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Concrete-reinforcing Steel Bars – Applications and Fatigue Tests

Abstract: The article describes the requirements set for concrete-reinforcing steel bars as to their fatigue strength and presents types of fatigue tests as well as examples of test results. The work also describes the effect of selected factors on the fatigue strength of concrete-reinforcing steel bars, demonstrates problems accompanying experimental fatigue tests involving reinforcing bars and presents a fatigue tests methodology enabling the obtainment of valid test results, developed by Instytut Spawalnictwa. The methodology was validated while testing B500SP grade reinforcing bars of diameters restricted within a 8-25 mm range.

Keywords: concrete-reinforcing steel bars, B500SP, fatigue tests,

Introduction

Steel ribbed reinforcing bars have numerous applications in building engineering. They are most frequently used in reinforced concrete structures as reinforcements transferring tensile stresses. Reinforcing bars can be found in slab, beam and pillar reinforcements in buildings and industrial structures such as tanks, foundations, chimneys, cooling towers, bridges etc. Presently, reinforcing bars are made of numerous steel grades characterised by high strength values.

In relation to reinforcing bars, appropriate standards and technical approvals require the performance of a number of mechanical (destructive) tests in order to verify the appropriate quality of a product, e.g. fatigue strength validation tests. Tests of reinforcing bars at static loads are not accompanied by any problems, yet tests of reinforcing bars at changing loads pose certain difficulties related to the fact that fatigue cracks are usually generated in the area where test specimens are fixed in the jaws of a testing machine, i.e. where significant notches are present. Then, the results of such tests cannot be regarded as reliable and should be rejected. While testing reinforcing bars it is not possible to make classic contracted specimens, e.g. those used during tests of other base metals as such specimens must be tested in the as-delivered state, i.e. without any interventions in their cross-sections. If fatigue tests involve fusion welded, pressure welded or bolted joints of reinforcing bars, the problem mentioned above is usually absent. This is due to the presence of a given joint type constituting a greater notch than that formed by the bar clamping force, where a fatigue crack is usually initiated in the joint area, i.e. where expected.

Fatigue Tests of Reinforcing Bars

Reinforced concrete structures such as bridges, crane beams or various coastal structures are exposed to changing loads. Therefore, while

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designing the structures mentioned above it is necessary to take into consideration the issue of fatigue strength. For instance, in Great Britain motorway bridges are designed to last 120 years, during which the structure can be exposed to as many as $7{\cdot}10^8$ load change cycles. The designed service life of coastal structures amounts to 30 years, during which, due to the operation of waves, such structures can transfer approximately 10^8 cycles. Until today, no fatigue failures of the motorway bridges mentioned above have been reported, yet it may happen at any time without previous indications. In one road experiment conducted by AASHO (American Association of State Highway and Transportation Officials) overload tests led to the fatigue failure of a concrete bridge. In that case, the external beam reinforcing bars failed after approximately 730 000 cycles, which in comparison with laboratory tests, was a far worse result [1].

The fatigue strength of reinforcing bars and of reinforced concrete elements has been the subject of research for many years. The development of new and increasingly durable reinforcing steel grades, as well as the construction of advanced objects including concrete reinforcing bars, imposes the necessity of continuous fatigue strength research.

Types of Reinforcing Bar Fatigue Tests

Axial tests

Axial fatigue tests are conducted using conventional testing machines and specimens in the as-delivered state. The advantages of axial tests include low costs at a relatively high testing frequency (up to 150 Hz) and the possibility of defining pre-set stresses precisely. A very significant disadvantage is related to problems connected with clamping bars in testing machines, where local stresses in bar clamping areas are responsible for the premature failure of the bars. It is also difficult to avoid the effect of secondary stresses caused by the non-rectilinearity of specimens or their misalignment in testing machine jaws. Reference publications [2] contain information about numerous attempts to properly prepare the grip parts of specimens; such attempts were always connected with using an additional layer between a specimen and a testing machine jaw. The author of the study [2] mentions the use of leather belts wrapped around the specimen grip part, low melting point metallic fillings, resins and aluminium pads. However, the author does not provide any information concerning the effectiveness of the measures mentioned. Available guidelines concerning bar fatigue tests focus mainly on determining the minimum specimen length between clamps, load change coefficient and load change frequency. In order to simulate the effect of concrete on a bar it was also necessary to make specimens covered by a concrete coating in the middle of their measurement part. To some extent, such specimens are an improvement in comparison with bars tested in the as-delivered state, yet results are not as satisfactory as those collected during the tests involving a reinforced concrete beam as a whole. However, also in this case there are significant problems connected with gripping a specimen in such a manner that a fatigue crack is formed on a concrete-covered fragment of a bar.

Bend tests

Bend fatigue tests are usually conducted on concrete beams containing a single reinforcing bar inside. The most important advantage of these tests is the fact that during testing the real mutual effect of steel and concrete is taken into consideration, yet a disadvantage is the low testing frequency of 3 Hz due to significant beam bend ranges and the necessity of avoiding friction-induced heating of the beam. In such a case, active life tests of 10^7 cycles take approximately 6 weeks, which significantly increases their cost. Other inconveniences include the necessity of making certain assumptions related to a force affecting concrete and the need to precisely place a bar in concrete. Bend fatigue tests are performed on beams subjected to classic bending as well as three-point or four-point bending, in accordance with DIN 488-2:2009 [3]. A load in beams being tested usually has a sinusoidal course with constant force amplitude.

Comparative tests revealed that bent beams can be characterised by a slightly higher fatigue strength than that observed during axial loading of specimens, yet differences are very small (see the results of comparative tests for Unisteel 410 - Fig. 1).

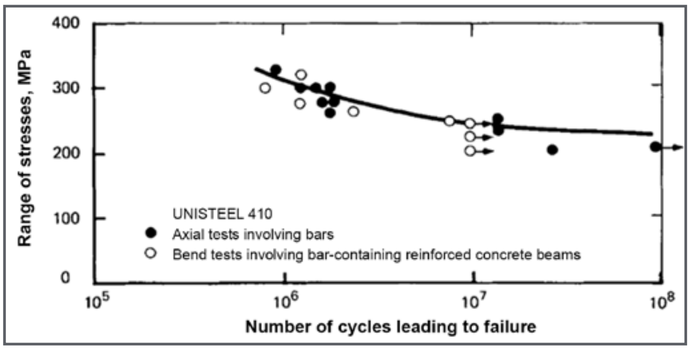

Fig. 1. Comparison of fatigue test results concerning reinforcing bats in the as-delivered state subjected to cyclic axial loads and of reinforced concrete beams subjected to bend loads [2]

Effect of Joining Processes on the Fatigue Strength of Bars

The welding of concrete reinforcing bars obviously affects their strength. Axial fatigue strength tests of various types of butt joints of Unisteel 410 bars revealed that the welding process-induced reduction of fatigue strength amounts to 40% at $2{\cdot}10^6$ cycles [2]. Other tests conducted for $8{\cdot}10^5$cycles revealed that the reduction of fatigue strength of reinforcing bar welded joints amounts to as much as 50% [4].

In the tests [5] concerning the effect of a joining process on the fatigue strength of bent reinforced concrete beams reveal that the fatigue strength of flash welded joints is almost identical as that of unwelded bars. The joints of arc welded bars revealed the fatigue strength lower by approximately 15% (on the basis of 2·106 cycles) than that of unwelded bars (Fig. 2).

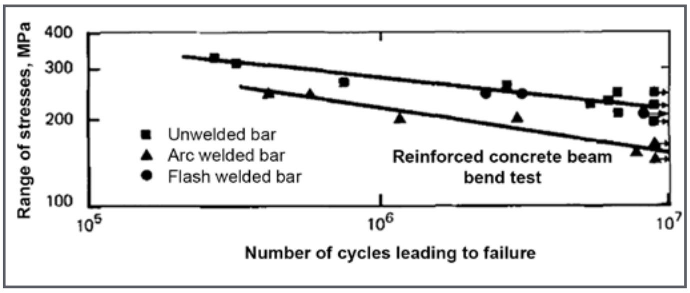

Fig. 2. Fatigue strength of bars and that of bar joints subjected to fatigue bend test [5]

Tests also involved the effect of the method used for making short tack welds (used, among others, for welding beam suspension rods) on fatigue strength. The results reveal a significant decrease in the fatigue strength of bent reinforced concrete beams containing such welds. The reduction of fatigue strength amounted to 28-50% for 10^6 and $5{\cdot}10^6$ cycles respectively [6]. As can be seen, the joints of reinforcing bars reveal a greater fatigue strength decrease when tested under an axial load than the reduction of fatigue strength observed during fatigue bend tests of reinforced concrete beams.

Effect of Corrosion on the Fatigue Strength of Reinforcing Bars

Corrosion-induced failures can pose significant problems in relation to road bridges, e.g., particularly those where de-icing road salt is used or those having contact with seawater (coastal structures). In many cases, salt migrating as a solution near reinforcing bars causes their corrosion, with volume-increasing corrosion products locally bursting concrete coatings thus depriving bars of their protection. Presently, objects where de-icing road salt is used are safeguarded with appropriate protective measures such as cathodic reinforcement protection, epoxy coatings, reinforcement electroplating, and the use of stainless steel or by using concrete of higher density. The combination of corrosion and stresses in bridge structures can have serious consequences including the construction disaster of a whole object, such as, for instance, the collapse of the Point Pleasant Bridge in Ohio, USA, in 1967 (Fig. 3) which claimed 46 lives.

Fig. 3. Bridge collapsed due to corrosion and stresses in Point Pleasant in 1967 in the USA

The study [7] developed by the authors conducting fatigue tests of Unisteel 410 reinforcing bars both in air and in seawater indicated the disadvantageous effect of corrosion on the fatigue strength of bars. The tests based on 10^7 cycles revealed that the fatigue strength of corroded bars subjected to standard axial tensile tests was lower by 35% than that of the bars tested in air. Similar tests based on the same number of cycles and performed on reinforced concrete beams subjected to cyclic bending revealed the corrosion-induced fatigue strength was reduced by 22% (Fig. 4).

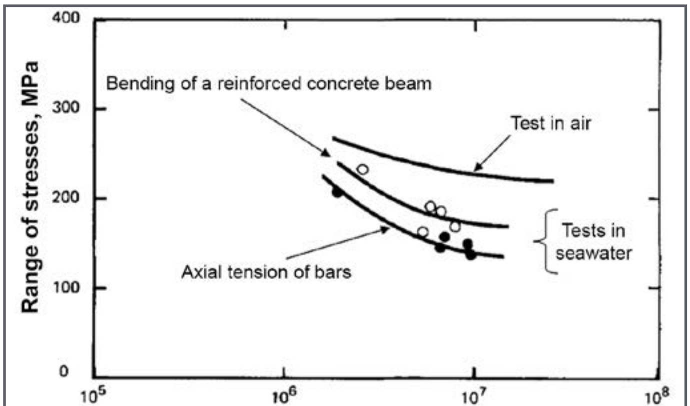

Fig. 4. Effect of corrosion on the fatigue strength of reinforcing bars [7]

Fatigue Strength-Related Requirements for Concrete-reinforcing Steel Bars

The section below discusses the main requirements concerned with testing conditions and acceptance criteria related to the fatigue strength tests of the most popular reinforcing bar steel grades, i.e. B500SP, BSt 500 WR, RB 500 W and BSt 500 S.

Standard 15630-1:2001E [8] concerning methods of testing steels for reinforcing and tensioning concrete (bars, wire rods and wire) contains information related to the fatigue test principle, specimen dimensions (specimen extension of at least 140 mm or 14*d*, whichever value is higher), testing equipment accuracy requirements, specimen loading manner as well as the criteria for test completion and test validity. A test finishes with a specimen cracking before reaching the defined number of cycles or reaching the defined number of cycles without specimen cracking. If a crack is due to a defective material or if a specimen cracked in the clamps or not further than 2*d* away from the clamps, a given test can be classified as invalid. However, the standard mentioned above does not provide a specimen preparation manner in the specimen grip part.

Concrete-Reinforcing B500SP Steel Bars and Ribbed Wire Rods

Bars and ribbed wire rods made of B500SP steel are used for reinforcing concrete elements and structures designed in accordance with the principles and requirements specified in PN-EN 1992-1-1:2008P [9] for C class steels having a characteristic yield point of 500 MPa. Ribbed bars made of B500SP steel can be used for reinforcing concrete structures exposed to dynamic and multiple changing loads.

Requirements for fatigue strength tests according to the Technical Approval [10]:

- maximum stress in experimental tests: σ_{max}=300 MPa,
- stress amplitude: σ_a=150 MPa,
- load change frequency: 1-200 Hz,
- testing method: according to PN-EN ISO 15630-1:2011E [8],
- acceptance criterion: failure-free transfer of at least $2{\cdot}10^6$ load change cycles.

Concrete-Reinforcing BSt 500 WR and RB 500 W Steel Bars and Ribbed Wire Rods

Bars and ribbed wire rods made of BSt 500 WR and RB 500 W steels and having diameters of 8-16 mm are used for reinforcing concrete elements and structures. Ribbed bar-reinforced structures can be exposed to static and changing loads in a temperature range from -60°C to +100°C as well as be subjected to dynamic and multiple changing loads.

Requirements for fatigue strength tests according to the Technical Approval [11]:

- maximum stress in experimental tests: σ_{max}=0,7 R_e MPa,
- stress amplitude: σ_a=200 MPa,
- testing method: according to ZUAT-15/I.01/2003 [12],
- load change frequency: 1-200 Hz,
- acceptance criterion: failure-free transfer of at least $2{\cdot}10^6$ load change cycles.

Concrete-Reinforcing BSt 500 S Ribbed Bars

BSt 500 S ribbed bars are used for reinforcing concrete structures. BSt 500 S bar-reinforced structures can be exposed to static and changing loads in a temperature range from -60°C to +100°C as well as be subjected to dynamic and multiple changing loads.

Requirements for fatigue strength tests according to the Technical Approval [13]:

- maximum stress in experimental tests: σ_{max}=0,7 R_e MPa,
- stress amplitude range: 2σa=215 MPa,
- testing method: according to PN-EN ISO 15630-1:2011E [8],
- load change frequency: 1-200 Hz,
- acceptance criterion: failure-free transfer of at least $2{\cdot}10^6$ load change cycles.

As can be seen in the requirements presented above, the values of maximum loads and the amplitudes of changes of these loads differ depending on the grades of reinforcing bars tested. However, the acceptance criterion remains the same irrespective of bar grades, i.e. bars should reveal a fatigue strength of at least $2{\cdot}10^6$ cycles.

Experimental Fatigue Tests of Reinforcing Bars

A typical problem encountered while fatigue testing of reinforcing bars, already referred to in the introduction, is the premature failure of a specimen in the area of the testing machine jaws. In order to confirm such behaviour of reinforcing bars, during tests under changing loads it was necessary to mark out B500SP grade bars manufactured by Huta CMC Zawiercie S.A. /CMC Steelworks/ in the process of hot rolling with controlled cooling and tempering. The chemical composition of B500SP steel for manufacturing bars is presented in Table 1, whereas the mechanical and technological properties of the bars are presented in Table 2. The bars selected for tests had diameters of 8, 12, 16, 20 and 25 mm.

The fatigue tests of reinforcing bars were conducted following the requirements of the standard [8] and of the technical approval [10] using a test rig equipped with an MTS 810 testing machine of a testing capacity of ±1000 kN (Fig. 5).

Fig. 5. Test rig at Instytut Spawalnictwa (MTS 810 testing machine)

The tests were conducted in a cyclic axial tension mode, with test parameters selected for each diameter of bars tested in such a manner that imposed forces generated maximum stresses of σ_{max}=300 MPa and minimum stresses of σ_{min}=150 MPa. The tests were conducted until cracking or reaching the boundary number of cycles of $2\cdot10^6$. The conducted fatigue tests of bars in the as-delivered state, i.e. without any preparation of specimen grip parts, confirmed that in such conditions, fatigue cracks, irrespective of a bar diameter, were initiated in a specimen in the jaws of the testing machine. The results are presented in Table 3, whereas the fatigue crack area is presented in Figure 6. An exemplary fatigue fracture is presented in Figure 7.

Table 1. Chemical composition and carbon equivalent of B500SP steel for bar production [10]

According to	Mass content of chemical elements, %					Carbon equivalent C_{eq}*
	C*	N*	S*	P*	Cu*	
1	2	4	5	6	7	9
heat analysis	≤ 0.22	≤ 0.012	≤ 0.050	≤ 0.050	≤ 0.80	≤ 0.50
product analysis	≤ 0.24	≤ 0.013	≤ 0.055	≤ 0.055	≤ 0.85	≤ 0.52
* chemical composition and carbon equivalent according to PN-EN 10080:2007						

Table 2. Mechanical and technological properties of bars made of B500SP steel [10]

No.	Properties	Requirements	Testing methods
1	2	3	4
1	Yield point R_e, MPa	≥ 500	PN-EN ISO 6892-1: 2009 PN-EN 10080:2007 (R_e equivalent to $R_{0.2}$)
2	Tensile strength R_m, MPa	≥ 575	
3	R_m/R_e ratio	$1.35 \geq R_m/Re \geq 1.15$	
4	Total elongation at the maximum force A_{gt}, %	≥ 8.0	
5	Relative elongation A_5, %	≥ 16	
6	Resistance to bending out by an angle α = 20° after bending by an angle α = 90° and ageing, on the probe having a diameter of: $5\cdot d_s$, at d_s = 8÷12 mm $6\cdot d_s$, at d_s = 14÷16 mm $8\cdot d_s$, at d_s = 18÷32 mm	lack of cracks	PN-EN ISO 15630-1:2011
7	Fatigue strength, MPa, at σ_{max} = 300 MPa, frequency of up to 200 Hz and 2 σ_a = 160 MPa	≥ 2 x 10^6 cycles	PN-EN ISO 15630-1:2011

Table 3. Fatigue test results of bars in the as-delivered state

Bar diameter, mm	Number of cycles performed	Remarks	Result
8	237120	crack in the jaw area	negative
12	176900	crack in the jaw area	negative
16	195337	crack in the jaw area	negative
20	279821	crack in the jaw area	negative
25	320423	crack in the jaw area	negative

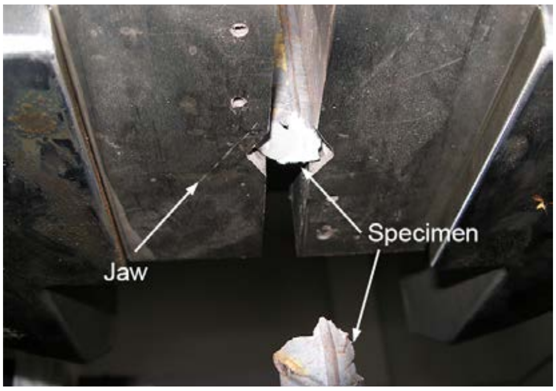

Fig. 6. Premature failure of a bar having a diameter of 20 mm fractured in the jaws of a testing machine

Fig. 7. Cracked bar having a diameter of 20 mm and the fatigue fractures of the bar

The test results concerning the bars without properly prepared grip parts confirmed that it is not possible to obtain valid test results due to the premature failure of a specimen in the grip area.

At Instytut Spawalnictwa, the research work [14] involved testing the influence of many various manners of preparing test reinforcing bars for fatigue tests which enabled the selection of the most convenient procedure. The related test results enabled the development of a testing methodology concerning the proper preparation of specimen grip parts, making it possible to effectively perform fatigue tests of reinforcing bars and obtain valid results.

The primary idea of the developed procedure consisting of several stages is based on activities aimed to locally change stresses in the specimen grip area and to use various layers of intermediate elements capable of taking over plastic strains of bars tested during the clamping of the jaws of the testing machine. Properly selected conditions of such local changes of stresses make the notch in the grip area of the specimen (placed in the testing machine jaws) too small to lead to the premature failure of the test element in the jaw area, where the central part of the specimen tested remains in the as-delivered state.

The test results concerning the B500SP grade reinforcing bars with the grip part modified according to the methodology developed by Instytut Spawalnictwa are presented in Table 4. All the tests performed on five series of specimens having various diameters (3 specimens in each series) were successful, i.e. the reinforcing bars, on a failure-free basis, transferred the required number of load change cycles amounting to 2·106, specified in the related technical approval. Thus, the quality of bars in terms of required fatigue strength was confirmed.

Table 4. Fatigue test results of B500SP grade reinforcing bars

Bar diameter, mm	Number of cycles performed	Remarks	Result
8	2000000	crack-free	positive
	2000000		
	2000000		
12	2000000	crack-free	positive
	2000000		
	2000000		
16	2000000	crack-free	positive
	2000000		
	2000000		
20	2000000	crack-free	positive
	2000000		
	2000000		
25	2000000	crack-free	positive
	2000000		
	2000000		

Conclusions

On the basis of the tests performed, the following conclusions were formulated.

1. The fatigue tests of steel bars for reinforcing concrete in the as-delivered state do not enable the obtainment of valid results due to the premature failure of the elements tested in the grip area.

2. It is possible to perform fatigue tests of reinforcing bars if the appropriate specimen preparation methodology is applied.

3. Instytut Spawalnictwa, on the basis of previously conducted research works, is prepared to conduct tests of reinforcing bars having diameters restricted within an 8 mm – 25 mm range.

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