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Experimental Stress Analysis

Experimental methodology for evaluation of high cycle fatigue properties of tubes with variable diameter

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Abstract: In spite of recent considerable progress in numerical modeling and calculations for predictions of durability, safety and reliability of machinery structures, experimental evaluations of mechanical and fatigue properties of real subcomponents, components or their models remains an important part of research and development programmes with applied outputs. A new method of high-cycle fatigue testing of tubes with variable diameters with the use of a special testing resonance system containing two masses and the specimen as a springy element was proposed and is described in the paper. A comparative experimental programme of fatigue tests under rotation bending and flat bending was performed on a high strength steel to verify an agreement of results obtained during these two types of tests. In the second stage, a method of fatigue testing of tubes was elaborated and experimentally verified, including specimen attachment method and static calibration. The method uses dynamic strain gauges signals measured at different surface sites of the tubes including stress concentrators. Dynamic load amplitude is controlled using the strain values. Records of dynamic stresses enabled to separate crack initiation and growth stages. An agreement or some small disagreement between theoretical and measured static strains is discussed in the paper.

Keywords: High-cycle fatigue, Tubes with variable diameter, Fatigue crack initiation, Dynamic stress

1. Introduction

High cycle fatigue resistance is an essential property of materials and components exposed to variable loading with a considerable number of loading cycles during operation. Significance of a careful evaluation of high cycle fatigue properties has been recently growing due modern design concepts with a tendency to reduce mass of structures as much as possible and increase intervals between maintenance to reduce life cycle costs [1]. An emphasis is being put not only on an evaluation of materials fatigue properties, but also on size effects [2] resulting in requirements on full-size component testing in specific real cases [3,4].

In spite of recent increasing use of numerical modelling and calculations representing a powerful and useful tools to predict durability, safety and reliability of machinery structures, an experimental evaluation of mechanical and fatigue

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properties of real subcomponents, components or their models is always an important part of research and development programmes with applied outputs. In such cases, it is important to find an adequate method of attachment of tested pieces as well as loading method to receive relevant and reproducible results. This contribution describes a development and verification of a method to evaluate fatigue properties of medium-size tubes with a variable diameter manufactured using advanced methods reduction forming – rolling. The tubes represented full-scale models of sections of hollow shafts with a perspective use in machinery.

2. Experimental method and verification

High cycle fatigue properties of metallic materials and components have to be preferentially experimentally evaluated using resonance fatigue machines because of possibilities to generate variable loading of fairly high frequencies and acceptable operation costs of the machines. To keep the testing costs low, it was decided to use a special resonance machine based on two parallel masses connected to each other by the tested piece serving as a springy element (Fig. 1).

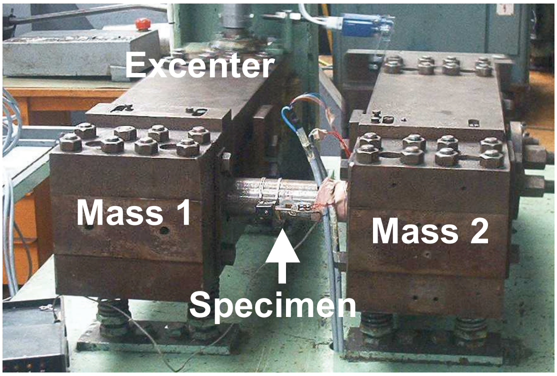

Fig. 1. Machine resonance system with masses and tested specimen as a springy element.

One of the two masses in Fig. 1 is being excited by an internal eccentric, the rotation being introduced by the external electric engine. The masses oscillate in the horizontal plane. As the system works bellow its natural frequency, the amplitude can be controlled by the oscillation frequency. A certain disadvantage of the machine is an absence of load cell. Stresses have to be therefore dynamically measured directly on the specimen surface, either by strain gauges or extensometers or both.

Unlike this situation of plane bending, shafts are usually loaded in operation by rotating bending. A comparative experimental programme of fatigue tests of a railway axle steel was carried out to verify, weather there are significant differences between the two types of loading, namely rotating and plane bending. A subsidiary aim of the testing programme was to verify possibilities of the testing system, exactness of load amplitude and comparability of results.

The used materials A4T was a standard alloyed heat treated steel for railway axles, strength R_m = 790 MPa. The specimen dimensions were: 500 mm total length and 50 mm diameter of gauge length. Two strain gauges were longitudinally bonded at opposite sides at the centre of gauge length. Before attaching the tested specimen in the resonance machine, a careful static calibration was carried out on another hydraulic machine with an independently verified load cell, at four-point bending. During the static calibration, the specimen was several times turned bottom up, static loading was repeated. Strain values evaluated by the Hottinger Baldwin Messtechnik (HBM) Spider 8 devices were recorded together with actual static loading. Theoretical surface stress in the centre of the specimen was calculated and compared with the measured strain values. E-modulus value was supposed to be 210 GPa. Comparing the theoretical and experimental values, there was a very good agreement between strain measured on tension and compression sides, up to 1.5 %. The difference between measured and calculated values was higher, about 6 %, theoretical values being higher. The difference can be explained by the type of specimen supports used, which could cause some restriction against free horizontal motion.

Dynamic strain recording was performed during the whole fatigue test. The part before failure is shown in Fig. 2. An interesting issue is the sensitivity of the load amplitude to crack initiation and gradual growth, which enables to separate crack initiation and growth stages.

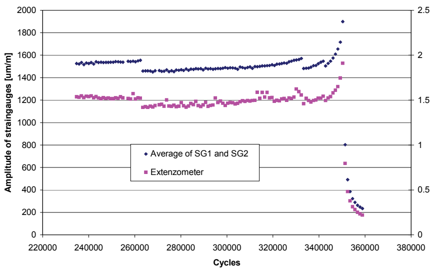

Fig. 2. Record of strain gauges and extensometer during fatigue test.

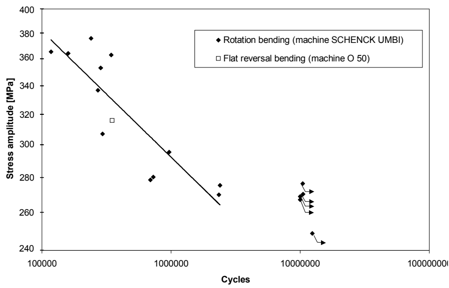

Fig. 3. Comparison of the flat bending fatigue test with rotating bending tests.

The last step of the experiment was a comparison of the test result with a set of results obtained on the same specimens under rotation bending on the SCHENCK UMBI machine. Certain differences between flat and rotation bending tests exist, particularly in terms of the total specimen surface area exposed to maximum load amplitude. Whilst during rotation bending, all the specimen surface is exposed to the same maximum cyclic stress, during flat bending it is just a limited area near in the plane of bending. It can be easily evaluated that if a total area corresponding up to 3 % stress drop off is considered, which corresponds to usual precision of fatigue limit estimation, the total area exposed to such a load represents 15 % of the total specimen surface area. This fact can be important in case of randomly and rarely distributed material defects like large inclusions, because the probability that an inclusion initiates fatigue crack then grows with a larger total surface area. The tested material A4T is of a high quality, quite homogenous, so no difference between the two types of tests was observed – Fig. 3.

3. Fatigue test of tubes with variable diameter

The main part of the work consisted in a verification of a methodology of fatigue tests of tubes with variable diameter. The trial tube was manufactured of a 16MnCrS5 (DIN) low-alloy case-hardening steel by reduction rolling. Strength of the material corresponded to 640 MPa according to an estimation from hardness measurement, HV 30 = 183. The tube contained three straight sections with different diameters, namely 57 mm, 42.3 mm and 38 mm (outer diameters), as shown in Figs. 4-5. The nominal wall thickness was approximately 5 mm. exact thickness values varied from 4.9 mm at the end of the maximum diameter over 5.5 mm in the central section to 4.6 mm at the small end. The material microstructure was quite homogenous with practically no defects, so results obtained under flat bending could be assumed as comparable to those under rotating bending as mentioned above.

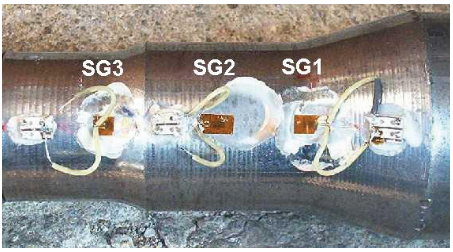

Fig. 4. Position of strain gauges.

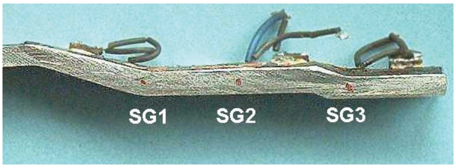

Fig. 5. Tube thickness on longitudinal cut.

The solution of the task contained three steps: (i) an attachment of specimen to the machine, (ii) load specification – static calibration and measurement of actual stress and strain at different specimen surface sites and (iii) fatigue test itself with dynamic recording of stress-strain amplitudes.

3.1. Attachment of specimen

Several possibilities of attachment were considered. Eventually it was decided to use arbors press fitted in the tube to be tested, which could be attached in the machine grips. Press fitting was made with the temperature difference about 200 ^{o}C between the tube and the pins. The limited temperature difference was used to avoid material changes in the rolled tubes. Oversize of the pins was exactly calculated considering the temperature difference and material dilatation. The specimen with arbors prepared for the press fitting is in Fig. 6.

3.2. Static calibration

Strain was measured at three important surface positions of the tube: at the specimen centre as a reference site and at the two shallow notches - radii. Strain gauges (SG) positions are documented in Fig. 4. Tube wall thickness and shape is shown on longitudinal cut in Fig. 5. The cut was made after finishing the fatigue test with the aim to obtain exact dimensions of the tube to evaluate theoretical stresses retrospectively.

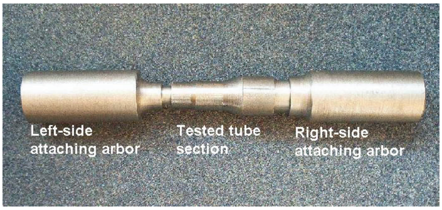

Fig. 6. Specimen with attaching arbors.

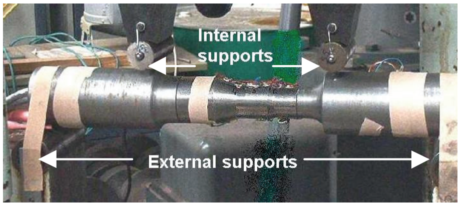

Fig. 7. Static measurement of surface strains.

Static measurement was performed at four-point-bend loading – Fig. 7, at two specimen positions, the second one corresponding to specimen turned bottom up. Results of surface SG measurement are in Figs. 8-9. In the SG3 position, ie. in the radius of the smallest diameter, not only highest stresses were measured, but also some irregularities were ascertained – Fig. 8. Always during the first loading cycle at both the specimen positions, SG3 showed a kind of strengthening, which can be explained by some plastic deformation in the internal surface due to residual stresses. An counteracting, but not so distinct behaviour was observed at the SG1 site – some positive non-linearity during first load cycle (Fig. 9).

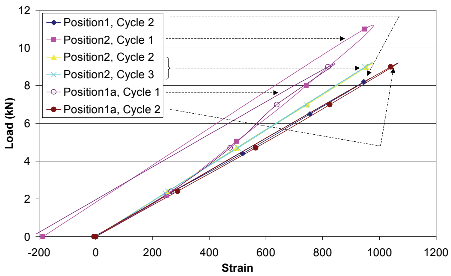

Fig. 8. SG3 values during static load cycles.

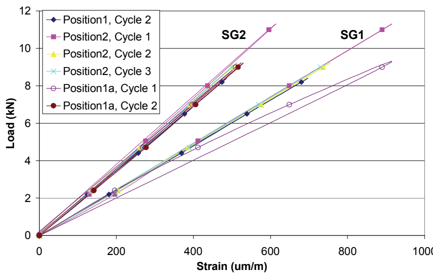

Fig. 9. Comparison of SG2 and SG1 values.

Comparison of SG1 and SG2 average values (Fig. 9) enables to evaluate actual stress concentration factor in the radius (SG1) in comparison with the central part of the tube (SG2). This concentration factor is 1.43. Stress value was highest at SG3 site, ie. at radius between the smallest diameter and central section of the tube, and were 2.0-times higher in comparison with the cetral straight section. A comparison between calculated and measured stresses was made for the straight central section (SG2). Measured values were by 14% lower, which can be explained by the loading type, particularly by a relatively small test span in comparison with high vertical distance of action points due to large arbor heads of the diameter 75 mm and supports not ideally free.

3.3. Fatigue test

Verification fatigue test was performed on the resonance machine under flat bending. The principle and machine verification are described in [5]. All the SGs were monitored using HBM Spider 8 dynamic device, values were used to control the load amplitude. In addition, surface stress was monitored using an INOVA high precision semiconductor extensometer.

Fatigue test was performed at strain amplitude 1550 μm/m at the SG3 position of maximum stress concentration. Corresponding stress amplitude was approximately 325 MPa. Records of average values of dynamically measured strain amplitudes exactly confirm the stress concentration factors evaluated during static calibration – Figs. 8-10.

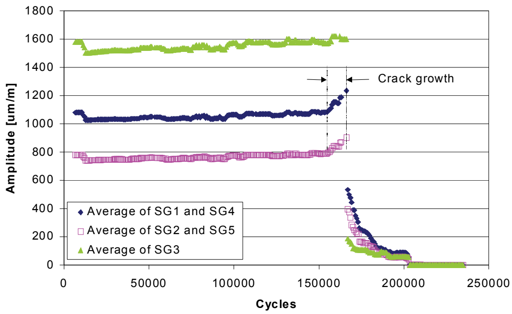

Fig. 10. Strain amplitudes recorded during fatigue test.

It follows from Fig. 10 that the test method and the testing system enables not only to evaluate number of cycles to failure, but also enables to separate crack initiation and crack growth stages. The initiated and growing fatigue crack namely results in a re-distribution of dynamical stresses on the component. Furthermore, due to the existing and growing crack, natural frequency of the oscillating system with the two masses and specimen as a springy element continuously changes resulting in changes of stress amplitudes if excitation frequency of the machine remains constant.

4. Conclusions

A new method of high-cycle fatigue testing of tubes with variable diameters was proposed with the use of a special testing resonance system containing two masses and the specimen as a springy element. In the first stage of the work, a comparative experimental programme of fatigue tests under rotation bending and flat bending was performed on an A4T high strength steel used for railway structures. In the second stage, a method of fatigue testing of tubes was elaborated and experimentally verified. The method contains three steps: (i) specimen attachment, (ii) static calibration and (iii) fatigue test. The main conclusions can be summarised as follows:

- In case of a material with homogenous microstructure and without defects like the A4T railway steel, fatigue results under flat bending correspond to rotation bending with quite a high precision.
- The method of tube attachment using press fitted arbors was successfully verified.
- Static calibration provided experimental results of stress concentration factors in tube radii. Actually measured strains during static four-point-bend loading were by 14% lower than theoretically calculated values. The differences were discussed.
- Fatigue test was successfully carried out. Mutual proportions of recorded dynamical strains exactly corresponded to those evaluated during static loading.
- Records of dynamical strains enabled to separate crack initiation and growth stages. Continuously growing crack resulted in a stress redistribution on the tube surface and in some changes of load amplitude due to changes of natural frequency of the resonance system.

Acknowledgements

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