PREMATURE FRACTURE DURING FATIGUE TESTING OF REINFORCED-CONCRETE STEEL BARS

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ABSTRACT: The problems faced during low-cycle fatigue tests of reinforced-concrete steel bars are presented and a specimen preparation method is described that will aid researchers on fatigue testing to obtain accurate test results and save on material and time. The results of mechanical tests on bars of various diameters under axial loading according to EN 10080 and EN 1421-3 are discussed and correlated with optical and scanning electron microscopy examination used to study the specimen fracture surfaces. Finite Element Modelling was employed to evaluate the effect of the newly introduced specimen preparation method on the problems faced during testing.

KEY WORDS: Steel bar, fatigue test standards, premature failure, specimen preparation method

1 INTRODUCTION

The fatigue strength of reinforced concrete bars has been the subject of research for many years. Usually the fatigue characteristics of reinforced-concrete steel bars are studied with axial fatigue tests using conventional testing machines and specimens in the as-delivered state, usually ribbed rods. The advantages of axial tests include low costs at a relatively high testing frequency (up to 200 Hz) and the possibility of defining test conditions 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 (Sismanis & Mastorakis, 2008). A number of studies (Tilly, 1979; Krasnowski, 2015; NordTest method, 1989) contain information about various methods to prepare the grip parts of specimens usually connected with using an added layer between a specimen and a testing machine jaw and /or slight machining of specimen ends. Some of these include the use of leather belts wrapped around the specimen grip part, low melting point metallic fillings, resins and aluminium pads. However, little information is available concerning the failure mechanism of untreated bars and the effectiveness of the measures mentioned.

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Bars and ribbed rods made of B500SP steel are used for reinforcing concrete elements and structures designed in accordance with the specifications in EN 10080 (EN 10080, 2005) for C class steels of a yield point of 500 MPa. The requirements for fatigue strength tests are described in EN 10080 and EN 1421-3 and are summarised below:

Maximum stress, σ_{max}=300 MPa, Stress amplitude, σa=150 MPa, Load cycle frequency, 1-200 Hz, Acceptance criterion, failure-free after $2{\cdot}10^6$ load change cycles.

Finite Element modelling was used to provide some refined insight as to the failure mechanism of the untreated bars and explain how the proposed treatment might assist in avoiding premature failure that is not associated to the materials strength characteristics.

2 EXPERIMENTAL

High cycle fatigue tests were conducted on reinforced-concrete steel 8, 12 and 20 mm diameter bars to study their behaviour under axial tension loading according to EN 10080 and EN 1421-3 using a 100kN capacity Instron machine (Figure 1) until cracking or reaching the boundary number of cycles of $2{\cdot}10^6$.

The maximum and minimum loads were calculated so as to agree with the EN specifications of maximum stresses of σmax=300 MPa and minimum stresses of σmin=150 MPa. The load cycle frequency was set at 25 Hz.

Hardness and tensile tests were also carried out so as to determine whether the material was in agreement with the EN standards concerning concrete steel bars. The chemical composition of the material was determined using optical emission spectroscopy and the steel microstructures were studied using optical and scanning electron microscopy (SEM) to investigate the presence of inclusions that could lead to premature failure during testing. The fracture surfaces of the mechanical tests were further studied using scanning electron microscopy to obtain a better picture of the failure process.


Figure 1. 100kN capacity Instron fatigue testing machine

3 RESULTS AND DISCUSSION

3.1 Experimental Analysis and Characterization

The chemical compositions of the steel bars tested were the same at 0.22 %C, 0.57%Mn, 0.16%Si, 0.045%S, 0.024%P. The mechanical test results are given in Table 1. Both are in agreement with the EN specifications so any failure during testing could not be attributed to poor quality of the material.

Table 1. Mechanical tests results

Bar diameter (mm)	Yield Strength (MPa)	Tensile Strength (MPa)	% Elongation	VPN
8	531	641	29	213
12	534	634	30	211
20	497	625	28	208

The fatigue tests of bars in the as-delivered state, that is without any preparation of the specimen grip parts, varied depending on the bar diameter Tables 2-4. The testing parameters were calculated according to EN 1421-3 and the tests were carried out at a load cycle frequency of 25 Hz for a maximum of $2*10^6$ cycles.

Table 2. Fatigue Test of 8mm bars Fmax =15.072 N, Fmin=7.536 N, Fmean=11.304 N, Famplitude=3.768 N

Specimen	Nominal diameter (mm)	Length (mm) 140,14d	Failure (yes/no)
Φ 8-1	8	140	no
Φ 8-2	8	140	no
Φ 8-3	8	140	no
Φ 8-4	8	140	no
Φ 8-5	8	140	no

Table 3. Fatigue Test of 12mm bars (Fmax =33.912N, Fmin=16.956N, Fmean=25.434N, Famplitude=8.478N)

Specimen	Nominal diameter (mm)	Length (mm) 140,14d	Failure (yes/no)
Φ 12-1	12	168	yes 934331 cycles
Φ 12-2	12	168	no
Φ 12-3	12	168	no
Φ 12-4	12	168	no
Φ 12-5	12	168	no
Φ 12-6	12	168	yes 934331 cycles
Φ 12-7	12	168	yes 964063 cycles
Φ 12-8	12	168	no

Table 4. Fatigue Test of 20mm bars (Fmax =94.200, Fmin=47.100N, Fmean=70.650, Famplitude=23.550N)

Specimen	Nominal diameter (mm)	Length (mm) 140,14d	Failure (yes/no)
Φ 20-1	20	280	yes 1088570 cycles
Φ 20-2	20	280	yes 1854310 cycles
Φ 20-3	20	280	yes 1115141 cycles
Φ 20-4	20	280	yes 675589 cycles
Φ 20-5	20	280	yes 759420 cycles

As can be seen all five bars of eight millimetre diameter withstood the required number of 2·106 cycles when tested at a frequency of 25Hz. However, when the 12 mm bars were tested, a number of specimens failed usually within or very near the grip jaws (Figure 2). Moreover, all (10/10) specimens of 20 mm diameter failed and this caused suspicion about the quality of the bar material.

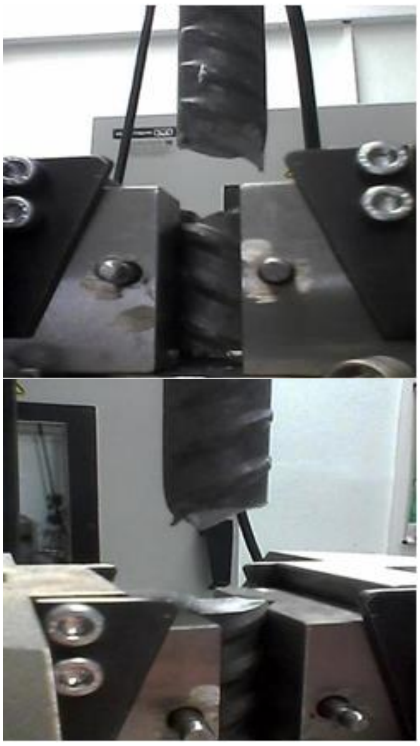

Figure 2. Premature failure within or near grip jaws

To exclude any such possibility the steel microstructures were studied using optical microscopy (Figure 3). As it can be seen all diameter bars exhibited a ferrite - pearlite microstructure and no martensite or other phases were present that could account for the premature failure observed.

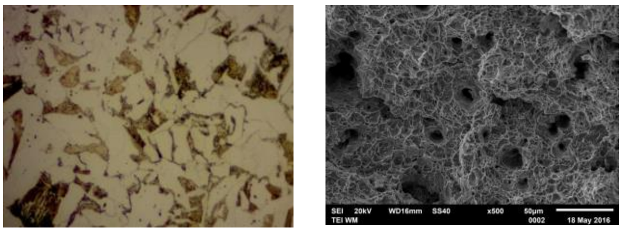

Figure 3. Steel microstructure and the fracture surfaces observed using SEM showing manganese sulphide inclusions.

As expected, the fracture surface observed using scanning microscopy revealed the presence of manganese sulphide inclusions (Figure 3) but this cannot by itself explain why premature fracture occurred only in the 12 and 20 mm bars. Studying the literature showed that fatigue strength of concrete steel is diameter dependent (Sismanis & Mastorakis 2008; DIN 1045-1, 2007; DIN 488-1, 2009; BS 4449, 2005). Steel bars of smaller diameter exhibit higher fatigue strength than steel bars of the same quality but bigger diameter. In German standards for concrete steel a gradual reduction in the requirements for fatigue strength is reported and in BS 4449 (BS 4449, 2005) the specifications differ depending on group diameter.

In the present study the results appear to agree with the above and originally the difference in fatigue strength of the 12 and 20 mm bars in relation to that of the 8 mm ones was attributed to their larger diameters. However, a closer look at the bibliography (Tilly, 1979; Krasnowski, 2015; NordTest method, 1979, Bannister, 1975; Burton et al., 1967; Walker et al., 1975) reveals that premature failure inside or close to the fatigue machine grips is a common problem with fatigue testing of reinforcing bars. This is due to the 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. Thus, the results of such tests cannot be regarded as reliable and should or may be rejected according to the EN 1421-3.

Tilly (Tilly, 1979) reports information about numerous attempts to properly prepare the grip parts of specimens so as to eliminate the problem of crack initiation in the grip part of the specimens; such attempts were always connected with using an additional layer between a specimen and a testing machine jaw. He mentions the use of leather belts wrapped around the specimen grip part, low melting point metallic fillings, resins and aluminium pads. However, Tilly does not provide any information concerning the effectiveness of the measures mentioned.

Krzysztof Krasnowski (Krasnowski, 2015) mentions a successful method that was used to eliminate the problem but does not give any information of the steps taken. In addition, in the NordTest method for fatigue testing of concrete reinforcement steel bars (NordTest method, 1979) four different methods for preparing the grip parts of specimens are described in detail. However, they all seem rather complicated and/or time consuming.

In order to locally change stresses in the specimen grip area and to make the notches caused by the jaws too small to lead to the premature failure the following technique was used with surprising success in the present study. For the 20 mm bars, firstly, a 50 mm length of the specimen ends was turned to 19.5 mm diameter, until the relief on the surface was almost completely removed.

Figure 4. Machined specimen ends and specimen ends wrapped with aluminium tape.

There was also a 4 mm long curved part machined past the grip part (Figure.4). This resulted in a larger surface area being gripped by the machine jaws and eliminated the applied stress concentrating on only four or five points that may cause failure. Then, approximately 0.5 mm of aluminium, 5 cm wide, tape was wrapped around the specimen ends to reduce the depth of the notches caused on the specimen surface by the machine jaws part (Figure. 4).

The fatigue test results of such specimens showed that none of the required five, as per EN 1421-3, failed. Therefore, the problem with specimen failure was not due to material quality but specimen surface morphology that results in stress concentration and notch creation caused by the machine jaws as was proven by the finite element analysis that follows.

3.2 Numerical Analysis

The geometry of an "as received" bar, as well as that of a treated one was digitized using a 3D scanner (Z800 – 3D SYSTEMS) and the resulting .stl file imported into the pre-processing software ANSA (by Beta CAE Systems).

The verification of the model was largely based on the development of a mesh independent grid (Zienkiewicz & Taylor, 1989; Tsouknidas et al., 2013), generated in ANSA. Convergence studies were conducted up to a 2% results deviation indicated the optimum mesh density in terms of processing time and results. The structure of the employed validation process (trend validation) emphasized on the evaluation of theoretical scenarios allowing a comparative evaluation of the two scenarios under the applied tensile load.

Although the use of nonlinear properties is preferable to determine possible failure mechanisms at high plasticity (Bouzakis et al., 2012), linear elastic properties were applied (Krasnowski, 2015) for both scenarios, as this comparative analysis was meant to serve as an indication of critical stress concentrations that might occur during loading. The model was then imported into ANSYS (ANSYS® Academic Research, Release 15) with a non-linear solver formulation and subjected to an axisymmetric tensile load. A summary of the obtained results can be seen in Figure 7.

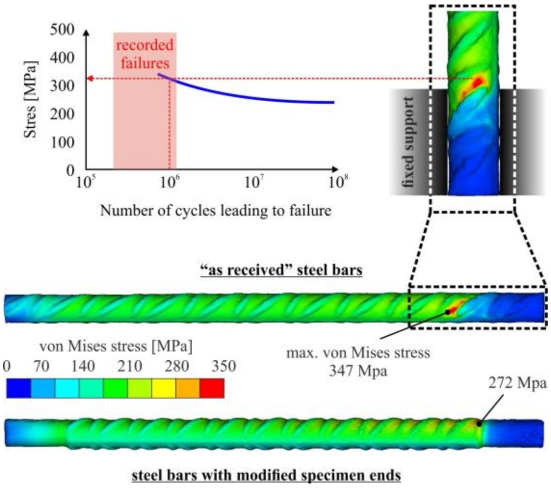

Figure 7. Comparison of developing stress fields on the as received and treated bars.

Finite Element models have been widely accepted as effective in the evaluation of wear propagation (Bouzakis et al., 2008) and failure (Bouzakis et al., 2011) of mechanical components. As it can be seen, the developing max. von Mises stress in the "as received" bar is recorded just above the tester's grip. This can be attributed to the surface area of the bar being in contact with the grip, which is lower when compared to the modified one, as the bar's surface protrusions minimize the bar/grip interface. As a result, the "as received" bar develops a max.

von Mises stress which is 27,5% higher than the one observed in the modified one.

According to the Smith diagram, in the top left part of Figure 8, this increase is capable of leading to failure at about 10^6 cycles, a behavior that coincides well with the experimental results.

4 CONCLUDING REMARKS

High cycle fatigue tests conducted on reinforced-concrete steel ribbed rods in accordance with the specifications in EN 10080 are difficult to perform due to premature failure appearing within or near grip jaws. The specimen preparation method described above will aid researchers on fatigue testing to obtain accurate test results and save on material and time.

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