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The Design of Fatigue Strength Machine Being One of the Methods for Determining the Mechanical Properties of the Materials Used in the Industry

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Abstract

Machine parts fail to perform their tasks due to the fatigue with the rate of 90%. The fatigue applications have been known since the early days of the industrial revolution. The field of study on metal fatigue has started to expand due to the increase in the use of steel constructions in the systems of railway bridges in particular. It is of critical importance for all of the engineering fields to produce designs against the fatigue. Moreover, it is quite difficult to determine the initial damages of the fatigue by way of observation and the initial damages of the fatigue cannot be mostly recognized until a structural component becomes unusable. Therefore, the determination of fatigue life of the structural members during the stage of design and development results in a considerable decrease in unexpected damage risk that may occur during the use. Thus, reliable methods which can accurately predict the fatigue life are required. However, it is very difficult to find one single method to determine the fatigue life because of the presence of different loads and different designs. Finding a generally accepted and unified method which can accommodate to the desired condition removes difficulties in determining the fatigue life for each of the designs separately and facilitates the design process against the fatigue. The fatigue strength is normally found by means of "Wöhler method". It is also called as the method of (S-N) curves. In this method, each of test parts which are completely same in terms of material, shape and the quality of surface are continually forced to the stress at different levels and the number of cycles with which the fracture occurs is determined.

In this study, a bending fatigue strength machine was designed in accordance with the method of Wöhler curve. A linear motor enabling a linear movement was used in the bending fatigue testing machine. The designed bending fatigue machine was different from the existing machines in terms of not occupying much area, noise being lower, non-requirement of the additional apparatus (strap, camshaft, etc.) as the movement is linear; determination of the force applied on the test sample directly in computer software and easiness of the measurement and obtaining data such as on which life number the test sample fractured.

1. INTRODUCTION

Several machine parts and structural elements operate under repeated stresses (loads) and vibrations during the use. Although the stress of materials operating under the repeated stresses is smaller than the static strength of the parts; a crack generally occurring on the surface at the end of a certain repetition number and the following rupture event are called as fatigue and the elapsed time is called as life [1-5].

The fatigue applications have been known since the early days of the industrial revolution. The formation of fatigue applications has been started to be searched on the construction of passageways, aircraft turbines, bridges and the vehicles operating under the vibration and repeated loads and when the use of vehicles made of steel in terms of technology around the world has increased. Approximately 90% of the mechanical damages observed in the parts in automotive and aircraft industries as well as the parts of machines such as compressors, pumps and turbines occur as a result of the fatigue. The metal fatigue has

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been started to be investigated in detail for the first time after a train accident causing the death of at least 80 people nearby Versailles, France in 1842.

The first records on the fatigue were kept by German Mining Manager Wilhelm August Julius Albert in 1829 on sudden breaking of chains of the hoists used in the mines under normal loadings. Wilhelm Albert designed a mechanism in which repeated loads are applied on the chains in order to understand this event better. In tests he performed, and observed that the fractures were associated with the amount of load and the number of repetitions [1-10].

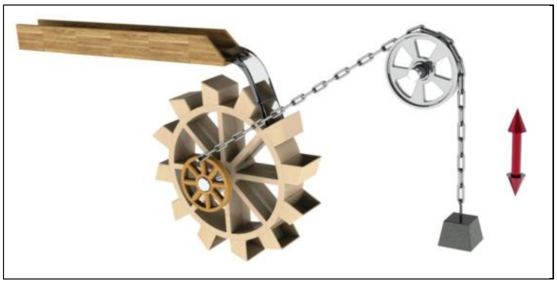

Figure 1. *First set-up to understand the concept "fatigue" [11]*

The fatigue was used as a term by Jean-Victor Poncelet, a French mathematician and engineer, who designed mills and turbines, in 1839. William John Macquor Rankine has been known specially for his studies on thermodynamics. Rankine also conducted studies on the stress concentration [11-14].

Joseph Glynn stated the importance of the cross-section variation regions and the beginning of the crack in fatigue failure in 1844. The railway vehicle inspectors utilized from these studies and reported in 1848 that rivet holes increased the probability of the fatigue fracture [15-18].

Eaton A. Hodgkinson, developing experimental formulas on the strength of metal structured bridges during his period, prepared a report on calculation of the amount of safe load of the metal structures under continuously changing loads in 1849 in order to submit to the Parliament of England [6-19].

Several studies were conducted on this issue as it caused lots of accidents in the past and these studies are still ongoing. The measurement of the fatigue strength of the materials is very important in terms of the life of the material. In particular, it is really hard to estimate when and where the material operating under a certain temperature will rupture. The heat differences are considerably observed in airframe during every single flight. This value is at 30-360^{0}C on the ground while it drops to -5^{0}C in the air. This shortens the life of material. The life of machine parts operating at such different temperatures is required to be tested.

William Fairbairn, a Scottish Engineer, who conducted studies on the optimum section of the metal structures with Hodgkinson during 1830s, and August Wöhler, a German Engineer, who started working for a company manufacturing the railway vehicles in 1940s, started systematically to deal with the fatigue tests in 1860s.

Wöhler developed a device, imitating the repeated loads exposed by shafts during operation in order to investigate unexpected fractures of the shafts and announced the results of his studies in 1867. In his study, he emphasized that the number of the repetition of stress was more effective than the maximum amount of stress and also, he was the first person to mention the fatigue life. S-N Diagram, axes of which are composed of the amount of stress (S) and the number of cycles where the fracture occurs (N), developed by Wöhler ensured that he was known as the father of the fatigue test [20-35].

The experimental data on the strength limit is very important to determine the fatigue properties of a material. The fatigue strength limit is a stress value under the stress where no real time fracture occurs. The number of cycles required to achieve the strength limit varies according to the materials. However, 1 million or 10 million cycles are used as the number of cycles which are considered to reach the strength limit. A general trend of the fatigue tests is that the dispersion of test results is wide. A great number of samples must be tested to obtain statistically reliable results. Finally, test time required to determine the fatigue properties of the machine is quite long. In order to shorten this long period; test time can be reduced by increasing the test frequency. However, the increase in test frequency can result in occurrence of some problems in the material used such as false simulation, hysteric heating and mechanic degradation. These problems are important in particular for polymer materials. The test conditions must be as close and similar as to the real conditions of use to the extent possible [21-44].

In this study, a bending fatigue machine was designed by considering that test conditions are as close as to the real conditions of the use. In current fatigue machines, linear movement is obtained from the rotational movement. In this design, linear movement was directly used. The approach of obtaining linear movement by means of electric motors generating the rotational movement has some problems since such approach necessitates additional tools and equipments. These disadvantages are as follows: bedding problems of engines, friction losses, requirement for maintenance, weight, and complexity. Hydraulic or pneumatic systems need complex auxiliary units so as to operate. Therefore, they both require more maintenance and result in frequent failures. On the other hand, the need for the machines which do not require auxiliary parts and equipments, have no wear problems, have lower energy loss, do not require additional systems except for the driver, therefore decrease of the failure probability and maintenance requirement, decreases the production and operating costs, can be operated in wide rate range, can be produced as a modular that is not big and heavy, at a length which is short or long, can directly generate the linear movement, increases.

2. EXPERIMENTAL STUDY

2.1. Linear Motor

Linear electric motors enabling the linear movement are electro-mechanic systems which directly convert the electrical energy to the linear movement. The linear motors used to obtain the required linear movement have the following advantages when compared to the other systems [45-46].

Linear motors can move throughout the magnetic field created. Therefore, they can be used to manufacture the transportation vehicles without any limitation for the length. Linear motors can operate with high accuracy thanks to the feedback and control system of the high quality. Linear motors can easily operate at 3 m/s with a precision of 1 micron or 5 m/s with a lower precision. The same precision cannot be achieved in hydraulic and pneumatic systems due to their properties of the compression and expansion of the fluids with heat. Linear motor can respond faster than the motors generating the rotational movements. Also, since windings of several linear motors cannot be simultaneously energised, the parts which are not operated are given chance to cool and therefore, the linear motors get warm less. In linear motors, the speed of motor decreases during the first start and loading and a soft start is achieved, the acceleration and braking distances become shorter when they are used in the transportation vehicles [45-47].

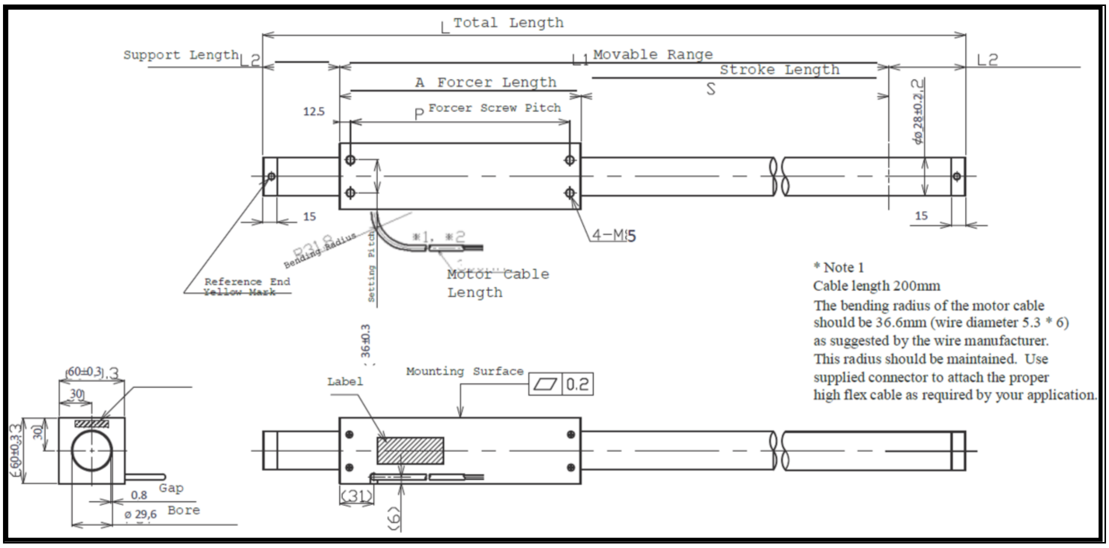

Figure 2. *Elements of linear motors.*

2.2. Bending fatigue test sample and implementation of the experiment

The bending fatigue machine to be manufactured perform dynamic fatigue tests on samples made of thermoplastics, non-ferrous metals, and steels. Figure 3 shows the sizes of the samples prepared.

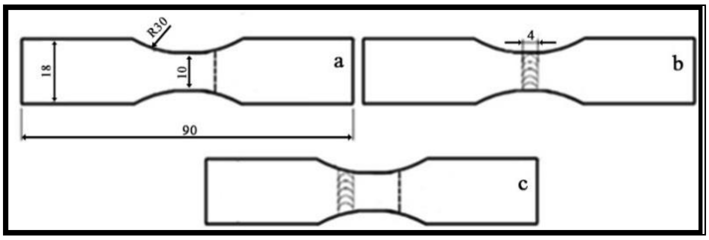

Figure 3. *Fatigue tests of samples obtained from a) non-welded sheets b)butt welded sheets c) overlap welded sheets [22, 27-32, 48-51].*

The values obtained as a result of the bending fatigue tests and Wöhler curves were drawn by being logarithmically marking the number of cycles corresponding to the highest tension. At least 6 samples were prepared for each of the test series. In every test, $N=2x10^6$ which is suggested in the literature was taken as the number of limit cycles (fatigue strength limit).

Out of the bending moment (Me) values used in the tests; rectangular parts are calculated as follows by using classical strength information on the bending stress (σ) values;

$$W = \frac{b.h^2}{6} \qquad 1.2$$

$$\sigma = \frac{M_e}{W}$$

$\sigma =$ Bending stress (kg/cm^2)
$W =$ Axial resistance moment (cm^3)
$M_e =$ Bending moment (kgcm)
$b =$ Width (cm)
$h =$ Thickness (cm)

In this study, the force was applied on the test sample with the linear movement obtained from the linear motor to determine the bending fatigue stress of the sheet materials used in the industry. The test sample moved forward and backward as long as the path set with the force applied from the linear motor. The number of life was recorded by the system as this forward/backward movement. A new sample and different force were applied until the sample ruptured or until the life value of $2x10^6$ was found. A value close to the yield strength of the material must be applied as the maximum value. The test was completed by applying 6 different forces to the 6 test samples.

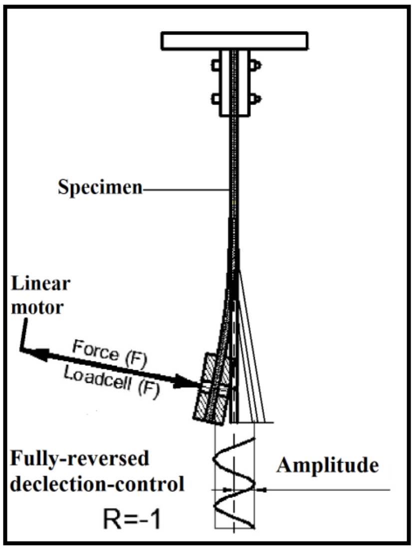

Figure 4. *Schematic view of the bending fatigue machine*

The length and movement stroke of the module with linear tubular motor used were 900 mm and 100 mm, respectively. There was air gap between the linear force and motor. The movement was obtained by magnetic field principle and with contact-free structure. There was a linear optical ruler with a precision of 5 microns and there was a linear motor driver with a power of 1.5 kW. The system was designed to transmit data to PC with Ethernet. The control of the system were provided as torque controlled and position controlled. The operation of the system was controlled by changing the speed, force and life values via a HMI screen. These operations were carried out with the help of PLC. Its speed was maximum 180 m/min, its acceleration was 5G and its resolution had a precision up to 0.001 mm. Both fixed displacement and constant force can be chosen and applied on the test sample. It operated silently, its maintenance costs were low and it had a high efficiency.

When test sample started cracking, the system gave warning and when test sample ruptured, the system automatically stopped.

Once the number of life applied exceeded $2x10^6$ (the number of fatigue strength life), again the machine automatically stopped and the test sample was manually removed [22-24, 27-33, 48-54].

In the fatigue tests; the samples of a material with same shape and properties were separately tested. The test was maintained until the material was ruptured or visibly damaged. While the number of cycle where damage occurred was recorded on the axis of abscissa, maximum, minimum or stress value was recorded on the axis of the ordinate. The tests were repeated on different values of the ordinate. In this way, a point on which S-N curve passed during each test was marked on graphic. The ambient temperature and the frequency of applying force must be added to the graphic since they are known to affect the results of the test. The axis of the cycle number is logarithmically shown in general.

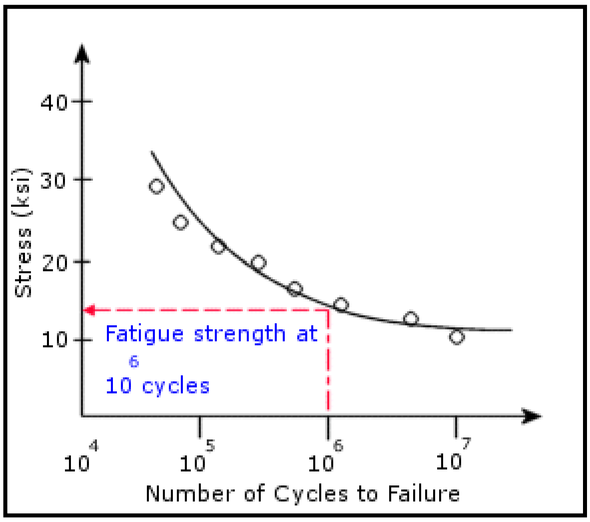

Figure 5. *Wöhler curve (S/N)*

To the extent permitted by the capacity of the machine, dynamic and static loads can be loaded as variables. Wöhler diagrams and (S-N) diagrams, a complete fatigue strength test, that comply with the German Standard DIN 50100 can be created in the machine (Figure 5). In time strength zone of Wöhler curve, the life is limited with the time. This stress value is called as the fatigue limit. It should be remembered that such expressions are applicable to the test samples from which Wöhler curves are obtained. In time strength zone of Wöhler curve, the life is limited with the time. If σ_D value shown in the figure is not exceeded from a certain point, it is asserted that material has practically infinite life. This stress value is called as the fatigue limit. It should be remembered that such expressions are applicable to the test samples from which Wöhler curves are obtained.

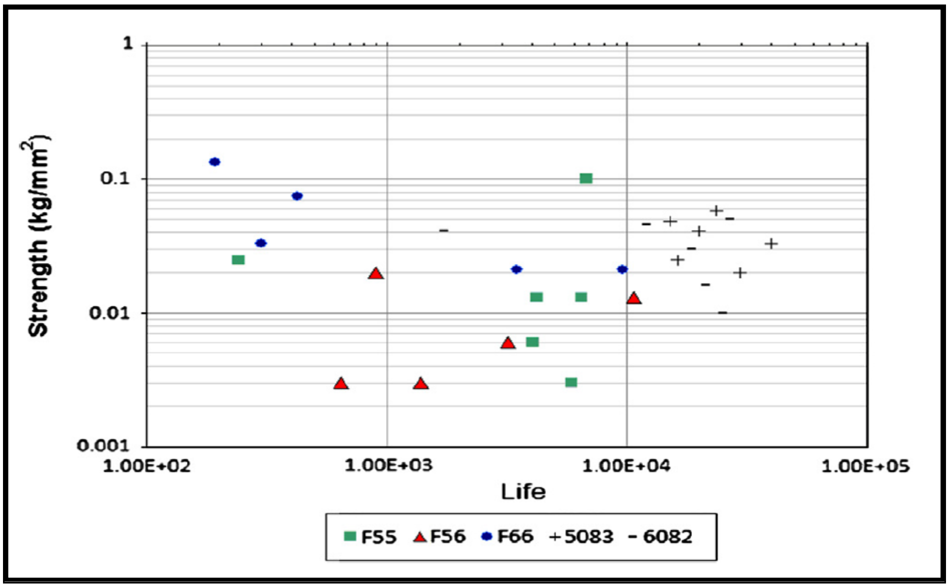

Figure 6. *Graphics of bending fatigue strength of the structural steel (St 52-3) samples joined with SG2 wire and the mixtures of 3 different gases [55]*

For a certain mean stress, Wöhler curves are drawn between the stress amplitude and the repetition number of the load. The fatigue strength of the material in which structural steel is used is given as example in Figure 6.

3. CONCLUSION

To the extent permitted by the capacity of the machine, dynamic and static loads can be loaded as variables. Wöhler diagrams and (S-N) diagrams, a fatigue strength test, that comply with the German Standard DIN 50100 can be created in the machine (Figure 5). Both fixed displacement and constant force can be applied to the test sample. The speeds can be changed and test can be continued when required. All of the required data can be obtained in the digital media. The movement is obtained by magnetic field principle and with contact-free structure. The amount of stress on the test sample of the moving force applied to the test sample during the movement or moving force can be determined. If the test sample is fractured or ruptured, the stop mechanism closing the circuit automatically can be activated and can stop the operation. It is a design with silent operation, low maintenance cost, and high efficiency.

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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