Designing Fatigue Strength by Actively Using CAE Tools

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Keywords Fatigue strength design, Fatigue database, CAE

Abstract

Fatigue strength design is essential for products which experience metal fatigue resulting from repeated loads during their life time. Such metal fatigue may lead to structure fracture of the products by propagating slight cracks every time a load is applied to the material. The method of fatigue strength design to apply, however, must be selected according to the magnitude of the load or environmental conditions. In addition, since the procedure is complex, it is time-consuming to estimate the impact of various factors that can reduce the fatigue strength. In order to improve and realize effective design procedure, we have introduced a Computer Aided Engineering (CAE) tool dedicated to fatigue strength design. By importing our R&D results into the CAE tool, we realized the effective design work.

1 Preface

Since 1983, we have adopted three-dimensional Computer Aided Engineering (CAE) tools. Presently, the use of analytical technologies has become very common across our company. In the field of structural analysis, we are using the CAE tool for the analysis of static strength to prevent the destruction or permanent deformation of structures under overloads. This tool is also used for the analysis of dynamic characteristics such as natural frequency analysis. Conventionally, an evaluation of static strength was possible only for materials with a simple shape. This is because computation of stress concentration was possible for only simple shapes. With the use of CAE tools, however, such analysis became possible even with complicated material shapes. As a result, stress estimation accuracy was raised and labor hours were shortened. In regard to fatigue of metals caused by repetitive loads, however, using CAE tools is not common. The reason for this lies in the factors that affect fatigue strength. For fatigue strength, there are a number of influencing factors and the computation takes a long time and labor-intensive. In addition, factors relating to shapes and sizes also involve material constants. Stress values obtained from the calculation using a structure analysis tool cannot, therefore, be used directly.

In order to improve such situations, we established an efficient fatigue design system by combining our expertise and an evaluation supporting tool for fatigue strength design. This paper introduces the contents of the method.

2 Fatigue Strength Design Method

2.1 Application Method and Object

According to the stress level to be applied to an object and operating environment, fatigue strength design requires the selection of, and in some cases a combination of, different methods described below.

(1) High-cycle fatigue analysis

This method is applicable to an analysis of a fatigue phenomena where fatigue strength is analyzed for a relatively small level of load stress and the stress is repeated frequently until it leads to a fracture. Fatigue life is evaluated based on the S-N curve that specifies the relationship between the intensity of load stress and the number of repetitions until fatigue destruction. In the case of Meiden products, some of examples of objects of this type of fatigue analysis are, a driving section of an Automated Guided Vehicle (AGV) where a load stress is applied during the start and stop periods, or a shaft of a rotating product where a torsional load stress is applied during operation due to changes in torque.

(2) Low-cycle fatigue analysis

This method is applicable to analysis of fatigue phenomena where fatigue strength is analyzed for a relatively large stress load and the stress is repeated infrequently until fatigue fracture occurs. Fatigue life is evaluated based on the ε-N curve that specifies the relationship between the intensity of strain and the number of repetitions until reaching fatigue destruction. In the case of Meiden products, some of examples of objects of this type of fatigue analysis are a rotor coil or a generator fan where a centrifugal load stress is applied during the start and stop period.

(3) Fatigue crack propagation analysis

This method is used to analyze the fatigue strength of a material with cracks. Fatigue life is evaluated based on the crack propagation curve that specifies the relationship between the crack propagation speed and the stress intensity factor that explains the field of stresses in the vicinity of crack tips. In the case of Meiden product, some examples of the objects of this type of fatigue analysis are the unwelded parts of a rotor in a rotating product that has a welded structure.

(4) High temperature strength (creep strength) analysis

This method is used to analyze the amount of distortion that develops with time under high-temperature conditions. In the case of Meiden products, some examples of objects with this fatigue analysis are the soldered parts of electronic components where they continue to deform over time due to generated heat in the components.

(5) Actual load analysis

When the intensity of an actual load is not constant and keeps changing, this method is used for the fatigue analysis in consideration of the effect of such condition changes.

2.2 Influences by Various Factors

Compared with the fatigue of metals caused by monotonous tensile loads, destruction of metals can be caused by relatively lower repetitive loads. The fatigue strength, which does not occur even with a repetitive load at a specific frequency, can greatly change with a variety of influencing factors. Fig. 1 shows influencing factors of fatigue strength. This example indicates the effect of various factors in regard to fatigue limit which no fatigue destruction occurs even though repetitive loads are applied permanently. In fatigue strength design, it takes a longer time to calculate the goal strength because it is necessary to estimate the effect of the aforementioned factors. Those influencing factors are shown below.

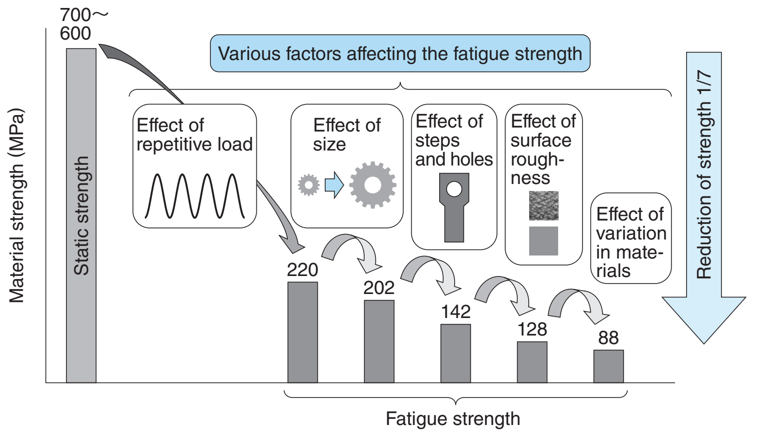

Fig. 1 Influencing Factors of Fatigue Strength

Fatigue strength is greatly changed by the effect of factors. Factors come in various types and it is time-consuming to calculate the impact.

(1) Size

The larger the size, the lower the strength.

(2) Steps and holes

The strength is lowered where stress concentration exists.

(3) Surface roughness

If the surface roughness of a material is prominent, strength of the material is lowered.

(4) Variation in materials

Fatigue strength may vary even it is made of the same material.

3 Improvement of Fatigue Strength Design Efficiency

3.1 Outline of Fatigue Strength Design Supporting Tools

For fatigue strength design, it is necessary to select different methods in a given case or use a combination thereof, and consider the effect of various influencing factors. For this reason, the computation is time-consuming and challenging. To improve this situation, we have introduced the METIS/Win ("METIS" hereafter), which is a CAE tool to support quantitative and unified fatigue strength design based on actual data of material strength. This tool was originally the UNIX-version METIS developed by multi-client project where about 20 firms, including us, joined and was sponsored by Mitsubishi Research Institute, Inc. ("MRI"). The MRI later changed it into the Windows version.

Fig. 2 shows the outline of fatigue strength design supporting tools and **Table 1** shows the requirements of the database and calculation programs. The METIS is provided with a database where fatigue test data are stored for the respective analytical methods and calculation programs for various factors that affect the fatigue strength. One of the METIS features is that actual fatigue test data (data of each test piece) are directly recorded. These data involve fatigue test data of The Society of Materials Science, Japan and former National Research Institute for Metals (present National Institute for Materials Science) and user's data can be registered. This data is useful because it is possible to evaluate data variation that cannot be identified with only diagrams which are derived from such data. In addition, it is also possible to confirm how far the test was conducted so that it can be used to prevent improper extrapolation of a line in the diagram. Furthermore, given the effect of mean stress, in case there are any data that match the condition, strength evaluation can be carried out by using the actual data without using the influencing factor calculation program.

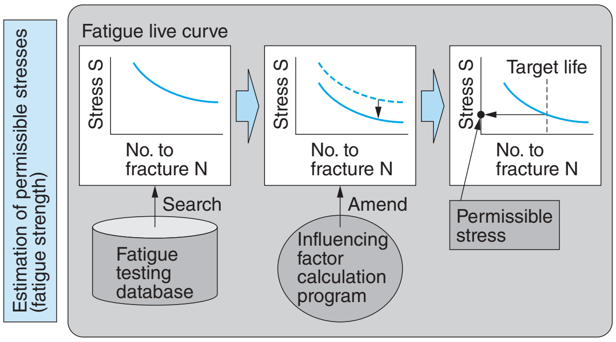

Fig. 2 Outline of Fatigue Strength Design Supporting Tools

In order to improve fatigue strength design efficiencies, we introduced a tool consisting of a fatigue testing database and influencing factor calculation programs.

Table 1 Requirements of Database and Computation Programs

In addition to this database, our internal empirical data are also registered. (For example, high-temperature data relating to solder)

Function	Database	Calculation program
High-cycle fatigue analysis	Steel 264, copper materials 11, aluminum materials 66, and 8 materials of other kind (4178 items)	Establishment and presumption of S-N curves, calculation of FSRF, calculation of equivalent stress
Low-cycle fatigue analysis	Steel 49, copper material 1, aluminum materials 8, and 6 materials of other kind (420 items)	Establishment and presumption of ε-N curves, presumption of stress-strain curves, calculation of FSRF, calculation of equivalent stress, calculation of fictitious stress amplitude, calculation of safety factor
Fatigue crack propagation analysis	Steel 94, copper materials 3, aluminum materials 11, and 1 material of other kind (729 items)	Establishment and presumption of fatigue crack propagation resistance curves, calculation of stress intensity factor, calculation of crack propagation life
High-temperature strength	Steel 52, aluminum materials 3 (1817 items)	Establishment of stress-creep rupture time curves, establishment of LMP diagrams, calculation of safety factor
Actual load	—	Cycle count calculation, establishment of pseudo-random waves

3.2 Improvement of Efficiency in Fatigue Stress Reduction Calculation

For a Fatigue Stress Reduction Factor (FSRF) that is one high influencing factor among other influencing factors, a description about the improvement of efficiency is given below. The FSRF denotes a degree of fatigue strength reduction attributable to stress concentration caused by steps, holes, and such shapes. The FSRF is, however, not always in proportion to the Stress Concentration Factor (SCF) that shows a degree of stress concentration. For this reason, it is impossible to evaluate the fatigue strength simply by using a stress, even if it reflects the stress concentration by using a structure analysis tool. In order to define the FSRF, we have to use an empirical formula proposed by The Japan Society of Mechanical Engineers and calculate various factors as shown on the left side of **Fig. 3**. In the case of METIS, the shape of a spot where stresses are concentrated is chosen from the shape

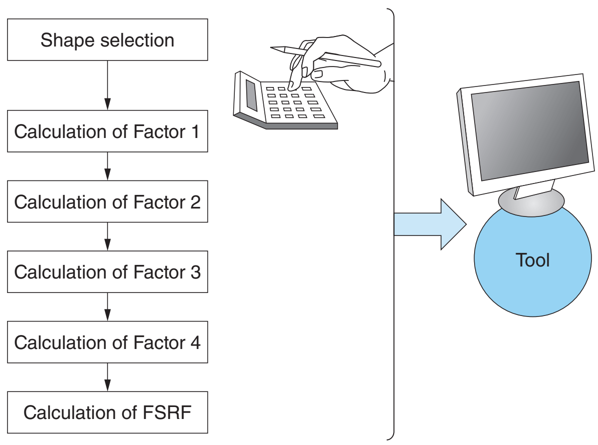

Fig. 3 Calculation of FSRF

Formerly, it took a long time to calculate the FSRF. It was made simple by using a unified method.

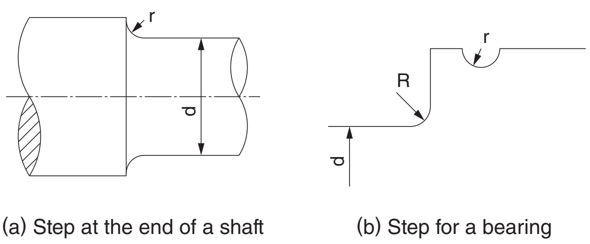

Fig. 4 Example of a Stepped Section

For a rotating shaft where a stepped section exists, we realized improvement of efficiencies for fatigue strength calculation and defined the application standard. Character d in the diagram denotes the shaft diameter and Character r or R shows the fillet radius in the stepped section.

library registered in advance and size and material constant are specified. It is then possible to easily calculate the FSRF.

4 Case Study of Efficiency Improvements

4.1 Case Study of Fatigue Strength Calculation

Fig. 4 shows an example of a stepped section. For a rotating shaft where a stepped section exists, we used the METIS to calculate the effect of factors like FSRF and performed strength calculation based on the method for high-cycle fatigue analysis. In addition, we drafted application standards in order to define the selection standard for empirical formulae and the standard values of safety factors.

4.2 Registration of Fatigue Strength Research Results

We conducted a variety of research programs relating to fatigue strength and acquired useful knowledge to improve the accuracy for fatigue strength design for Meiden products[(1)-(5)]. The results of our research programs were registered in the METIS so that our expertise can be utilized with the same procedures for other data.

5 Postscript

We recently introduced the CAE tool to realize a more efficient fatigue strength design. To realize the improved efficiencies, the introduction of tools is not enough. It is critical to establish the application standard, investigate the influencing factors and material characteristics exclusively for our products, and replicate the acquired expertise on tools. We will continue to promote R&D programs for fatigue strength design so that we can achieve further improvement of efficiencies and realize adequate safety factors. In so doing, we would like to contribute to the promotion of an environment-friendly design.

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