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Experimental and Simulation Tests of the 1 MN Screw Coupling

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Summary
The article describes the requirements that screw couplings must meet before they can be put into service. In the paper, the results of fatigue testing simulating a 30-year service life of a screw coupling are presented, as well as the results of CT and Nondestructive Testing, NDT, non-destructive magnetic particle inspection, and then, the test results are compared with the results obtained with the application of Finite Element Method, FEM.

Keywords: FEM, screw coupling, crack

1. Introduction

Screw couplings are universal mechanical railway vehicle connections used in various types of passenger and freight wagons as well as traction units. The safety and integrity of the train during its operation depends on these devices. These devices are not only subjected to very high loads, but must also be able to withstand changing weather conditions over many years. The permission of screw couplings, draw gear, including hooks, to operate requires conducting tests with positive results, according to detailed guidelines, described in the standard [1] and according to Commission Regulation (EU) No 321/2013 [2] and Commission Regulation (EU) No 1302/2014 [3].

EN 15566:2016 standard [1] defines, as presented in Table 1 and Table 2, the division of screw couplings in terms of the forces they can be subjected to during operation – i.e. 1 MN; 1,2 MN; 1,5 MN and additionally in terms of their service life, i.e. 20 or 30 years. Each type of coupler used in operation should be marked in a permanent manner that defines its category of use and the maximum load that can be subjected to in service (1 MN, 1.2 MN, 1.5 MN).

A critical area of wear in the screw coupling is the area where the bow meets the hook. As a result of con-

Table 1

Conditions for dynamic testing of a screw coupling – range of applied forces and permissible operational loads depending on intended use

Range of applied test forces for the screw coupling		
Classification category / Intended use	**Step 1**	**Step 2**
1 MN	ΔF1 = 170 kN	ΔF2 = 575 kN
1,2 MN	ΔF1 = 205 kN	ΔF2 = 690 kN
1,5 MN	ΔF1 = 270 kN	ΔF2 = 910 kN
Range of applied test forces for hook or draw gear		
Classification category / Intended use	**Step 1**	**Step 2**
1 MN	ΔF1 = 200 kN	ΔF2 = 675 kN
1,2 MN	ΔF1 = 240 kN	ΔF2 = 810 kN
1,5 MN	ΔF1 = 300 kN	ΔF2 = 1015 kN

Own study based on [1].

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Table 2

Conditions for dynamic testing of a screw coupling – number of cycles depending on the required service life and intended use

Wymagany czas działania Cykl zatosowania w latach	Range of applied test forces for the screw coupling		
	Classification category / Intended use	Step 1 N_1 in cycles	Step 2 N_2 in cycles
20	1 MN 1,2 MN 1,5 MN	10^6	1.45×10^3
30	1 MN 1,2 MN 1,5 MN	1.5×10^6	2.15×10^3

Own study based on [1].

tact between the components and the transmission of considerable forces over a small area of the surface, surface friction occurs here, resulting in a high concentration of stresses. As a result of the mutual friction of the contacting surfaces, significant wear is observed over time, as shown in Figure 1.

Fig. 1. View of the worn (in operating conditions) surface of the bow caused by abrasion against the draw hook [pic. A. Aniszewicz]

After the fatigue tests, an assessment of the condition of the coupling components (including the defects and cracks) is carried out, which can be complemented by analyses and simulations using the Finite Element Method (FEM), which often allow the causes of damage to be understood [4, 5, 6, 7].

2. Experimental tests

Experimental tests include fatigue tests and are one of the most important tests of a screw coupling. The requirements for the test procedure are described in EN 15566. The static and fatigue tests as well as the loading described in the EN standard include both the individual elements of the screw coupler, joint, shackle, bolts, as well as the entire completed coupler.

Testing of the 1 MN screw coupling was carried out on the LFV fatigue testing machine shown in Figure 2. Figure 3 shows an example graph of the applied fatigue loads. The graph shows 698 load cycles of low amplitude ΔF1 and one cycle of ΔF2 high amplitude with values taken according to Table 2. Each block consists of dynamic loads ranging from 10 kN to 180 kN, followed by a 575 kN load cycle. The load pattern for given types of couplings results from the requirements described in EN 15566 [1] and Table 2. The described fatigue loading block was performed 2150 times, which corresponds to a simulated operation of the coupling for 30 years.

Fig. 2. 1 MN screw coupling during fatigue testing using an LFV machine [pic. D. Kowalczyk]

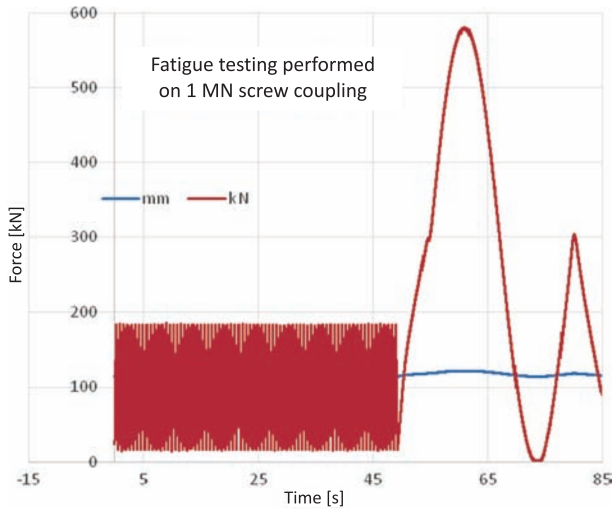

Fig. 3. Fatigue loading block for 1 MN screw coupling [study by D. Kowalczyk].

3. Non-destructive magnetic particle inspection

After completion of the fatigue testing, the screw coupling was subjected to magnetic particle inspection [8, 9]. The surface condition of the bow where it meets the hook was assessed. Figure 4 shows in green the area showing the results of these tests. The tested coupling revealed superficial cracks, the size of which does not exceed permissible values. According to the requirements and criteria for the assessment of the surface condition after fatigue testing, discontinuities – cracks of length and depth up to 20 mm are permissible according to the requirements of the standard [1].

Figures 5a and 5b show a view of the worn coupling bow surface caused by abrasion against the draw hook during fatigue testing. Fatigue tests performed with a fatigue testing machine indicate that the stress distribution in the contact area of the hook and bow may be different and non-uniform leading to significant local abrasive wear.

Fig. 4. Cracks in the 1 MN bow after fatigue testing using the magnetic particle inspection [pic. D. Kowalczyk]

4. Testing of the screw coupling using computed tomography (CT)

An additional test not required by the standard [1] was a computed tomography scan. As non-destructive magnetic particle inspection has shown, there are surface indicators (cracks) in the screw coupling bow the depth and shape of which cannot be precisely determined. Therefore, the bow was subjected to CT scans in order to determine the depth of the crack(s) and their distribution in a non-destructive manner (without interfering with the identified surface defects).

To test the screw coupling bow using computed tomography, GEphoenix v/tome/x m equipment with a 300 kV X-ray detector was used. X-rays of the coupling components confirmed the discontinuities and cracks revealed by non-destructive magnetic particle inspection.

a) b)

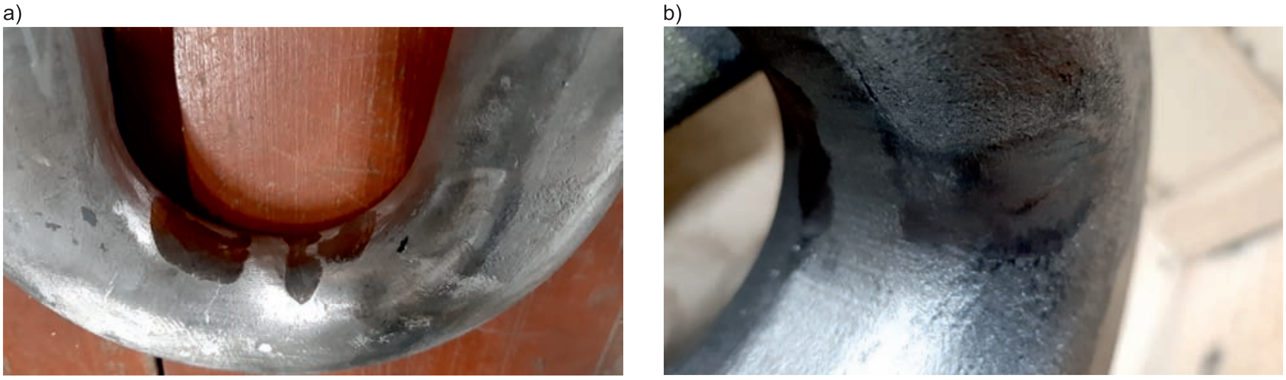

Fig. 5. View of the worn coupling bow surface caused by friction with the draw hook: a) left view, b) right view [pic. D. Kowalczyk]

The images obtained by CT scanning allow to observe crack propagation path in 3D and its actual length and depth to be determined. It should be noted that the requirements of current standards specify only the surface length of defects [1]. In fact, based on observations of tested sample, it has been found that cracks can propagate as deep as 5 mm below the material surface. The cross-section and longitudinal section of cracks within the material of the 1 MN screw coupling bow after fatigue tests are shown in Figures 6a and 6b.

5. Simulation tests

Simulation tests were performed using the finite element method (FEM), which has been widely used in the study of railway structures [5, 6, 7]. In the present case, FEM calculations were performed for comparison purposes and to determine the stresses occurring in the contact area between the hook and the screw coupling bow. For this purpose, a 3D model of a 1 MN screw coupling hook and bow was created in SolidWorks. Calculations were performed in Ansys Mechanical R2020 software on a static structural solver with a non-linear material model of 40CrMno4 steel taking into the account the plastic deformation range. The analysis on the solid model focuses on the part of the screw coupling bow where cracks most frequently occur (Fig. 4, 5 and 6.) The computational model was prepared for a fatigue load of 200 kN and 575 kN. The grid description assumes TETRA-type four-node elements for the bow and hexagonal six-node elements for the hook and a variable grid area, 214,000 nodes and 125,000 elements. The following mesh parameters were selected in the software: curvature-based solid mesh, Jacobian 4 points, mesh quality "high". Axial loading was chosen as the initial conditions. The available data for the 40CrMno4 steel [10] from which the screw coupling components are made and the results of a tensile test carried out on a material sample made from a part of the screw coupling were used. The data shown in Figure 7 from the tensile test of a sample made from the material used in the manufacture of the 40CrMno4 coupling contributed to the determination of the material model in terms of actual plastic deformation. Example results of FEM simulation tests of the loading of the 1 MN screw coupling bow are shown in Figures 8, 9, 10 and 11.

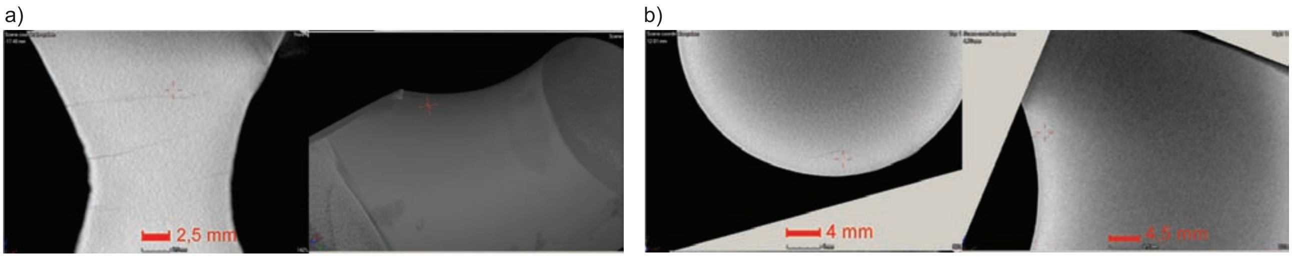

Fig. 6. Observations of the extent of cracks inside the material of the 1MN screw coupling bow after fatigue tests performed with the use of computer tomography: a) view in cross-section, b) view in longitudinal section [study by D. Kowalczyk]

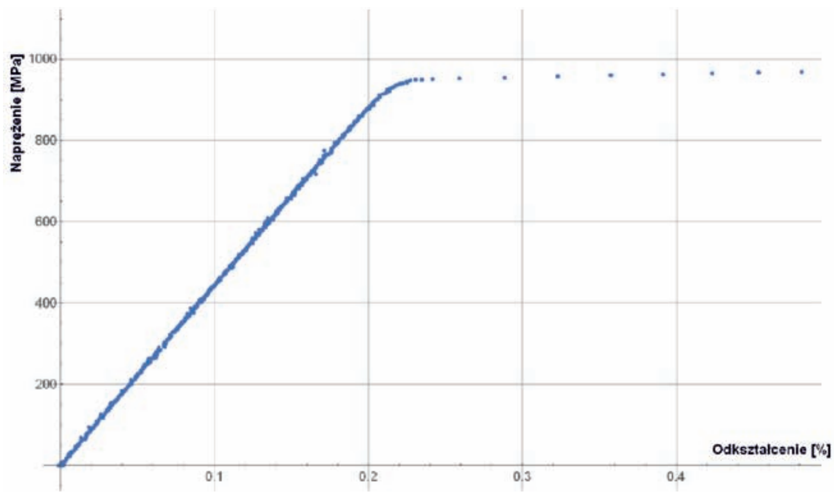

Fig. 7. Tensile test (stress vs. strain) of a sample made of 40CrMno4 steel [study by D. Kowalczyk]

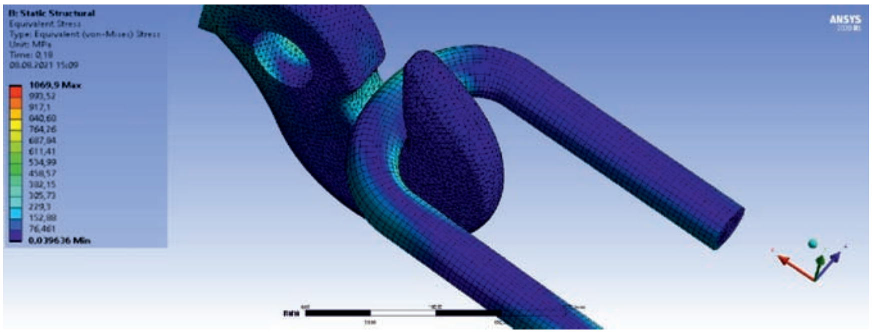

Fig. 8. Von Mises stress for a load of 200 kN [study by D. Kowalczyk]

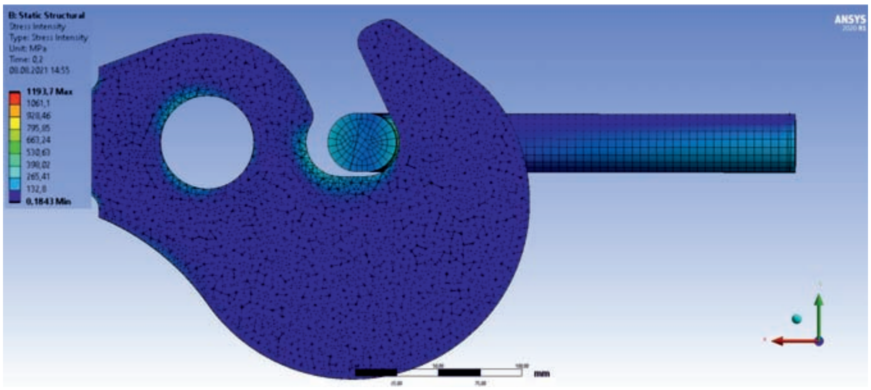

Fig. 9. Stress for plasticity under load of 200 kN [study by D. Kowalczyk]

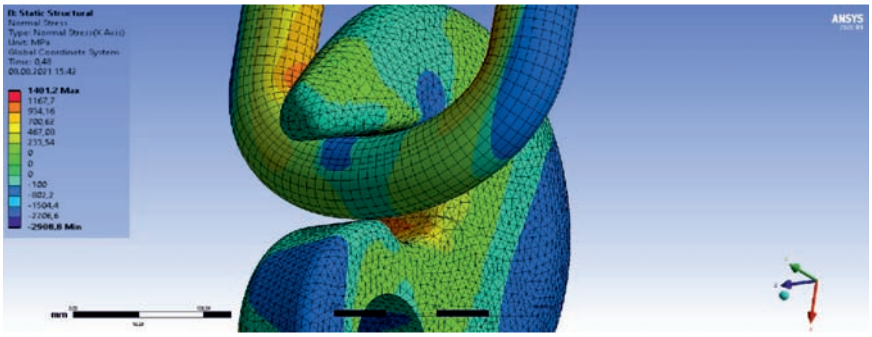

Fig. 10. Graphical representation of the stress distribution in the contact area of the hook and bow of a screw coupling (normal stresses) under load of 575 kN [study by D. Kowalczyk]

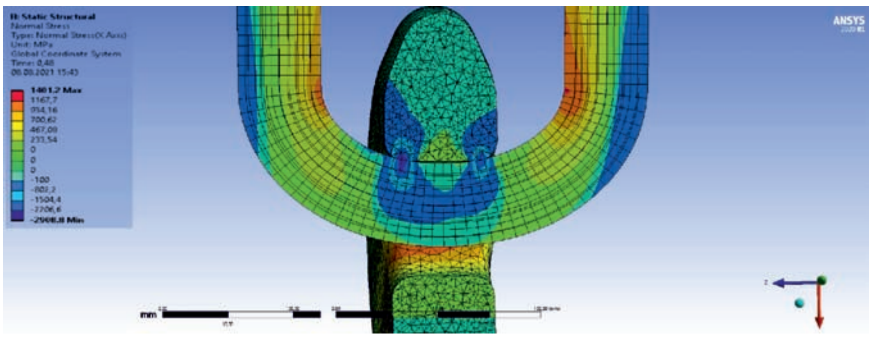

Fig. 11. Graphical representation of the stress distribution in the contact area of the hook and bow of a screw coupling (normal stresses) under load of 575 kN [study by D. Kowalczyk]

6. Results of FEM calculations

Obtained results of simulation tests on built FEM models in the defined fatigue load range according to EN 15566:2016 [1] indicate that during the loading of a force of 575 kN, a zone of high concentration of both compressive and tensile stresses in the material of the screw coupling bow arises in the contact area of the hook and the screw coupling bow. The simulation results obtained reveal tensile stresses locally capable of exceeding 1,000 MPa and compressive stresses as high as 1,500 MPa (Fig. 10 and 11). The analysis of

Figure 11 shows that the shape of the contact area and the area of operation of the bow and the hook are important for the stress distribution in this area. The better the fit, the more evenly the stresses are distributed over the whole contact area, so that their average value can be lower.

The test results presented in Figures 8, 9, 10 and 11 clearly confirm the causes of cracks in the contact area of the hook and bow. They are caused by the occurrence of extremely high stress values and close compressive and tensile stress zones in the bow and by high pressures on the contact surface of the bow with the hook.

7. Conclusions

Following fatigue testing of the 1 MN screw coupling, non-destructive magnetic particle inspection was carried out. Damage in the form of discontinuities and cracks was observed on the surface of the bow, the size of which does not exceed permissible values.

Non-destructive testing including magnetic particle inspection and CT scanning confirms that the contact surface of the bow and hook is an area particularly prone to crack occurrence and propagation. CT scans showed that in the case in question, the crack propagated up to 5 mm deep into the material of the bow (in the area of contact with the hook surface). The simulation tests and FEM analyses carried out confirmed the existence of a high stress concentration in this area and large stress differences in the compression and tension area (hook and screw coupling bow contact). The simulations indicate the importance of the geometry of the shape and surface fit of the bow and hook, which significantly affect the stress distribution in the components. The CT scanning made it possible to assess the depth of the cracks, to determine whether they are surface defects or cracks propagating into the material, and to observe in 3D their actual propagation path in the bow material.

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