

From the results obtained it can be concluded that the fatigue limit of the two bridge steels tested was reduced by approximately 40% in the COR 1 condition compared to COR 0. For the COR 2 condition the difference was 50% for A^{240} steel and 56% for B^{335} steel. The basic results of the fatigue tests carried out are presented in the form of Wöhler curves in different coordinate systems. Selected results from the tests carried out on A^{240} steel and B^{335} steel specimens are shown in Fig. 7 and 8. Figure 7 shows the results obtained in the $\ln\varepsilon_{ac}$ - $\ln(N_f)$ coordinate system on a double logarithmic scale. In contrast, Fig. 8 shows the results obtained in the $\ln\sigma$ - $\ln(N_f)$ coordinate system on a double logarithmic scale.

All results at the second degree of corrosion, COR 2, have a significantly larger scatter compared to the results at COR 0 and COR 1. Furthermore, the mutual position of the Wöhler curves obtained, shown in the graphs, confirms the negative effect of corrosion on the fatigue strength of the steel.

4. Conclusion and summary

Reduction in the cross-sectional surface area, surface changes and all other phenomena resulting from corrosion processes lead to significant alterations in the cyclic and strength properties of materials, especially their short-term strength and fatigue strength. Based on the author's research, it was clearly confirmed that fatigue life decreases with the depth of pitting on the steel surface.

The value of the fatigue limit of both types of bridge steel tested decreased significantly as a result of the corrosion process. The negative effect of corrosion on the fatigue strength of steel is demonstrated by the position of the Wöhler curves in relation to each other, as shown in the graphs. At COR 1, the value of this property for both steels was reduced to 60% of the initial value. At COR 2, the fatigue limit was 50% of the original condition for A^{240} and 44% for B^{335}.

The laboratory tests and analyses carried out showed that the correlation between the degree of corrosion of the steels and their fatigue strength allows for a more effective estimation of the total service life of existing bridges. This applies to steel structures of both road and railway bridges. This fact should be taken into account when carrying out analyses of steel bridges in service, as calculations and expert opinions usually only take into account the effects resulting from losses in the cross-section when corrosion is detected.

The results of the research clearly emphasise the importance of applying corrosion protection to steel structures, particularly those subject to cyclic fatigue loading. Continued operation of a bridge structure in the absence of corrosion protection results in a gradual reduction in strength both in terms of fatigue strength and service life [13].

CRediT authorship contribution statement

Adam Wysokowski: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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