VIBRATION FATIGUE - FEM ANALYSIS VS. REAL TESTING

KAREL RAZ, MILOSLAV KEPKA, JULIE VOLKMANNOVA

University of West Bohemia, Faculty of Mechanical Engineering, Regional Technological Institute, Pilsen, Czech Republic

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kraz@rti.zcu.cz

Main aim of this article is to present results of the basic research in the area of the fatigue of material. The work was focused on the improvement of the computational support (for the FEM approach) for the material fatigue evaluation. Tested parts were exposed to vibrations and therefore was noticed higher risk of the failure caused by the vibration-fatigue. The real testing is described in this work. Effect affecting the fatigue life are discussed also. Parts were made of steel DC01. Modern simulation tools and testing devices are used for improving knowledge in this field. For the testing was developed special testing stand.

KEYWORDS

Vibration, fatigue, steel, FEM, testing

1 INTRODUCTION

Knowledge of the fatigue behaviour is a key factor for the good design of the final part. Vibration fatigue is important design issue in the automotive, especially for parts loaded by rotation. Identification of parameters which are influencing the fatigue was performed in the first stage of the research. These parameters have significant influence on the durability and fatigue life. This problem is well described for real parts and constructions but the durability is mainly verified by an experiment nowadays. Fatigue tests are defined by standards for many applications (such as railways, automotive, etc.). These tests are unsuccessful in many cases (the damage of the part occurs during the test). This leads to higher demands on the virtual simulations and predictions of the fatigue life. The main difference between high-cycle fatigue and vibration fatigue is in loading definition.

The loading for the vibration fatigue is not defined by the spectrum of oscillations but is defined by the power spectral density. The calculation is consisted from the following steps: Creation of the numerical simulations where is the part loaded by the „unit“ force and the fatigue calculation. The fatigue calculation is based on the theory of the vibration fatigue (based on the analysis of the frequency spectrum).

Our research was using commercial software for identification key parameters of the fatigue life. The software Siemens NX with solver NX Nastran was used for the determination of the response function. The nCode 11 software calculated the fatigue life.

2 BASIC CONCEPT

The industrial part is loaded by stress (caused by force, pressure or other conditions), which is much lower comparing to the breaking strength of the individual material. The failure occurs nevertheless. The reason is the damage accumulation and material fatigue phenomena. Fatigue life is influenced by many factors. Their schematic description is shown in Fig.1. The lifetime is mostly defined by the SN curve. This curve consists from the sloped part and from the fatigue limit (see previous figure). The SN curve is affected by following factors (Fig. 1 and Fig.2): [Radaj 1995]

- Ultimate strength – higher ultimate strength is mainly resulting in the fatigue life increasing
- Notches – stress in notch is significantly decreasing the fatigue life
- Loading – higher loading is resulting in the fatigue life decreasing
- Mean Stress – depending on value [MPa] (positive or negative) is decreasing or increasing the fatigue life of the part

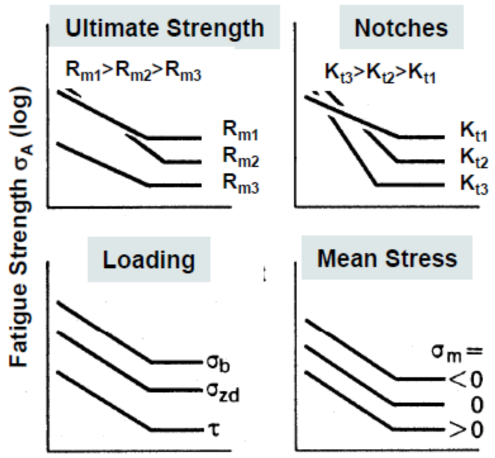

Figure 1. Effect of selected factors on the fatigue life – part 1

- Size – higher size (dimension of the part) is decreasing the fatigue life
- Surface Roughness – higher roughness is decreasing the fatigue life
- Temperature – higher temperature is decreasing the fatigue life
- Corrosion – appearance of corrosion is decreasing the fatigue life

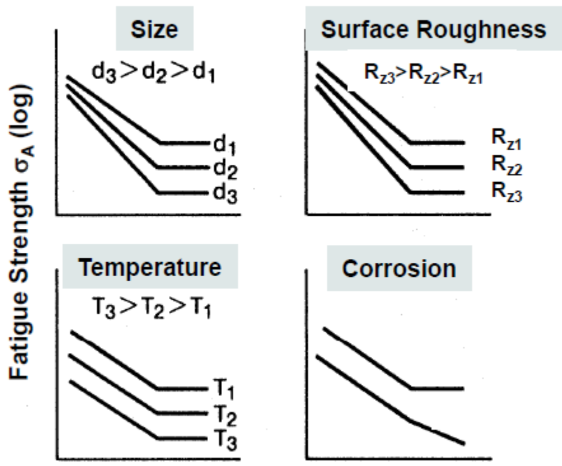

Figure 2. Effect of selected factors on the fatigue life – part 2

A simple fatigue demonstrator was created for validation of the numerical simulations. The fatigue-based tasks are for this demonstrator calculated numerically and validation is performed by the real test on the load stand.

The following figure (Fig. 3) shows the procedure of the lifetime determination for the vibration fatigue in the software nCode. It is describing all inputs, spectral densities (PSD, eventually some sines or swepts), counters of signals and it is resulting in the fatigue life. [Chmelko 2017]

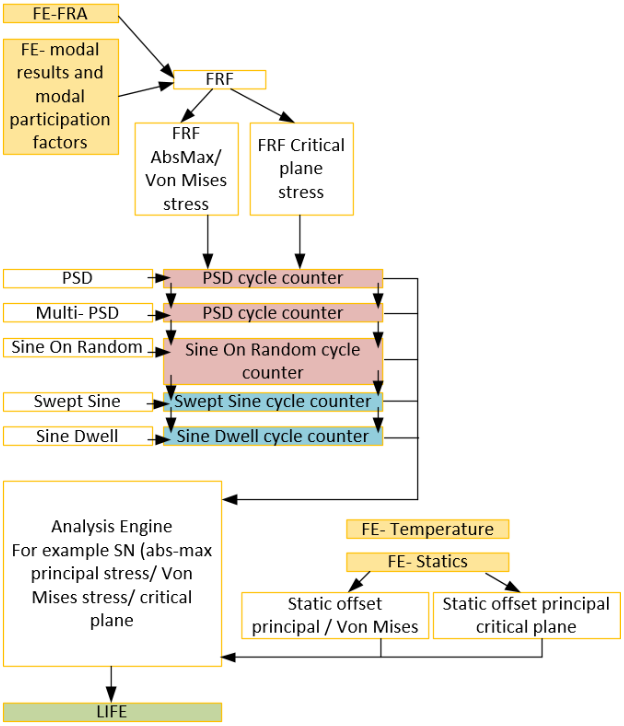

Figure 3. Lifetime determination procedure in the nCode manual

The frequency response function (FRF) is required for the numerical solution. This function is describing the dependency between the stress caused by the acceleration and frequency of the loading. The second input is the loading defined by the unit of acceleration in the frequency spectrum. [4,5]
Two different tools were used during the research. The solver NX Nastran was used for the determination of the frequency response function. The solution had following parameters. [Ruzicka 1987]

- Modal analysis SOL103 was used for the validation of correct frequencies of oscillation.
- Direct frequency response was solved by the solution SOL108.
- Modal frequency response was solved by the solution SOL111.
- Structural damping was 5 %, it means 0.05. This value is generally used value for steel. This damping was not specially measured.

The software nCode DesignLife 11 was used for the following simulations. The output from the NX Nastran 12.0.2.9 was used as an input to the nCode.

3 LABORATORY DEMONSTRATOR

The laboratory demonstrator with the design notch is made as a simple sheet metal part. Lengths of individual specimens are 95, 135 and 175 mm. Width is 15 mm.

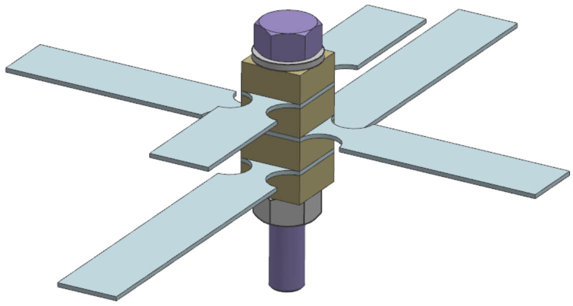

Figure 4. CAD model of the laboratory demonstrator

There are three different specimens with different length (it means different durability). The specimens have smaller cross-section in the critical area. These specimens are attached to the threaded rod, which is connected to the vibrating device (Fig. 4 and Fig, 5).

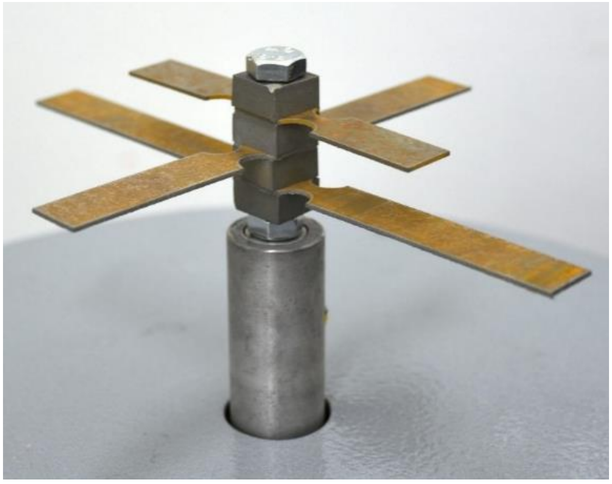

Figure 5. Real demonstrator for testing

4 MATERIAL

The laboratory demonstrator is made from the steel DC01 with the tensile strength 400 MPa and yield strength 280 MPa. The following synthetic Wohler curve (for the polished specimen) was designed in the nCode software (Fig.6). [Neugebauer 1989], [Raz 2015]

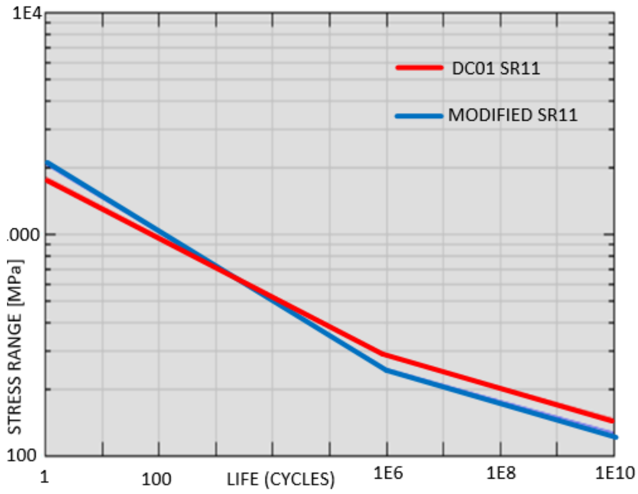

Figure 6. Wohler curve for the material DC01 (regular and modified)

5 INDIVIDUAL RESPONSES- DETERMINATION OF THE FREQUENCY RESPONSE FUNCTION

The stress response was determined in the critical point for each of three specimens with respect to the loading frequency. The loading was defined as 100 m/s2. The line in the Fig.7 with highest amplitude is for the longest specimen, the one with smallest amplitude is for the shortest specimen. It is obvious that the critical stress is different for each specimen and it occurs for different loading frequency.
This loading was defined as a „reference“ loading and it was used as an input to the nCode software. It is possible to scale these results in order to achieve suitable lifetime (damage during period of hours) during the real testing.

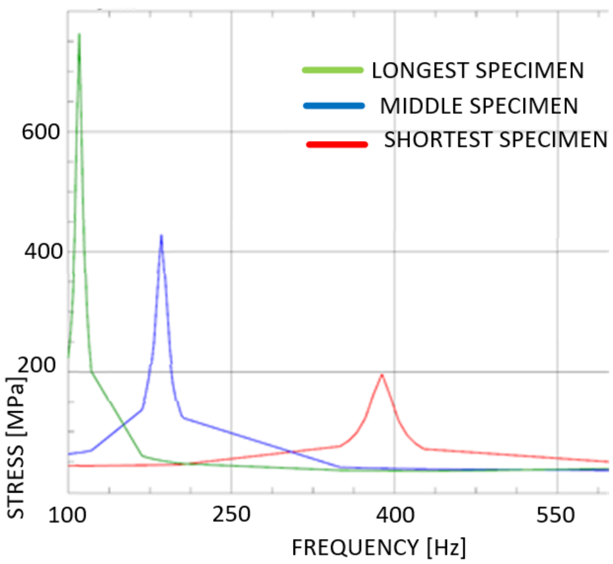

Figure 7. Stress response for individual specimens

5.1 Modal shape of specimens

Determination of the correct natural frequency is key factor from the vibrational point of view. First modal frequencies are obvious from the previous simulation. This modal shape is bending in the vertical direction. For the simplification is for all simulations used only symmetrical quarter of the model. The knowledge of natural frequencies can be used for the direct loading in area of these frequencies. The results can be summarized as follows (when considering linear behaviour of material in the NX Nastran):

- Long specimen

First natural frequency= 101.6 Hz
Maximal stress (push-pull) caused by 100 m/s2 loading by first modal frequency = 861 MPa

- Middle specimen

First natural frequency = 172.6 Hz
Maximal stress (push-pull) caused by 100 m/s2 loading by first modal frequency = 478 MPa

- Short specimen

First natural frequency = 364.3 Hz
Maximal stress (push-pull) caused by 100 m/s2 loading by first modal frequency = 196 MPa

It is obvious that the stress determined by the FEM analysis is during the maximal loading much higher comparing to the yield strength. These calculations were performed with respect to the validity of the Hook´s law. It is possible to convert (scale) them into the smaller stress and smaller loading. This procedure is used for the determination of the appropriate acceleration during the real testing.

5.2 Loading of specimens

We were focused on the following type of the loading during the testing. It is loading by the sine- sweep. This type of loading is describing the dependency between the amplitude and frequency. The local response B_{AMP} (f) can be described as equation (1):

$$B_{AMP}(f)=A(f)\cdot X_{AMP}(f) \quad (1)$$

Where X_{AMP} (f) is the response of the acceleration from the FEM analysis and $A(f)$ is the loading defined in the frequency area. The loading of specimens was 40 m/s2 (scaled input). Therefore, the damage was in the time period lower than one day. The speed of loading was logarithmic octave per minute. The stress in the critical plane (critical plane approach) was used for the determination of the durability. Orientation of the individual critical plane is defined by the angle (0-170 degrees; by the increment 10 degrees). [Siemens 2020], [Novy 2016]. The damage has to occur at the time 6 hours and 10 minutes for the longest specimen. The result is shown in the Fig.8.

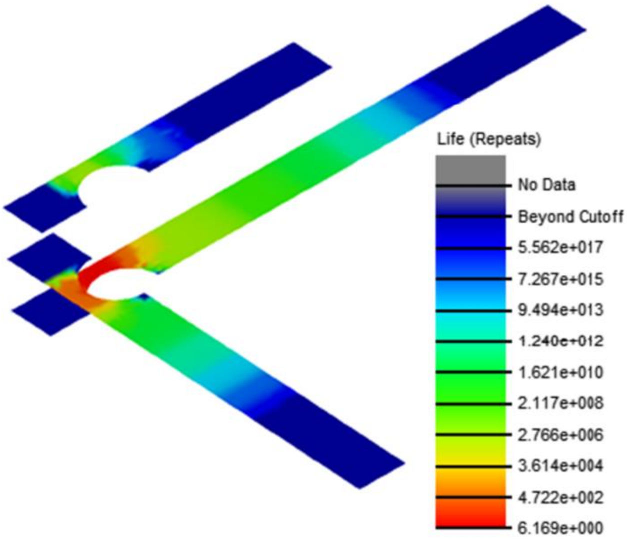

Figure 8. Lifetime of individual specimens in hours, loading by the sine sweep

6 REAL TESTING AND COMPARING

There is comparing between the experimental and numerical solution in this chapter. The loading was considered at the same level during the real testing. The testing device was using the solution Modal Exciter Type 4827.

	Experimental measurement [h]	Numerical solution - FEM [h]
Longest specimen 1	5:58	6:10
Longest specimen 2	6:01	6:10
Middle specimen 1	15:25	500
Middle specimen 2	16:25	500

Table 1. **Comparing of the fatigue life determined by the real testing and FEM analysis**

There are results from the numerical and experimental solution in the previous table. The shortest specimen is not mentioned, because there was no damage during the testing period. It is corresponding with the numerical solution. For the middle specimen is the difference way higher. It is caused by wrong slope of the SN curve. This problem will be removed by improving the curve description by material testing during the further research.

7 ANALYSIS OF THE FRACURE SURFACE OF THE SPECIMEN

Fractures caused by the fatigue are one of the most occurred fractures. It is possible to avoid these problems when considering behaviour of selected material (it means curve of the tensile test) and by usage of an appropriate safety coefficient.
The main problem of fatigue fractures is the time-varying stress. The fatigue crack can be developed because of the small non-

homogeneities in the material. This crack is increasing with the number of loading cycles. It also depends on the type of loading. Different loading types (bending, pushing, etc.) are resulting into the different fatigue behaviour. These increased cracks are reducing the cross-section. It can lead to the much lower force, which is necessary to final damage comparing to force from the tensile diagram.

The initiation of the crack always begins at the weakest place. These places are non-homogeneities in the material (internal or on the surface), porosity of the material or wrong design with sharp notches. These problematic areas are stress concentrators and there will the crack start. The increasing of the crack is more difficult in the fine-grained material. The analysis showed, that the fracture was caused by bending. The cracks were initiated from both sides (Fig. 9). The middle area was not so affected by the fatigue.

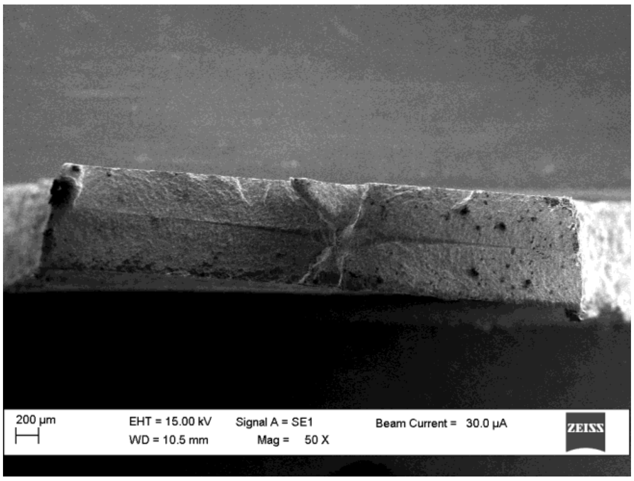

Figure 9. The crack was spreading from both sides. The material in the middle was not affected by fatigue after the experiment was completed.

8 CONCLUSIONS

This paper deals with a description of the fatigue properties of the material steel DC01. It is obvious, that the actual simulation tools provide a wide range of fatigue prediction. This phenomenon is affected by many different parameters and their correct definition is necessary to obtain correct results. It is still necessary to carry out fatigue test in order to validate the calculations.

The necessity of the validation is obvious from the obtained results. The difference between experimental and numerical solution is different for each length of specimen. The setting was for all specimens the same.

This research will continue with focus on determining the impact of individual factors that are affecting the fatigue life. Following aspects will be examined:

- size of the FEM mesh
- influence of the material dispersion (slope of the SN curve). This will be tested because there was noticed difference between fatigue limit of the middle specimen.
- influence of the aggressiveness of the load spectrum

Individual parameters will be investigated both numerically and experimentally. An industrial fatigue demonstrator will be designed based on the obtained results.

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CONTACTS:

Ing. Karel Raz, Ph.D.
University of West Bohemia, Faculty of Mechanical Engineering
Regional Technological Institute
Univerzitni 22, Pilsen, 306 14, Czech Republic
+420377638751, kraz@rti.zcu.cz