Focussed on Multiaxial Fatigue and Fracture

Structure service life assessment under combined loading using probability approach

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ABSTRACT. This article presents a basic research approach for probabilistic assessment of vehicle structure fatigue endurance under multiaxial loading. One representative welded structural detail of the bottom joint plate of an articulated bus was selected for the case study. The character of the loading on the joint during a service test is analyzed and discussed. The methodology for estimation of the damage level in the joint builds on deterministic procedures for railway vehicle assessment based on shear, longitudinal and transverse stress components. This approach based on the equivalent stress and particular load capacity factors was expanded to include the probabilistic perspective.

KEYWORDS. Service life; Combined loading; Damage; Vehicle; Probabilistic approach.

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INTRODUCTION

In-service loads acting on components and structural details in vehicles tend to be complex and, in most cases, multi-axial and time-variable. The stress response to such loads can (but need not) be multi-axial. Critical locations in vehicle structures are subjected to fatigue loading which can lead to initiation of fatigue cracks, fatigue crack propagation and, sometimes, to final failure. Even today, sizing and assessment of such critical locations often involves the deterministic approach. This means that both loading and strength are represented by their mean values for which adequate safety factors are sought.

In the following, a description is given of fatigue lifetime assessment of a welded joint operating under relatively complex loading in an articulated bus. The engineering approach which is normally used in technical practice has been expanded into a reliability analysis which gives a more accurate description of the risk of fatigue failure in the critical location of the structural detail.

SERVICE LIFE ASSESSMENT USING PROBABILITY APPROACH

Materials subjected to time-varying loads suffer damage caused by the fatigue process. Their load response can be described in terms of time-varying strain and stress, and the cumulative fatigue damage can be found using an appropriately chosen rule. In order to evaluate the service fatigue life of a structure, one needs not only information about its service loading but also some data on the structure's fatigue strength. The resistance of a structure to high-cycle fatigue damage is described by the *S-N* curve. The *S-N* curve can be constructed using fatigue data from a sufficient number of test pieces representing the structural detail under examination. However, it can also be determined by estimate or obtained from one of the standards for design of structures.

Fatigue life assessment is often based on the deterministic approach which relies on mean values of load-bearing capacity and load, and a set of factors of safety. If, however, the values of the safety factors are not chosen correctly, the load and the fatigue resistance of the material may prove to be mismatched under real-world service conditions, which may lead to fatigue damage or even failure of the part.

Probabilistic approach, on the other hand, uses distributions of random input variables for finding the fatigue life distribution function, i.e. the probability that the material enters its limit state with respect to strength after a certain period in service.

Fatigue life estimates are based on cumulative fatigue damage rules. Conformity to the life requirement may be formulated as the part's reliability. This means that over the required life t_{req} the probability of fatigue failure does not exceed the allowable value P_{allow}.

Statistical characteristics of input variables are obtained from measurement and tests (service loading measurement, fatigue testing), determined from experience, or derived from standards and codes. Important to the life estimates are the relationships between input variables, e.g. in the form of cumulative fatigue damage rules, and the mean stress of loading cycles. Comparison can be done using several different rules. This, however, enlarges the variance of the lifetime estimate.

Structures are normally designed to the guaranteed design life t_g and failure probability P_g. These values are guaranteed with certain margins Δt_g and ΔP_g, and therefore $t_g > t_{req}$, $P_g < P_{allow}$ (Fig. 1).

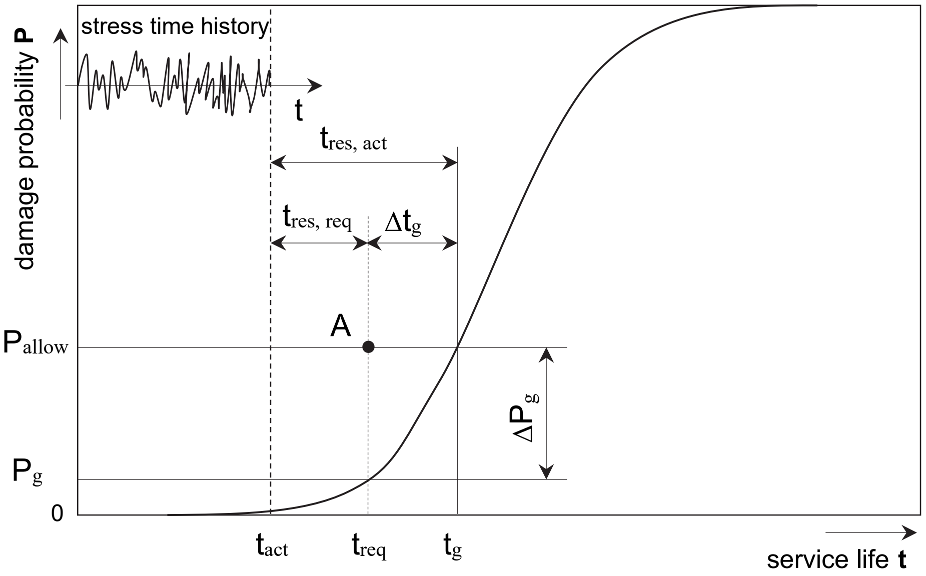

Figure 1: Schematic illustration of the probabilistic approach to life estimation – position of the point of design life of the structural detail with respect to the FLDF

While material properties of parts of equipment are given before it is put into operation, the actual service loads can only be estimated for an already-known steady-state process. Changes to the loading conditions or out-of-standard load states affect the form and position of the fatigue life distribution function (FLDF). They may shorten the life margin Δt_g and even lead to a loss of reliability at $\Delta t_g < 0$. Such occurrences must be prevented by identifying and signaling the onset of hazardous states. The way to achieve that is to continuously monitor the service loads on critical locations of the structure and track (calculate) the fatigue damage in them.

To find the fatigue life distribution function, one needs the following input information.

a) Service loads on the critical location. Continuous stress-time histories can be obtained from appropriate monitoring devices, for instance. Typical input into fatigue damage calculation is represented by a two-parameter histogram of cycle frequencies, reflecting cycle amplitudes and mean stress levels. Most often, this histogram (also referred to as "load spectrum", "stress spectrum", and otherwise) is obtained by the rain flow method but other techniques can be used as well. Signals obtained from the monitoring sometimes show trends (changes in variance with time, shifting mean value, and others) which can be accounted for in the fatigue damage predictions.

b) Material properties. The input into the calculation is an experimentally measured and statistically evaluated S-N curve, or more precisely, an implicit representation of its left-sided tolerance limits for various failure probabilities.

The probabilistic evaluation of service fatigue life of a structural detail of a road vehicle which was carried out in the present case study was based on the segmentation of random loading processes proposed by Kliman [5, 6].

Random loading process

The loading process of interest is analysed by appropriately segmenting a sufficiently long in-service measurement record from a critical location of the relevant part of a vehicle. A load record of certain length represents a random portion of a vehicle's service. Obviously, another measurement carried out at another time will be different due to the random nature of the load. If a loading process record of adequate length $\sigma(t)$ is segmented appropriately, it can be substituted for repeated measurement runs. In-service loads will thus be represented by a set of records – process segments $\sigma(t)$.

In order to calculate a faithful FLDF, one has to find the minimum acceptable length of the process segment. In practice, this means finding such length, at which the standard deviation and mean value of the calculated FLDF become stable (i.e. they do not change substantially with further increases of the segment length). The segment length is understood as a certain portion of the service run represented by time, mileage or otherwise.

The procedure is as follows. The stress-time history is analyzed using the rain flow method applied to a series of segments of a constant length where the overlap between these consecutive segments ("windows") is 95 %. For each "window", the fatigue life is calculated. Mean value and standard deviation are calculated for each set of lifetimes obtained with a certain segment length. The procedure starts with the shortest segment length and continues by increasing the length. An example of such procedure is illustrated in Fig. 2 which also shows the chosen optimal segment length.

The set of lifetimes obtained for the optimal segment length determined by the above procedure will be input into the FLDF calculation. Lifetime is calculated using an appropriate cumulative fatigue damage rule and the theory of accounting for the effect of the mean component of cycles.

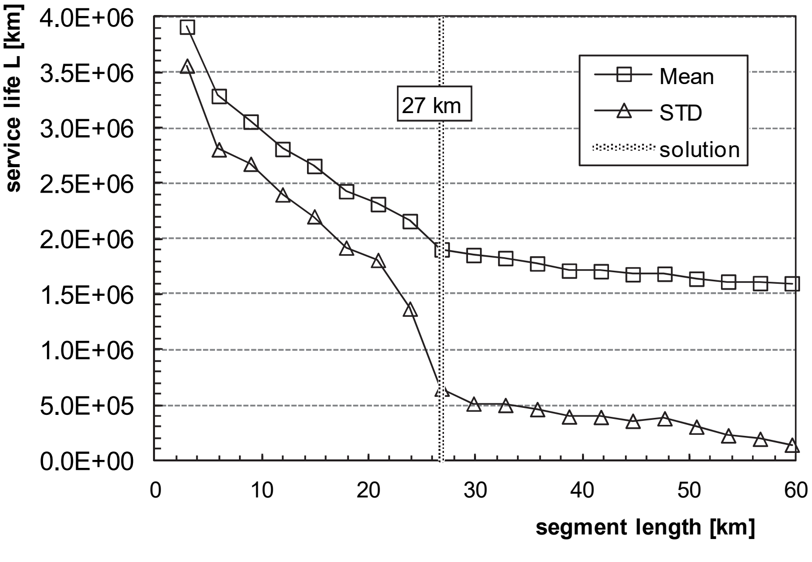

Figure 2: Example of determination of minimum segment length

Random nature of materials properties

Low-cycle or high-cycle fatigue properties of materials are described by the cyclic stress-strain curve, the lifetime curve or the *S-N* curve. These (or their coefficients) can be determined on the basis of fatigue tests. However, one can also estimate their values using various empirical formulas or find them in certain standards and codes.

Statistical evaluation of fatigue tests can provide confidence intervals and tolerance limits for the chosen probability of a particular curve and the corresponding coefficients. Such limits are often difficult to define analytically by means of simple equations. They can be somewhat simplified by using linear relationships. This is common practice with fatigue curves for typical structural details listed in various categories in standards. There, the left-sided limits of tolerance are simply expressed in the form of the residual standard deviation and the *d* quantile for the probability in question.

Kliman's methods requires that the parameters of the left-sided limits of tolerance of the lifetime curve are calculated for the probabilities $P = 1$ through 99 % in steps of 1 % (Fig. 3).

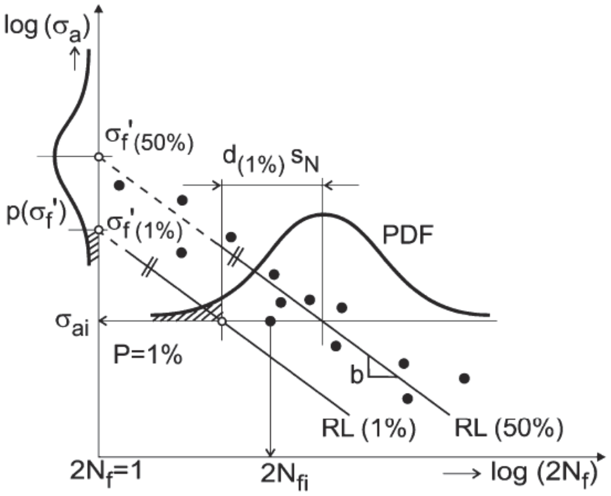

Figure 3: Schematic illustration of the method of finding materials parameters – standardized fatigue curves.

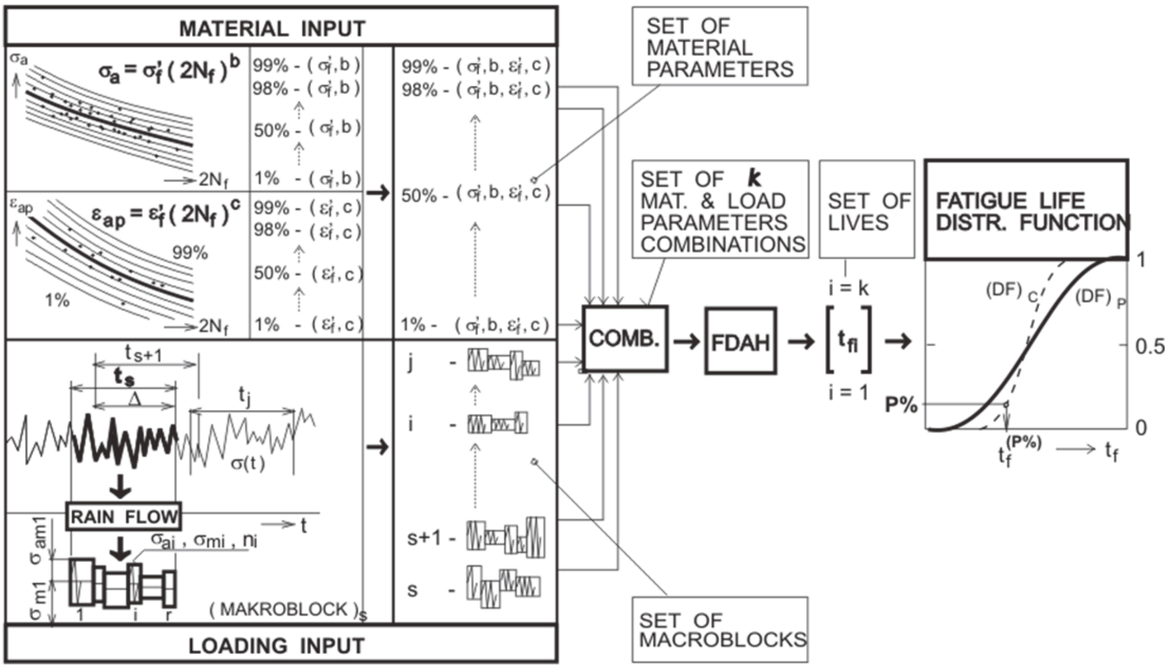

Figure 4: Schematic procedure for calculating the FLDF.

Determination of resulting fatigue life distribution function

The resulting fatigue life distribution function (FLDF) is to account for the random nature of loading, as well as the random nature of material properties. The input to the process of its determination consists of the quantity s of constant-length segments of the loading process, and 99 lifetime curves for individual failure probability levels. Hence, a total of $k = s\times 99$ combinations of loads and material properties are available.

The resulting FLDF is obtained by finding a set of distribution curves through process segmentation, using the lifetime curve for $P = 1$ %, then 2 %, and so forth until 99 % is reached. Finally, 99 distribution curves are obtained from which the resulting FLDF is generated for individual corresponding probability levels.

DEMONSTRATION EXAMPLE

The chosen demonstration example concerns a welded joint in an articulated bus which is located at the base of the fixed bracket of the articulated joint on the rear section (Fig. 5). In fact, some vehicles exhibited fatigue damage in this location. The purpose of the measurement was to assess the stresses in this structural detail, redesign it and validate this modification through another measurement run.

For this case study, stress analysis has been carried out for the location of the R1 strain gauge rosette which is a place where two welded joints meet. Engineering strain time histories from this rosette were used for evaluating the components of principal, longitudinal, vertical and shear stresses.

Road tests involved running a demanding route of approximately 13 kilometers in urban and suburban traffic: four times with the vehicle empty and four times with the vehicle loaded, although without real passengers. On this route, the frequency of failures occurring in buses was the highest. Along this route, the road is uneven with large differences in height which causes vertical excitation in the vehicle. In addition, there are many curves and upward and downward slopes which were expected to contribute to twisting loads on the joint.

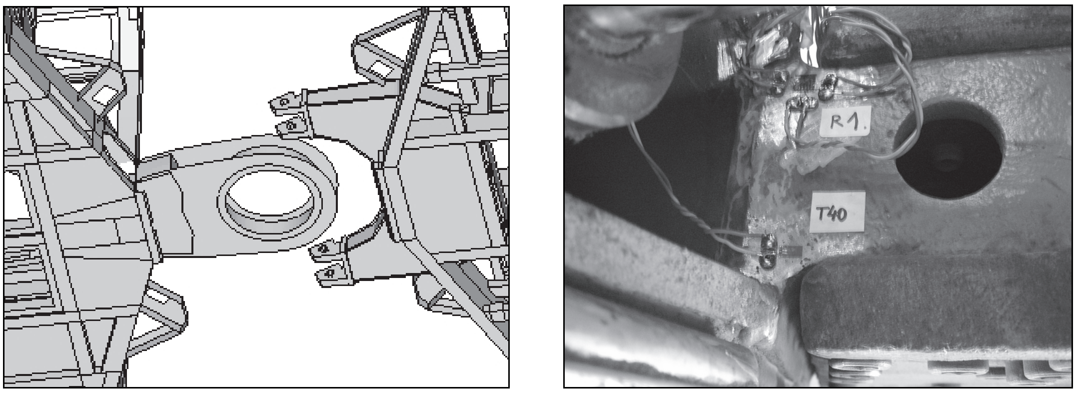

Figure 5: The joint of the rear section of an articulated bus – a schematic drawing and the strain gauge rosette R1.

Time histories analysis

Generally, the approach for multiaxial fatigue problems depends on the type of loading involved. The solution is less complicated for structural details under proportional loading. This is the type of loading in which the ratio of principal stresses (biaxiality ratio) $a = \sigma_2 / \sigma_1$ and the directions of the principal stresses remain constant. Non-proportional loading involves principal stresses whose directions rotate or undergo stepwise changes. The critical location of interest – the strain gauge rosette R1 – was studied using the nCode software. The figures below show results of the analysis for one of the stress-time histories obtained from the road test of the empty vehicle in real traffic.

Fig. 6 shows the dependence of the absolute maximum principal stress on its angle to the x direction. The graph indicates that the directions of principal stresses remain constant at all stress levels, except the very low ones. This is the necessary condition for considering proportional loading conditions.

The other graph in Fig. 6 from the same measurement run shows the dependence of the absolute maximum principal stress on the biaxiality ratio. At higher stresses, the biaxiality ratio fluctuates about 0.25 and approaches the Poisson's ratio, which is an indication of near-plane strain loading.

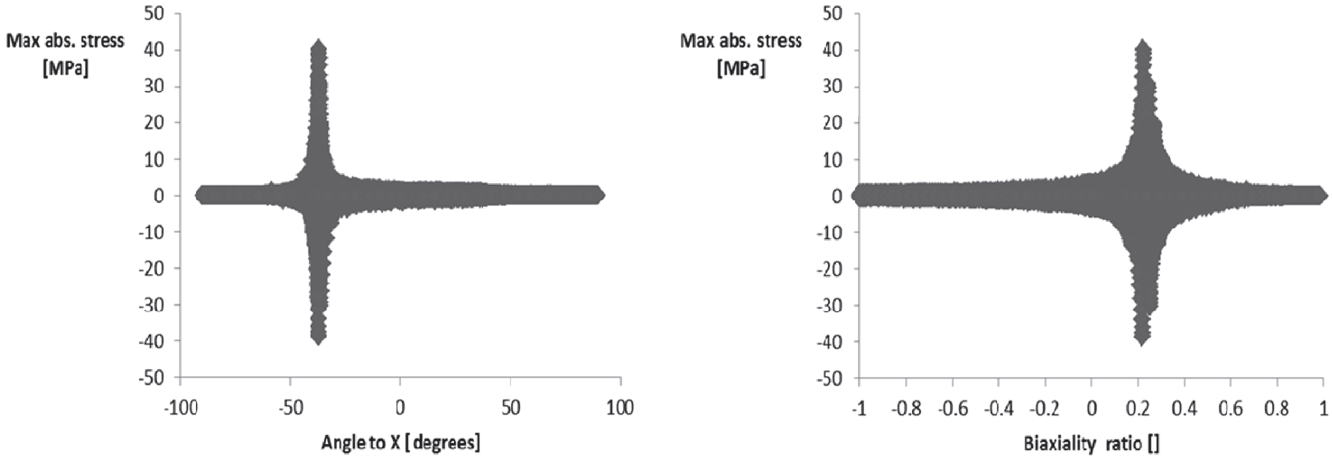

Figure 6: Absolute maximum principal stress against the angle to the *x* direction, absolute maximum principal stress vs. biaxiality ratio.

USED METHODOLOGY

The assessment of the endurance of the welded detail in question relied on a methodology which is used for rail vehicle testing in Germany. Allowable stresses were determined on the basis of nominal values and estimated notch factors according to IIW [1] and FKM [2] standards. Using the measured stress-time series in the location of the strain gauge rosette, stress components perpendicular to the weld $\sigma_{\perp}$, parallel to the weld σ_{II}, and shear stress components τ_{xy} were calculated. A similar approach is used for demonstrating the fatigue life of railway vehicles on test rigs [3, 4]. Decomposition of these series by means of the rainflow technique yields a matrix of stress amplitude rates and mean values of the cycle. The resulting matrices are combined into a single macro block on the basis of representative samples of service runs. In our case, the matrices were combined from four half-hour runs of an empty vehicle and four runs of a vehicle fully-loaded with a 1:1 passenger-equivalent load. The resulting matrix is converted to a single-parameter histogram of amplitude rates, accounting for the sensitivity to the mean value by using the coefficient M = 0.15 for normal stresses and $M = 0.09$ for shear stresses, as expressed in Eq. (1)

$$\sigma_{a,ef,i} = \sigma_{a,i} + M \cdot \sigma_m \tag{1}$$

Using notch factors, the measured stress values are transformed to notch stress values. Notch factors can be found in various sources. Here, they follow the principle used in the FEMFAT software for the notch radius of $r = 1$ mm.

The slope of the S-N curve for weldments is set as $m = 3$ for normal stresses and $m = 5$ for shear stresses. The characteristic stress amplitude for $N = 2{\cdot}106$ and for the base material S355, which is the material of the structural detail in question, and for normal stresses and a completely reversed cycle is $\sigma_{a,R=-1} = 150$ MPa, whereas for shear stresses and a completely reversed cycle it is $\tau_{a,R=-1} = 87$ MPa ($\sqrt{3}\cdot\sigma_{a,R=-1}$). These values are derived with respect to the IIW standard which has been developed for the stress ratio of $R = 0.5$. The S-N curve has no inflection point. It has been extended all the way to half the amplitude achieved upon $N = 5$ million cycles. This approach is more conservative than that used by the FKM standard. The allowable fatigue damage is $D = 1$.

The above approach relies on the calculation of load capacity factors a. Fig. 7 explains the calculation. An aggregate macro block is determined from individual load matrices. This macro block is converted to equivalent stress amplitude which would cause the same amount of damage as the entire macro block. The ratio of this equivalent stress amplitude $\sigma_{a,ef}$ and the allowable stress amplitude $\sigma_{a,BK}$ for the given number of cycles N_d is the load capacity factor *a*.

For each stress amplitude component $\sigma_{a,\perp}$, $\sigma_{a,II}$, τ_{xy}, the local load capacity factor a is calculated using Eqs. (2) through (4). Finally, a complex load capacity factor involving all three components (5) is determined in order to account for the multiaxial state of stress in a manner similar to yield criteria. If this factor is less than 1, sufficient fatigue strength of the detail in question has been demonstrated.

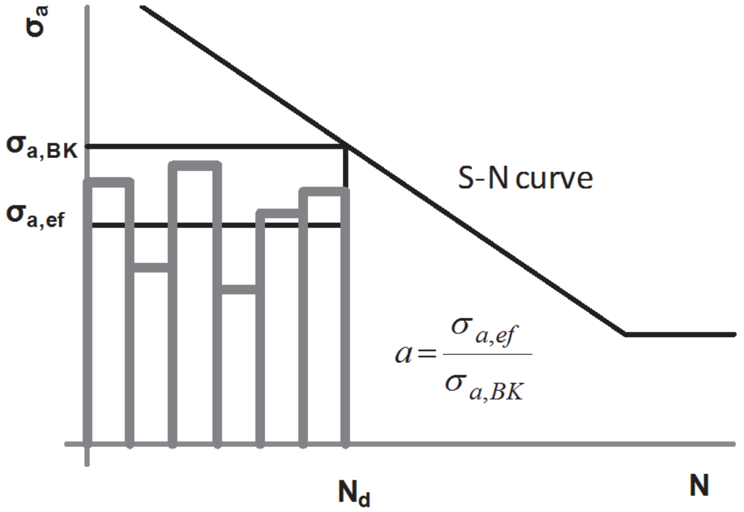

Figure 7: The relations between the effective stress amplitude $\sigma_{a,ef}$, the limit stress amplitude $\sigma_{a,BK}$ and the load capacity factor a with respect to the *S-N* curve and the total number of cycles N_d.

$$a_{BK,\sigma\perp} = \left[\sum_{i=1}^{j} \frac{n_i}{N_d} \cdot \left(\frac{\sigma_{a\perp,i}}{\sigma_{D,R=-1}}\right)^{k}\right]^{\frac{1}{k}} \tag{2}$$

$$a_{BK,\sigma=} = \left[\sum_{i=1}^{j} \frac{n_i}{N_d} \cdot \left(\frac{\sigma_{a=,i}}{\sigma_{D,R=-1}}\right)^{k}\right]^{\frac{1}{k}} \tag{3}$$

$$a_{BK,\tau=} = \left[\sum_{i=1}^{j} \frac{n_i}{N_d} \cdot \left(\frac{\tau_{a=,i}}{\tau_{D,R=-1}}\right)^{k}\right]^{\frac{1}{k}} \tag{4}$$

$$a_{tot} = \sqrt{a_{BK,\sigma=}^{2} + a_{BK,\sigma\perp}^{2} \pm a_{BK,\sigma=} \cdot a_{BK,\sigma\perp} + a_{BK,\tau=}^{2}} \tag{5}$$

PROBABILITY APPROACH FOR EVALUATION OF COMBINED LOADING

The methodology outlined above represents the deterministic approach. In a probability-oriented assessment, the random nature of the loading, as well as the random nature of materials properties must be taken into account. A load record of certain length represents a random portion of a vehicle's service. Obviously, another measurement carried out at another time will be different due to the random nature of the load. If a process record of adequate length $\sigma(t)$ is segmented appropriately, it can be substituted for repeated measurement runs. In-service loads will thus be represented by a set of records – process segments [5]. By this method, the segment length for a representative lifetime assessment and the variance of load spectra used in the lifetime calculation can be determined. In Fig. 8, this procedure is applied to the complex load capacity factor based on (5) which is calculated within a moving window of *L* size. In the figure, mean values and standard deviations for the set of values a_{tot} obtained are plotted for the expanding interval *L*. The segment length, at which the value of a_{tot} ceases to change significantly, is used for calculating the load capacity factor distribution function. In the present case, a distance of 21 km has been used.

The random nature of materials properties is reflected in the tolerance limits of the *S-N* curve. The variability of the number of cycles to failure *N* is expressed through the standard deviation s(log *N*) for the quantile *d*, depending on failure probability. For this purpose, a median *S-N* curve must be obtained first – by shifting the curve defined in the standards for 97.5 % failure probability. The *S-N* curve equation is as follows

$$\log N_i = \log C_1 - m \cdot \log \sigma_{a,i} + d \cdot s(\log N) \tag{6}$$

The actual probabilistic assessment of fatigue strength is carried out using an MS Excel sheet. First, the distributions of individual components of the load capacity factor for corresponding tolerance limits of *S-N* curves are found. Then, the distribution of the combined load capacity factor is calculated. The real distributions are approximated by lognormal distributions

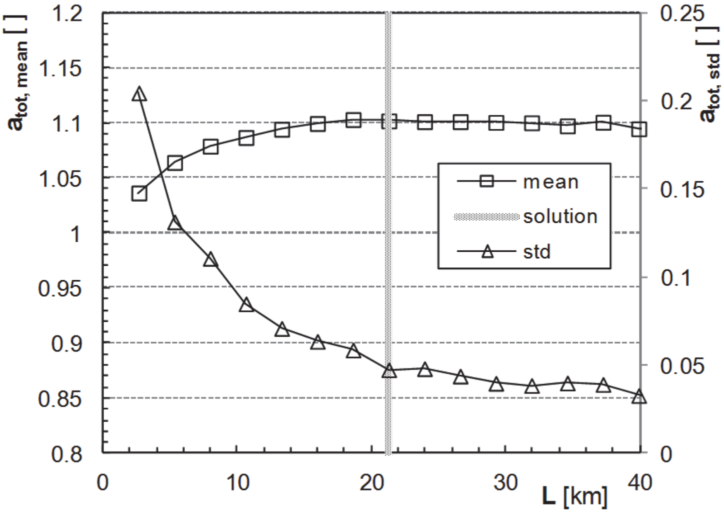

Figure 8: Determination of the moving window for the probabilistic characterization of the vehicle run.

OBTAINED RESULTS DISCUSSION

The above procedure was applied to the measured location of the articulated joint (Fig. 5). Distributions of individual components of the load capacity factor were determined. Fig. 9 shows example plots of their distribution functions using the median *S-N* curve. In this case, the random nature has been accounted for on the part of the load only.

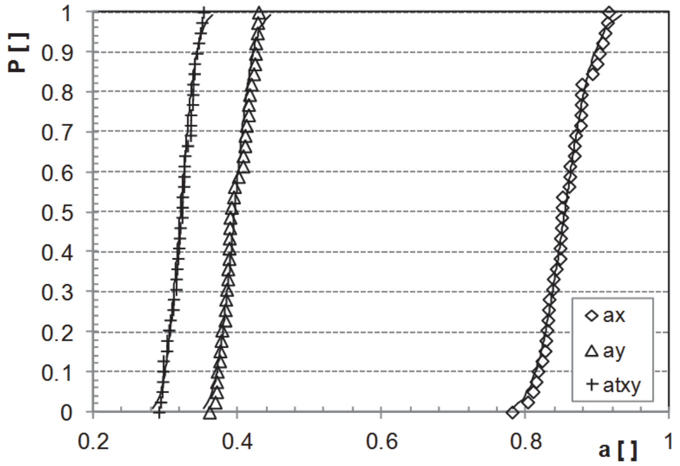

Figure 9: Probability distribution of particular loading factor components a_x, a_y and $a_{\tau xy}$.

The largest damage is caused by the longitudinal component of the load (bending load acting on the articulated joint). Fig. 10 shows plots of the distribution function of the complex load capacity factor for three design lifetimes of the bus. These distributions indicate the following outcomes. The probability that a_{tot} at the design lifetime of L = 1 mil. km will be less than 1 is lower than 30 %. There is a high probability of P = 97.5 % that the value a_{tot} will be less than 1 only at the lifetime of L = 250 000 km.

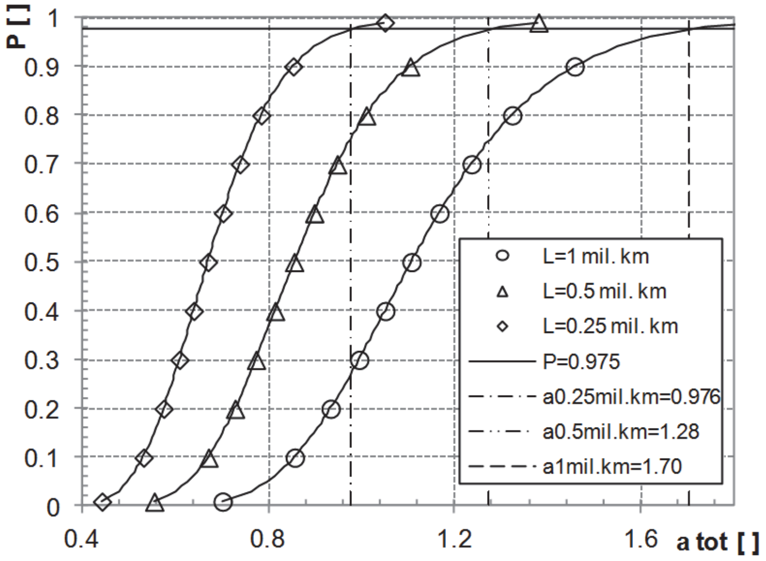

Figure 10: Distribution functions of the complex loading factor for three values of design service life.

CONCLUSION

The objective of this paper was to use an articulated joint of a bus for demonstrating the engineering approach for fatigue life assessment of welded parts operating under multiaxial loads, and expand this approach by incorporating the probabilistic perspective. The assessment of the resistance to fatigue damage is based on distribution functions of the complex load capacity factor which has been calculated from three load components acting on the welded joint by using a formula analogous to yield criteria calculations. This paper illustrates the following benefits of this approach.

If this structural detail was examined using no other than the deterministic approach, taking into account only the normal stress component which is perpendicular to the welded joint, and the median *S-N* curve, the detail would be found to meet the design lifetime requirement (Fig. 9, component a_x).

Even though the stress component perpendicular to the welded joint dominates in this case, the combined assessment of the weld shows that the probability of meeting the design lifetime is no more than 30 %.

The variance of in-service loading conditions has a milder effect on the life than the variance of material properties, provided that the lifetime estimates are based on a sufficiently long record of the loading process (21 km in our case). At half running distance, the variance doubles, which would broaden the distribution functions plotted in Fig. 10.

In the redesigned structural detail, the stresses in the welded joint were found to be substantially lower, as confirmed by repeated measurement.

ACKNOWGLEMENTS

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