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SPECTRUM LOADING EFFECTS ON STRUCTURAL DURABILITY OF COMPONENTS

UTICAJI SPEKTRA OPTEREĆENJA NA TRAJNOST KOMPONENATA U KONSTRUKCIJAMA

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Keywords
- load spectrum shape
- blocked and random sequence
- cumulative damage
- residual stresses
- corrosion

Abstract

Spectrum loading, i.e. load-time histories with variable amplitudes, occurs in almost all engineering structures during their service life. The behaviour of such structures and components cannot be assessed properly on the basis of constant amplitude data. Their safe design, in the context of weight reduction requirements, demands detailed and deep knowledge about the effects of spectrum shape, blocked or random sequences, material response, cumulative damage, residual stresses, environment and corrosion on lifetime in interaction with variable load amplitudes. Especially, the reliability of assumptions must be assured when test time reduction procedures are applied. Also, the substitution of variable amplitude loading by constant amplitudes is not generally possible because of the aforementioned influencing parameters and changed damage mechanisms. The proper consideration of effects of spectrum loading on structural durability requires a hybrid design procedure consisting of experiences in laboratory testing, knowledge of service behaviour, both implemented in numerical assessment procedures.

Ključne reči
- oblik spektra opterećenja
- blok- i slučajna sekvenca
- kumulativno oštećenje
- zaostali naponi
- korozija

Izvod

Spektar opterećenja, na primer, istorije opterećenje-vreme sa promenljivim amplitudama, dešavaju se u skoro svim inženjerskim konstrukcijama tokom njihovog radnog veka. Ponašanje takvih konstrukcija i komponenata ne može se pravilno oceniti na osnovu podataka konstantne amplitude. Njihovo sigurno projektovanje, s obzirom na zahteve smanjenja težine, specifičnih zahteva i širokog poznavanja o efektima oblika spektra opterećenja, kumulativnog oštećenja, zaostalih napona, uticaja okoline i korozije na vek u interakciji sa promenljivim amplitudama opterećenja. Posebno se pouzdanost pretpostavki mora obezbediti kada se primenjuju procedure za ispitivanje smanjenja veka. Takođe, zamena opterećenja promenljive amplitude sa konstantnim amplitudama nije moguće u opštem slučaju zbog već spomenutih uticajnih parametara i izmenjenih mehanizama oštećenja. Pravilno razmatranje uticaja spektra opterećenja na trajnost konstrukcije zahteva postupak hibridnog projektovanja koji se sastoji od iskustava u laboratorijskim ispitivanjima i poznavanja ponašanja u radu, gde oba moraju biti implementirana u postupke za numeričko procenjivanje.

INTRODUCTION

Spectrum loading of components occurs in almost all technical sectors, Fig. 1. Therefore, the structural durability assessment of components requires the proper consideration of the influence of variable amplitudes on lifetime, numerically as well as experimentally. But as variable amplitude testing is still regarded as an area which devours immense financial and personal resources and thus is often substituted by constant amplitude testing, which requires less effort. However, this simplification may cause often misinterpretations with regard to failure location, damage mechanisms, fatigue life assessments and consequently design and component dimensions if constant amplitude tests are carried out without expertise.

Therefore, in the following sources of misinterpretations by constant amplitude tests and the justification for performing tests under variable amplitudes will be displayed by discussing different influencing parameters as spectrum shape, mean-stress fluctuations, cumulative damage, spectrum type, material behaviour, corrosion, residual stresses and examples from different industrial sectors.

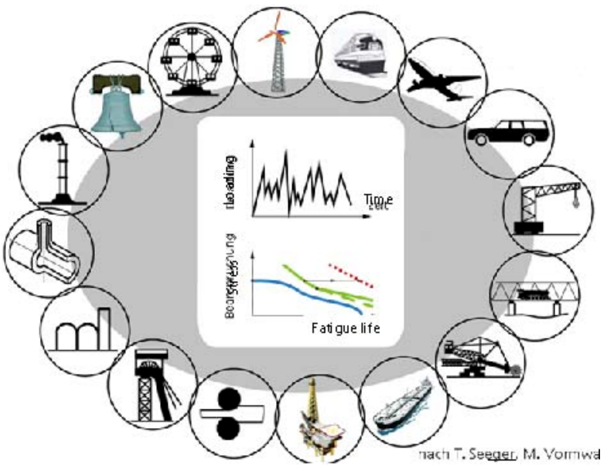

Figure 1. Technical sectors requiring structural durability proof.
Slika 1. Inženjerski sektori kod kojih se zahteva provera trajnosti

HISTORICAL BACKGROUND

Load spectrum

With regard to variable amplitude loading (spectrum loading), the importance of load spectra was recognized by Ernst Gassner, who in 1939, for the first time, formulated a procedure for simulating variable amplitude loading; the historical blocked programme sequence with a Gaussian-like distribution of loads /1/, Fig. 2.

This sequence was frequently used into the 1970s as a standard until blocked programme tests were replaced by random load sequences applied with modern servo-hydraulic actuators. In the meantime, different standardized load spectra for different application areas are developed, mainly for testing and comparison /2/.

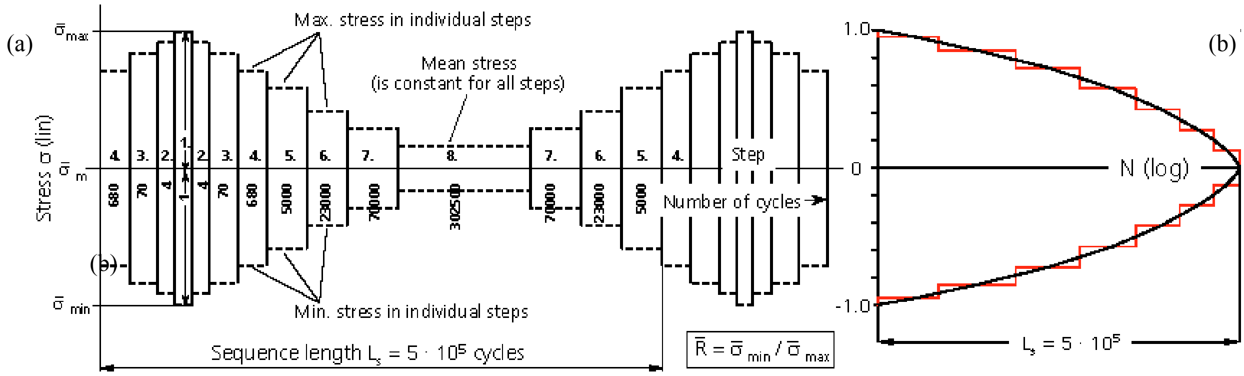

Figure 2. Ernst Gassner's historical 8 step-blocked-programme-sequence (1939). (a) Load sequence; (b) Cumulative frequency distribution.
Slika 2. Istorijska blok-programska sekvenca u 8 stupnjeva Ernsta Gasnera (1939). (a) Sekvenca opterećenja; (b) Kumulativna raspodela frekvencije

Spectrum shape and dimensions

Variable amplitude loading is often discussed in the context of fatigue life assessment forgetting the main benefit recognised by Gassner. Namely, the influence of spectrum loading on fatigue life and especially fatigue strength with regard to structural dimensions. Figure 3 shows the Woehler and Gassner curves for a steering rod tested under constant amplitude loading (rectangular spectrum), a Gaussian spectrum and a straight-line spectrum. Gassner curves correspond to variable amplitude loading, while the Woehler curve (SN-curve) relates to constant amplitude loading conditions. Gassner curves are presented in double-logarithmic plot by maximum stress amplitudes of the applied spectrum versus the number of cycles to failure, /3/.

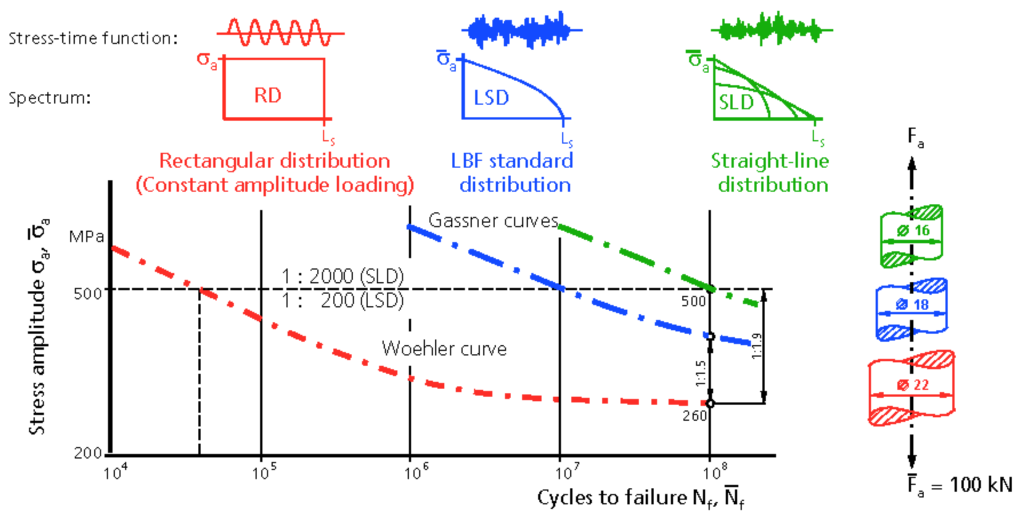

Figure 3. Influence of spectrum-shape on fatigue life and component dimensions.
Slika 3. Uticaj oblika spektra na zamorni vek i dimenziju komponente

Fatigue life is seen to increase with decreasing fullness of the spectrum: the higher the amount of small amplitudes, the longer the fatigue life. On the other hand, the increasing fatigue life displayed by the position of the Gassner-curves can be exploited for the reduction of dimensions; for a fatigue life of 10^8 variable amplitude cycles of a steering rod, the maximum endurable stresses are 50 to 100% higher than the constant amplitude fatigue strength at 10^8 cycles, depending on the spectrum shape. So, significant reductions of cross-sectional size and component weight can be realized. However, it must also be ascertained that an impact load does not lead to a catastrophic (brittle) failure, if a crack should be present. This last example underlines the contribution of spectrum shape to light-weight design.

FATIGUE LIFE ESTIMATION

Cumulative damage calculation

For realizing lightweight advantages given by variable amplitude loading the knowledge about the position of the Gassner curve is essential as outlined in previous section. But as experimental Gassner curves are not always available and experiments for all type of load-time histories, Fig. 4, /4/, would require too much time and efforts, it makes sense to determine their position by calculations.

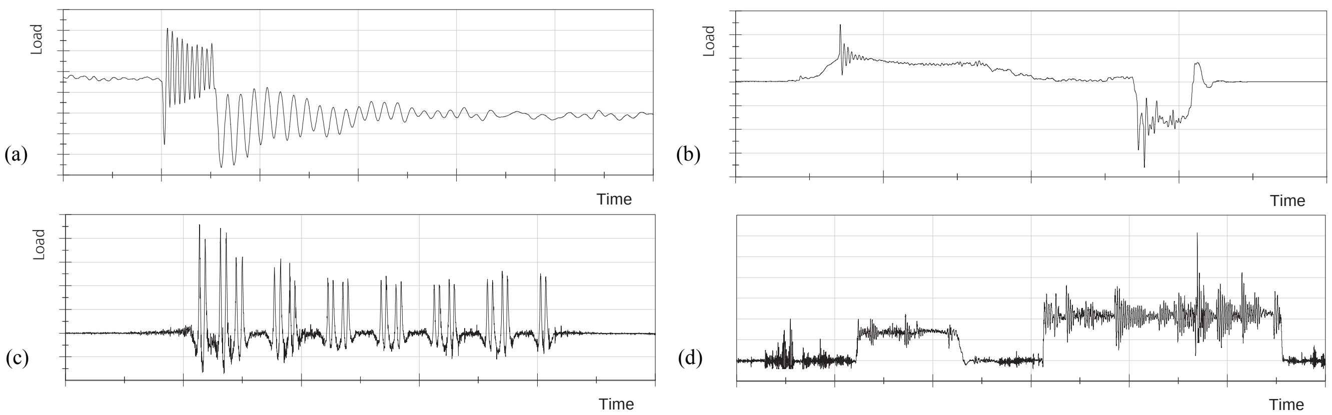

Figure 4. Examples of measured load-time histories: (a) wind energy plant, planet carrier, *special loading event*; (b) passenger car, trailer coupling loads *(acceleration, braking)*; (c) rail loads during train crossing; (d) fork lift truck service loads.
Slika 4. Primeri snimljenih istorija opterećenje-vreme: (a) elektrana na energiju vetra, planetni nosač, *specijalni oblik opterećenja*; (b) putničko vozilo, opterećenja veze prikolice *(ubrzanje, kočenje)*; (c) opterećenja šina pri nailasku voza; (d) opterećenja kamiona viljuškara

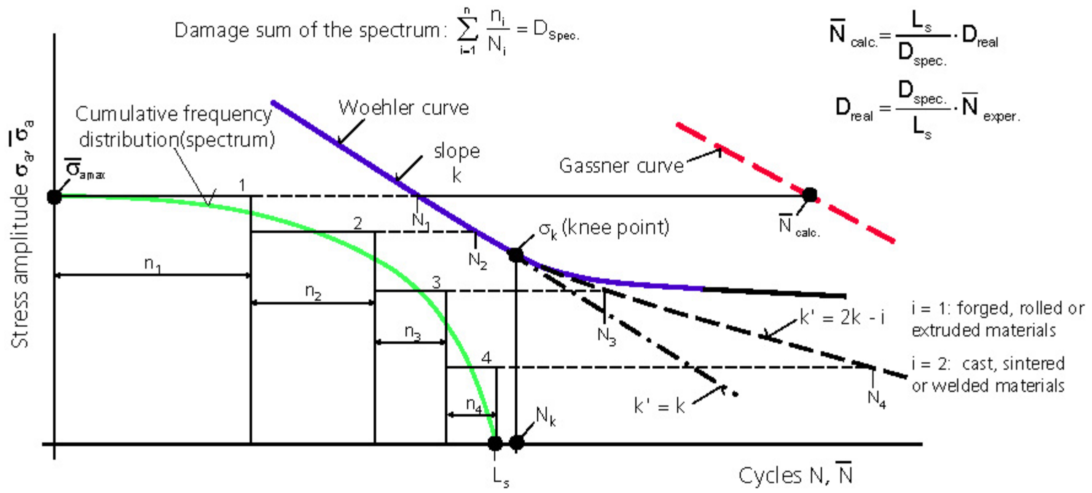

Figure 5. Most commonly used cumulative damage calculation methods.
Slika 5. Najčešće računske metode za kumulativna oštećenja

Since Palmgren (1924) and Miner (1944), attempts to estimate damage and fatigue life have continued /5-7/. Despite the complexity of this issue, the most commonly used method is still the modification of the Palmgren-Miner-Rule, where in the high-cycle fatigue area the inclination k of the S-N curve is maintained ($k' = k$) or reduced ($k' = 2k - i$) depending on the material /8/ in order to account for the damaging influence of small load cycles, Fig. 5.

In addition, these modifications postulate failure when the theoretical damage sum $D_{th} = \Sigma(n/N)_i = 1.0$ is reached. However, an extensive research project evaluating a vast database /9/ revealed a large scatter of the real damage sums ($D_{real} = N_{exp}/N_{cal}$ ($D_{th} = 1.0$)) for different materials, loading modes, stress ratios and spectra. Figure 6 displays results obtained for wrought steels with the failure criterion of crack initiation, as well as total rupture, using a modification of Palmgren-Miner-Rule with the fictive prolongation of the S-N curve with the slope $k' = 2k - 1$. The probability of finding the conventional value of $D_{th} \geq 1.0$ is only 5 to 10%; this means that only 5 to 10% of the fatigue life estimates were on the "safe" side, while the rest were "unsafe".

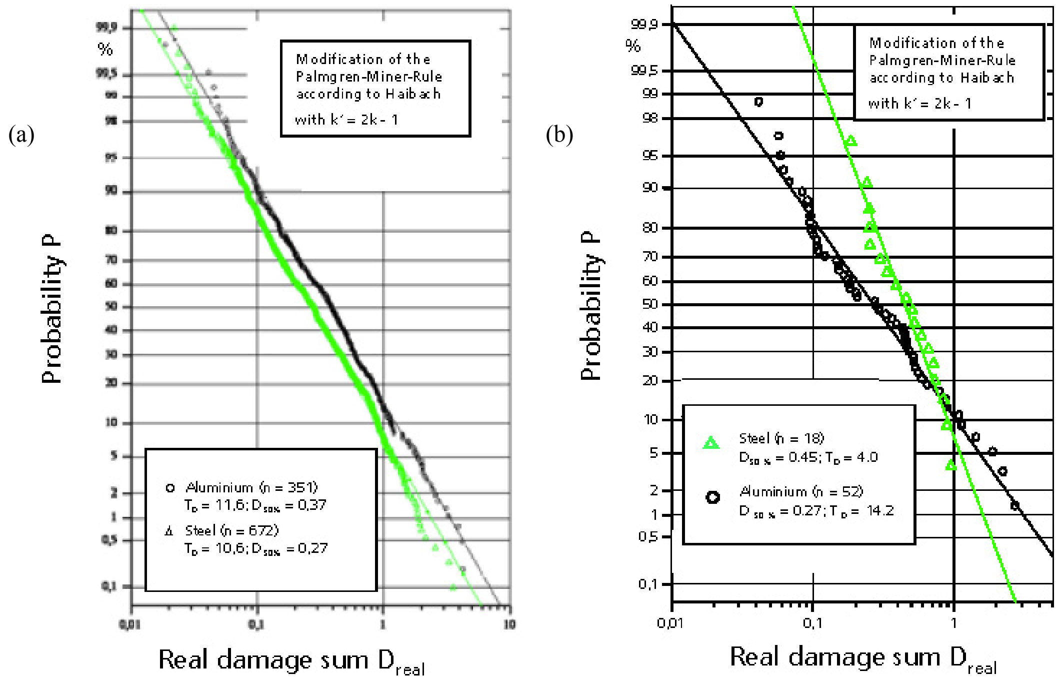

Figure 6. Real damage sum distribution for steels and aluminium alloys. (a) not welded; (b) welded joints, /9/.
Slika 6. Stvarna raspodela superpozicije oštećenja za čelike i legure aluminijuma. (a) ne zavareni; (b) zavareni spojevi, /9/

The main cause for this large scatter is that the damaging process is too complex, non-linear and not to be described alone by few mechanical parameters like stress, strain or stress intensities. Nevertheless, there are some parameters as mean value fluctuations and material which may explain to some extent the observed scatters.

Influence of mean value fluctuations on fatigue life

Another reason for significant failing of fatigue life calculations results from the fact that for load-time histories with mean value fluctuations, the additional damaging effect caused by the mean values is not accounted for properly; the consideration of the mean values by a mean-stress-amplitude diagram or a damage parameter is not enough. This is demonstrated by investigations carried out on forged stub-axles of commercial vehicles /10, 11/. The fatigue tests were performed with a truck load sequence ($\overline{R} = -1.4$, $I = 0.45$, $L_s = 0.95 \cdot 10^5$) derived from service measurements and containing mean value fluctuations caused by cornering, which are superposed on the mean value from the weight and payload, Fig. 7.

In order to study the effects resulting from mean values, a second test series with a Gaussian load sequence and a constant mean strain ($\overline{R} = -0.7$, $I = 0.99$, $L_s = 1 \cdot 10^5$) was also carried out. For both strain–time histories with comparable sequence lengths, the upper side of the stub axles was the expected failure location because of the more tensile strains. However, this was only observed to be true for the Gaussian sequence with the constant mean strain level.

In Figs. 8 and 9, applied spectra using different counting methods are presented for the particular failure locations shown in Fig. 7.

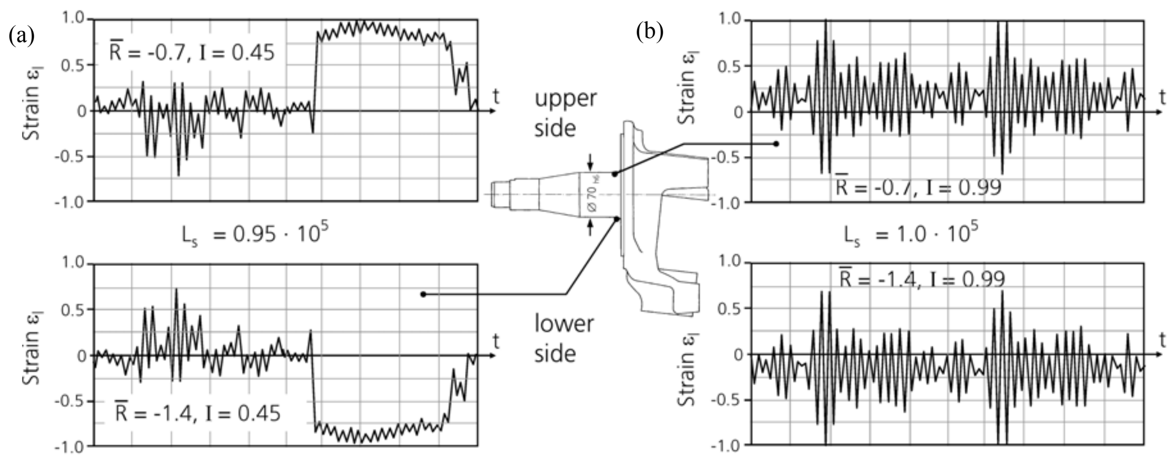

Figure 7. Applied local strain–time histories on a stub-axle and failure locations. (a) Truck strain–time history; (b) Gaussian strain–time history.
Slika 7. Primena istorije lokalnih deformacija–vreme na rukavac osovine i mesta loma. (a) istorija deformacija–vreme za kamion, (b) Gausova istorija deformacija–vreme

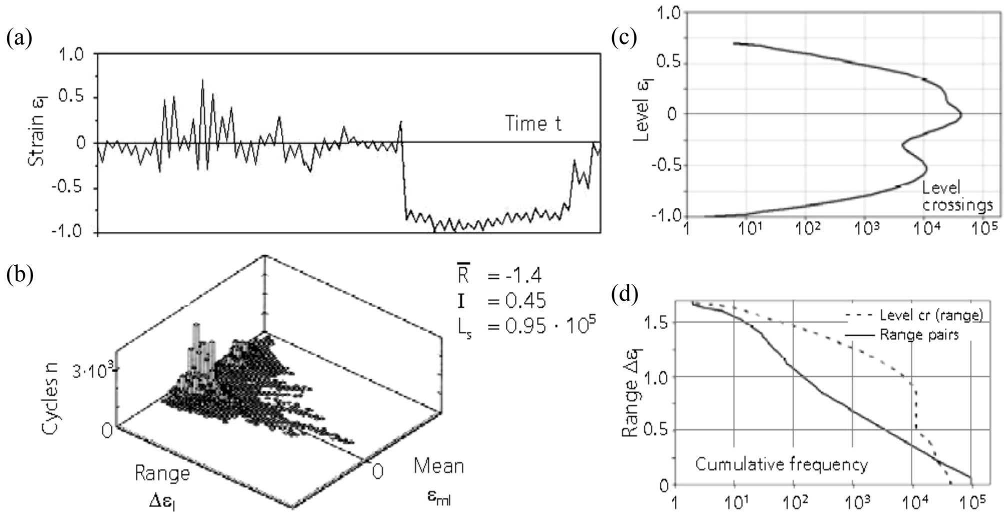

Figure 8. Truck load sequence. (a) strain–time history; (b) rainflow matrix; (c) level crossing counting; (d) level crossings and range pairs.
Slika 8. Sekvenca opterećenja kamiona. (a) istorija deformacija–vreme, (b) matrica toka; (c) broj prelaza nivoa; (d) prelazi nivoa i parovi raspona

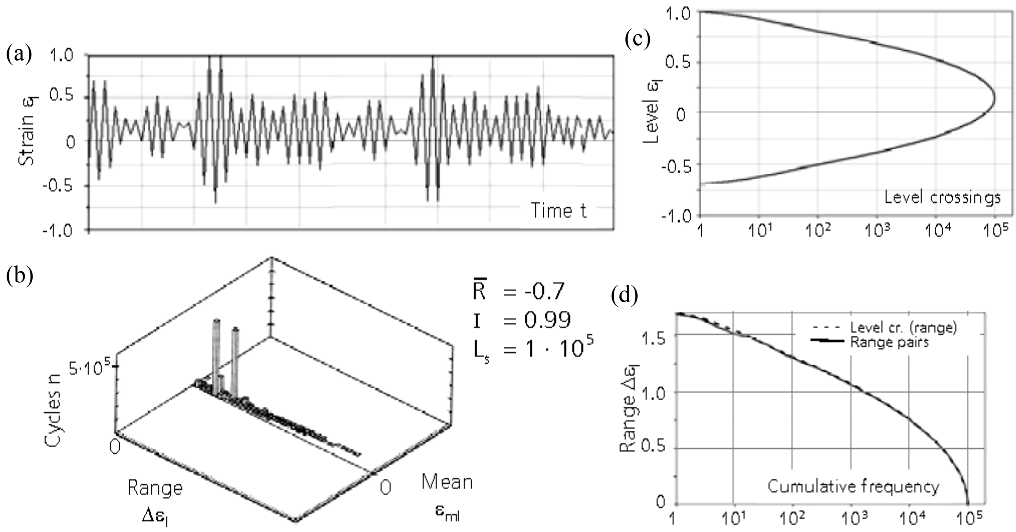

Figure 9. Gaussian load sequence. (a) strain–time history; (b) rainflow matrix; (c) level crossing counting; (d) level crossings and range pairs.
Slika 9. Sekvenca Gaus opterećenja. (a) istorija deformacija–vreme, (b) matrica toka; (c) broj prelaza nivoa; (d) prelazi nivoa i parovi raspona

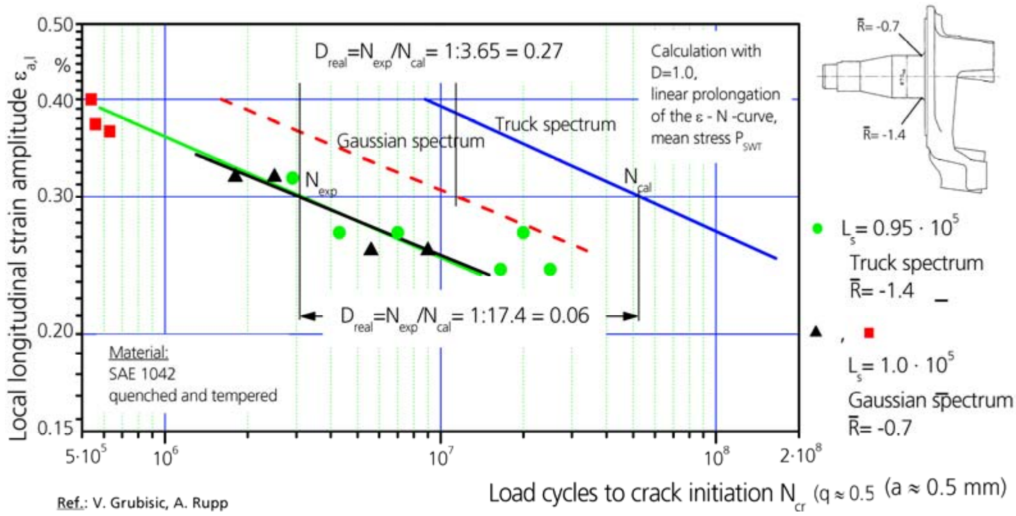

Figure 10. Experimental and calculated Gassner-lines, /10/.
Slika 10. Eksperimentalne i računske Gasner krive, /10/

The variable amplitude test results obtained with both spectra are plotted in Fig. 10 for the criteria of crack initiation for a defined crack depth of $a = 0.5$ mm. Figure 10 also contains the calculated Gassner-lines. The fatigue lives to crack initiation are assessed on the basis of the rainflow matrices and cyclic data of the material (cyclic stress-strain, strain-cycle and damage parameter-cycle curves). For the damage accumulation of small amplitudes in the high-cycle region ($N > 10^6$), the slope of the elastic part of the S-N curve is kept and failure is assumed for $D_{th} = 1.0$.

For both spectra, the numerical assessment is on the unsafe side: for the Gaussian sequence with constant mean value by a factor of about four corresponding to a real damage sum $D_{real} = 0.24$, and for the truck sequence with the high mean value fluctuation by a factor of about twelve, meaning $D_{real} = 0.08$.

This example underlines two important messages which justify the performance of variable amplitude testing, especially for complex structures:

- Despite the simple geometry of the stub-axle, the failure location for the truck sequence, the lower side, could not be predicted by the conventional local strain approach.
- Even if fatigue life assessment uses the strain-time history of the failure location, the fatigue life is significantly overestimated for the sequence with the high mean value fluctuation.

Fatigue life calculations for the stub-axle, also considering short crack propagation /11, 12/, could not improve the quality of the assessments.

Influence of material

One reason of the observed scatters of the real damage sums is that the ranking of materials under constant amplitude loading does not remain the same as under variable amplitude loading. In Figs. 11 and 12 the Woehler- and Gassner-lines for a surface hardened steel originating from different previous heat treatments and cast nodular iron alloys are shown. A cumulative damage calculation based on Woehler-lines would never estimate the position of Gassner-lines without special knowledge. Under constant amplitude loading the quenched and tempered steel after induction hardening reveals a superior behaviour compared with the controlled cooled variant from the forging heat. But under variable amplitude loading the controlled cooled variant becomes superior. In this observation residual stress states are probably responsible. Especially, the extreme high fatigue life increase of cast iron EN-GSS-800 in Fig. 12 is caused by the transformation of the ausferrite microstructure

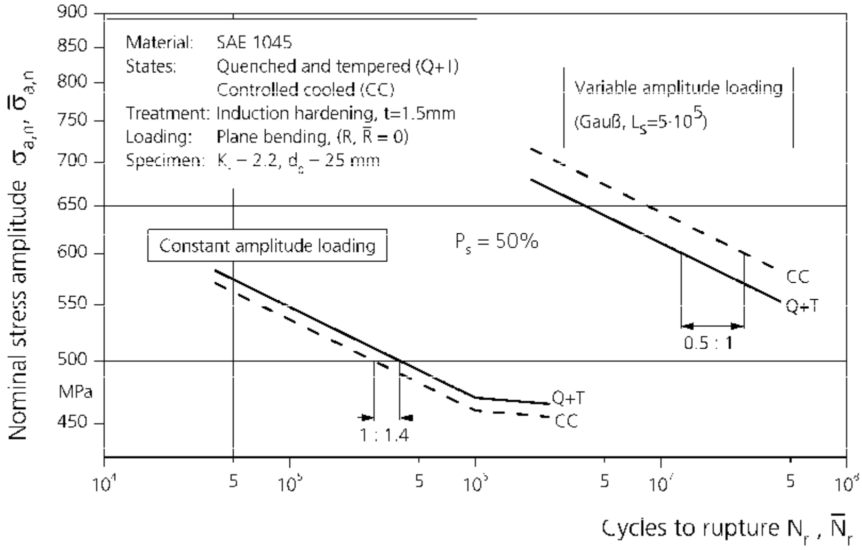

Figure 11. Woehler- and Gassner-lines of induction hardened steel variants.
Slika 11. Velerove i Gasnerove krive za varijante indukciono kaljenog čelika

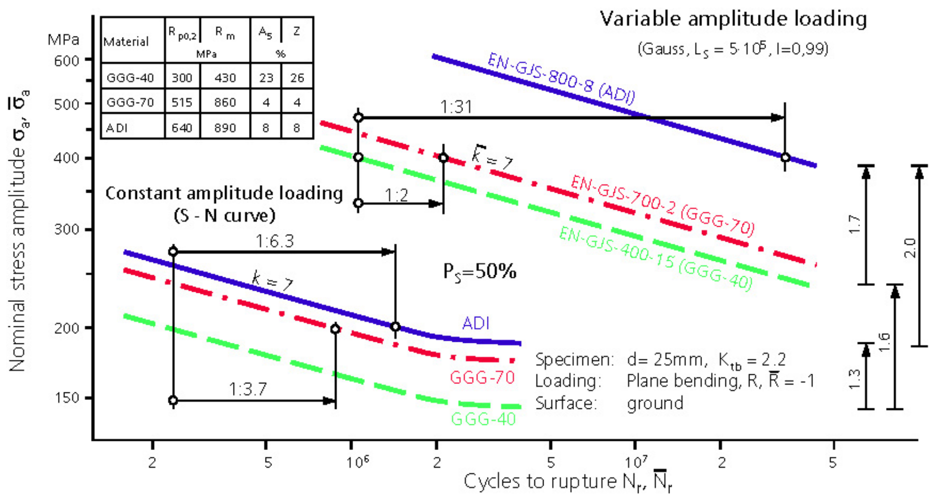

Figure 12. Fatigue behaviour of different cast iron materials under constant and variable amplitude loading.
Slika 12. Ponašanje zamora kod različitih materijala livenog gvožđa pod konstantnim opterećenjem i sa promenljivom amplitudom

into martensite due to high local elastoplastic stresses, resulting in locally higher strength and compressive residual stresses /13/, and cannot be estimated without experimental expertise. The ratios between the other materials cannot be explained. Fracture mechanics data of crack propagation of these materials /14/ are also not able to verify this behaviour.

The influence of variable amplitude loading on crack growth and crack front formation for high strength aluminium alloys used in the aircraft industry may also be completely different than for constant amplitude loading. In Fig. 13, it is shown that, especially for alloy 7075-T6 under a flight simulation loading with standard load sequence TWIST /2-4/, a significant tongue forming during high gust loads occurs, which is not as pronounced for other alloys /15, 16/. In all these three cases, the cracks remain in tensile mode. However, under constant amplitude loading, tongues do not occur /15/ and, after a certain crack length, a growth in shear mode is observed.

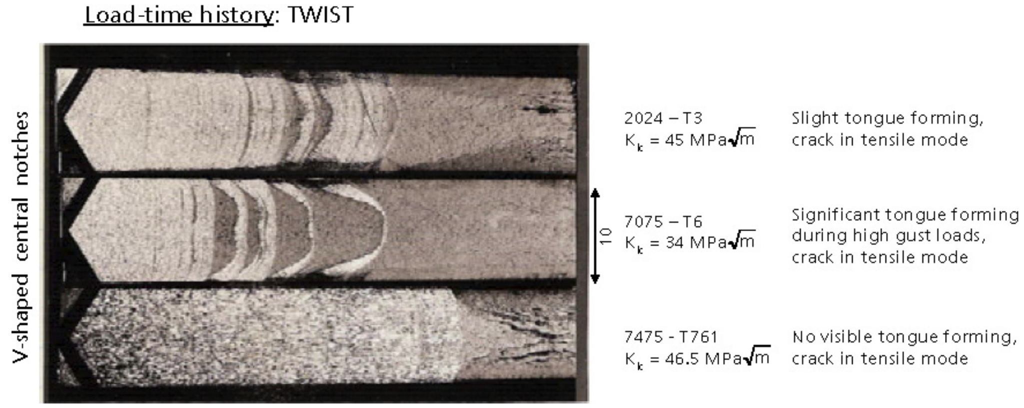

Figure 13. Material influence on crack front formation under variable amplitude loading, /15/.
Slika 13. Uticaj materijala na formiranje fronta prsline pod opterećenjem promenljive amplitude, /15/

Recommendations for fatigue life estimations

Hence, to overcome the scatter of the real damage sums for fatigue life estimates, some recommendations can be given for practitioners, based on aforementioned experience /3, 8, 9, 10/, see Tab. 1. The allowable damage sums for the assessment of load-time histories with non-fluctuating mean stresses are already included in newer design codes /17, 18/. These values lie, for about 90% of known cases, on the safe side, but for safety components, if comparable experiences with regard to spectrum, material, fabrication and design are not available, experimental verifications are recommended.

Table 1. Allowable damage sums.
Tabela 1. Dozvoljene sume oštećenja

Material state (steel, aluminium)	D_{PM} Constant mean stress	D_{PM} Varying mean stress
Not welded components (forged, rolled)	0.3	0.1
Welded or cast components	0.5	0.2

Calculation of the damage sum according to Palmgren-Miner and modified according to Haibach with $k' = 2k - m$, with $m = 1$ for forged or rolled components, $m = 2$ for welded and cast components.

ARRANGEMENT OF LOAD SEQUENCES

Tests with blocked load arrangements are still carried out, even though, in practice, blocked loadings are exceptional. Therefore, if a blocked loading is applied, it must be assured that the fatigue life obtained corresponds to reality. Following the introduction of servo hydraulic actuators, comparisons between Gassner's blocked-programme sequence and random sequences with almost identical amplitude distributions are carried out, Fig. 14. It could be shown that, under realistic random load arrangements, the fatigue life diminishes by factors of 2 to 10 /19/.

In /20/, these differences between blocked and random arrangements are confirmed. However, if the blocked load sequences are short enough, the fatigue life of a random arrangement can be realised. In /21/, a modified Gassner's blocked-programme sequence with a length of $L_s = 5.2 \cdot 10^5$ cycles resulted in a fatigue life that was a factor of more than three higher than for a random sequence of the same size and almost the same Gaussian-like amplitude distribution, Fig. 15. An omission of the sixth step with the lowest stress level did not influence the fatigue life. But, tests carried out with a partitioning of this sequence into five sub-blocks of size $L_s = 4 \cdot 10^4$ cycles delivered almost the same fatigue life as the random sequence, proving that a random arrangement is not conditionally required to reproduce the original fatigue life. This example shows under what conditions tests with blocked sequences can be accepted.

A similar result is observed also under pure crack propagation, Fig. 16, /16/. The repetition of block (programme) loadings with small sequence lengths results in almost same fatigue lives obtained under random loading. However, blocks with same large sequence lengths as the random sequence render much higher crack propagation lives due to the not suppressed sequence effects.

SUBSTITUTION OF VARIABLE AMPLITUDE LOADING BY CONSTANT AMPLITUDE LOADING

As variable amplitude testing requires large amounts of effort and time, there has always been an attempt to substitute spectrum loading by constant amplitude loading. Figure 17 shows schematically how a spectrum equivalent SN-curve is derived.

The prerequisites for determining the required SN-curve are the position of the knee point, the slope of the SN-curve k and the modified slope k' after the knee point and the

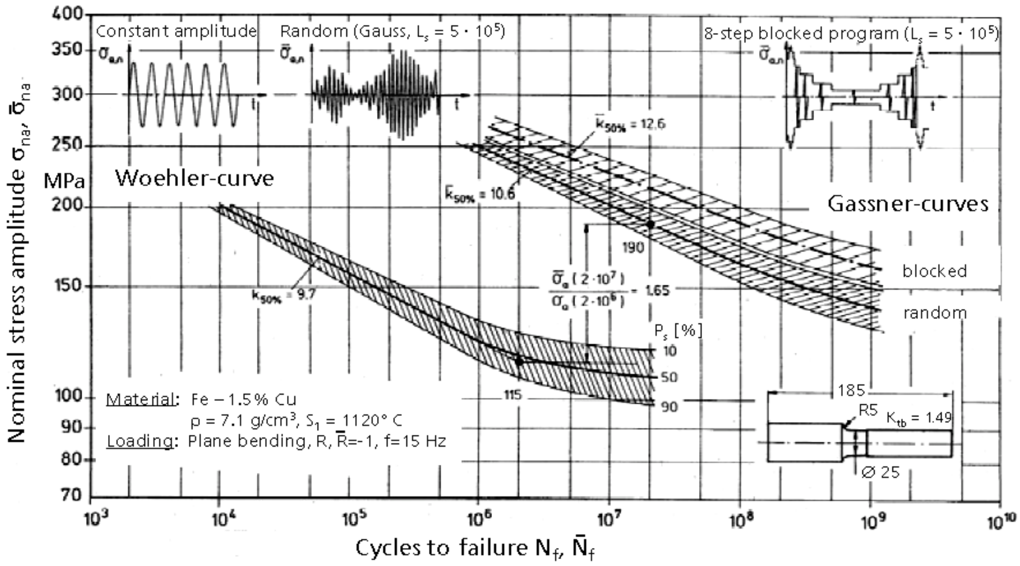

Figure 14. Influence of load sequence arrangement on fatigue life.
Slika 14. Uticaj preraspodele sekvenci opterećenja na vek zamora

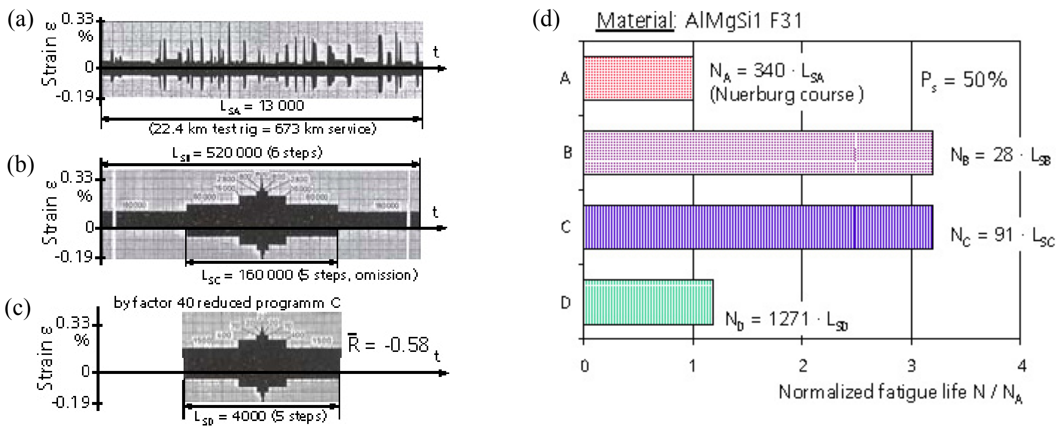

Figure 15. Influence of load mixing on variable amplitude fatigue life. (a) Original local strain-time history (A). (b) Blocked programs (B, C). (c) Sub-block programme (D). (d) Fatigue lives, /21/.
Slika 15. Uticaj preraspodele sekvenci opterećenja na vek zamora. (a) Originalna istorija deformacija-vreme (A). (b) Blok programi (B, C). (c) Pod-blok programi (D). (d) Vek zamora, /21/.

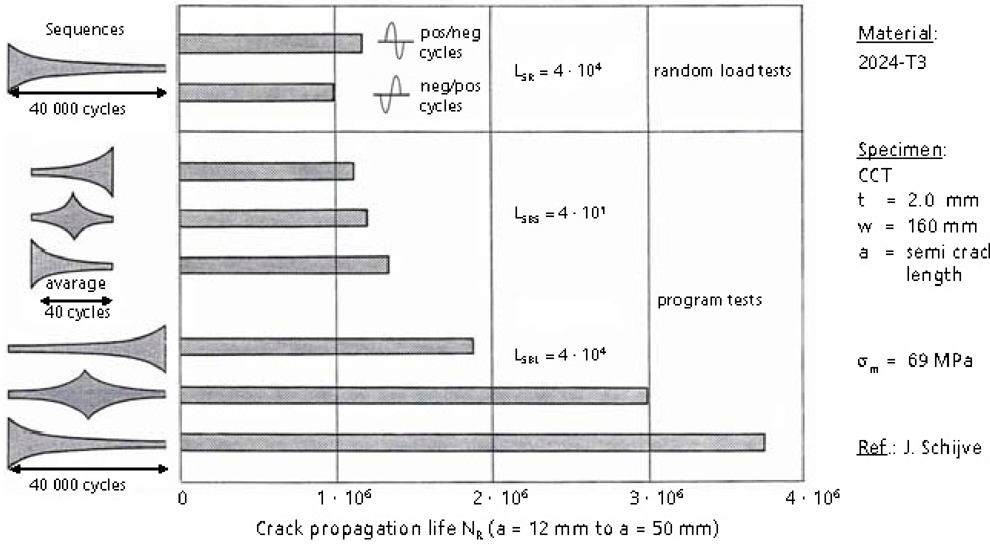

Figure 16. A comparison of fatigue crack growth lives under random loading and different types of programme loading by a gust load spectrum, /16/.
Slika 16. Poređenje veka rasta zamorne prsline pod proizvoljnim opterećenjem i različitim tipovima programskog opterećenja u spektra, /16/

allowable damage sum D_{al}, Tab. 1, /22/. If the equivalent SN-curve is determined, from this the level for a constant amplitude test with σ_a ($N < N_k$) can be fixed.

However, the constant amplitude test can only be regarded as valid, if the failure position is identical with the failure position under variable amplitude loading. At components with complex geometries, Fig. 18, the failure position is determined by interaction between the local stress level, stress concentration and stress gradients. Under constant amplitude loading, three different failure locations are possible depending on the torque level. However, under spectrum loading the failure site is determined by the spectrum shape and the most damaging part in relation to the particular SN-curves. Therefore, the selection of stress level for a constant amplitude test should consider the most highly damaged spot of the component under spectrum loading.

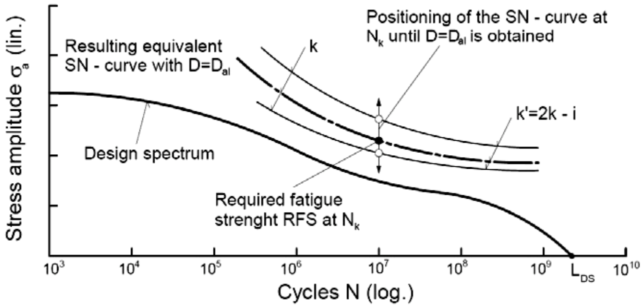

Figure 17. Determination of spectrum equivalent SN-curve for constant amplitude testing.
Slika 17. Određivanje spektra ekvivalentnih SN krivih za ispitivanje konstantnom amplitudom

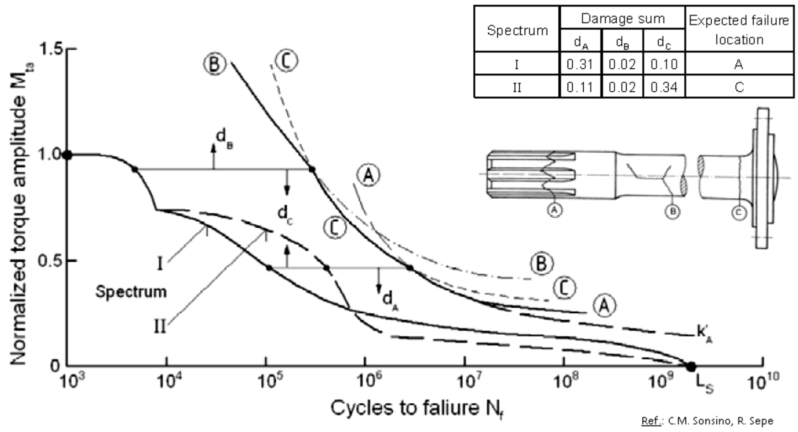

Figure 18. Failure sites of a driving shaft under constant and variable amplitude loading.
Slika 18. Mesta loma pogonskog vratila pod konstantnim opterećenjem i sa promenljivom amplitudom

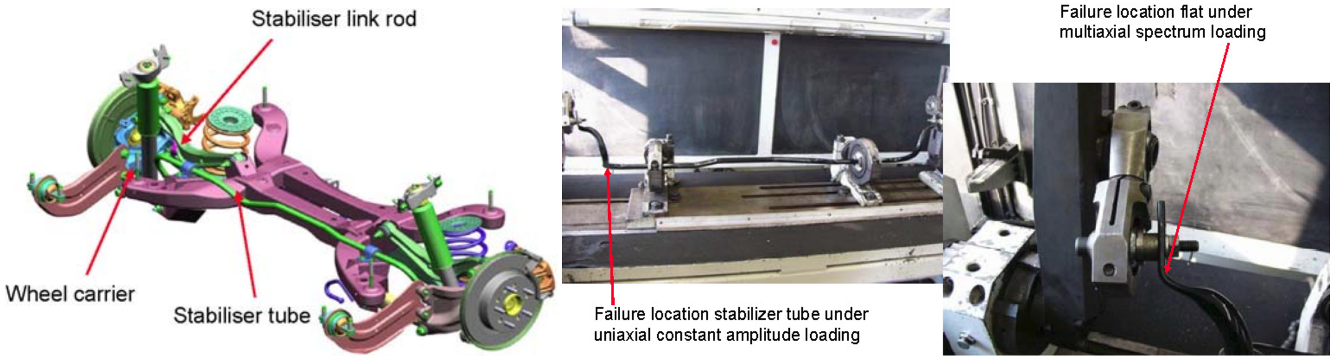

Figure 19. Rear axle stabilizer system with short link rods.
(a) Overview of the stabiliser, (b) Failure locations under constant and variable amplitude loading.
Slika 19. Sistem stabilizatora zadnje osovine sa kratkim sponama.
(a) Pregled stabilizatora, (b) mesta loma pod konstantnim opterećenjem i sa promenljivom amplitudom

In cases where multiaxial spectrum loading has to be substituted by uniaxial constant amplitude loading, the condition of reproducing the same failure position becomes even more difficult. In Fig. 19, this is demonstrated through the example of a rear axle stabilizer system with short link rods /23/. Under the simulated multiaxial service spectrum load, the flat end of the stabilizer fails due to bending. However, under simplified uniaxial testing with constant amplitudes the stabilizer tube fails.

Also, in aircraft development, the question of constant or variable amplitude testing is a matter of discussion for a long time. In /24/, it is reported that, on the tension skin of the centre section of a F-27 transport aircraft under variable amplitude loading, specific type of cracks are observed, that did not occur under constant amplitude loading /24/.

SPECTRUM LOADING AND RESIDUAL STRESSES

The allowance of stresses under variable amplitude loading exceeding the knee point of the SN-curve may cause, in components containing manufacture-dependent residual stresses, a redistribution of these stresses and so a different behaviour compared to constant amplitude loading.

Not welded components

In Fig. 20, the influence of surface treatments, such as rolling and induction hardening, on fatigue life under constant and variable amplitude loading is displayed /25/. Axles of steel SAE 1045 are tested under fully reversed ($R = -1$) plane bending. The increase of fatigue strength after surface rolling under spectrum loading is much less than under constant amplitude loading due to decreased compressive residual stresses. The higher the stress level and so the local plasticity, the less will be the benefit of this surface treatment. The compressive residual stresses due to induction hardening seem to remain stable.

Under torsional spectrum loading, a lack of benefit of the surface rolling of SAE 1042 axles along the Gassner-curve can even be observed, Fig. 21, /26/. Probably, due to the shallower stress gradients under torsion and higher plasticity in the notch, compressive residual stresses are removed completely.

Both examples demonstrate that, from knowledge of constant amplitude loading of surface rolled components, their behaviour under spectrum loading cannot be assessed. Therefore, a fatigue life calculation based on the SN-curve for the surface treated state will also fail.

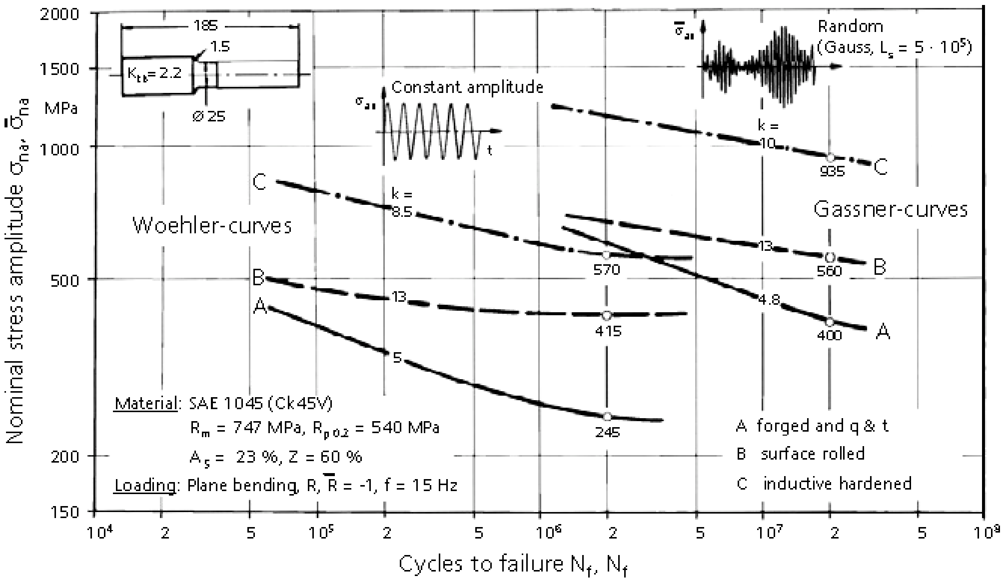

Figure 20. Influence of surface treatments on fatigue life of SAE 1045 axles under constant and variable amplitude fully reversed bending.
Slika 20. Uticaj površinske obrade na vek zamora kod osovina od SAE 1045 pod konstantnim opterećenjem i sa promenljivom amplitudom pri naizmeničnom savijanju

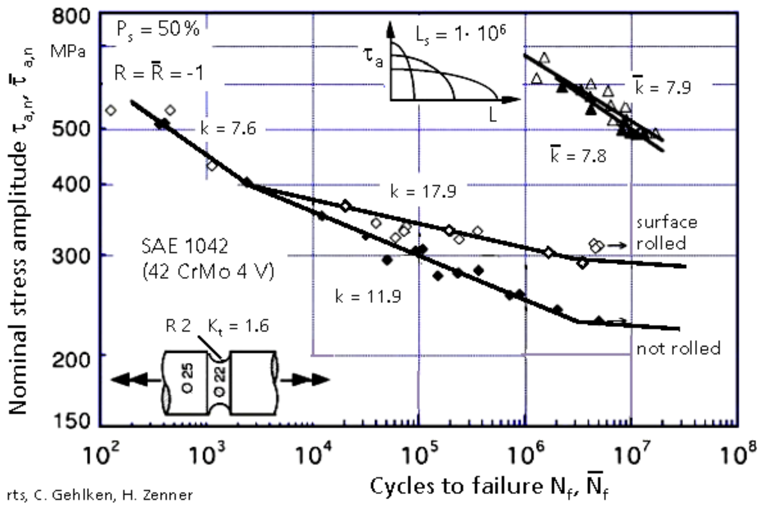

Figure 21. Influence of surface rolling on fatigue life of SAE 1042 axles under constant and variable amplitude fully reversed torque.
Slika 21. Uticaj površinskog valjanja na vek zamora kod osovina od SAE 1042 pod konstantnim opterećenjem i sa promenljivom amplitudom pri naizmeničnim vučnim momentom

Welded joints

Especially in welded joints from thick plates (t > 3 mm), tensile residual stresses occur /27/. A thermal stress relief can, in many cases, improve fatigue behaviour. In Fig. 22, the fatigue behaviour of longitudinal stiffeners of a structural steel is presented. Cracks start at the front end of the weld seam where stress concentration is very high. After a thermal stress relief, under constant amplitude loading only the fatigue behaviour in the high-cycle range after the knee point is improved where local stresses are elastic, /28/. At higher stress levels, due to the plasticity caused by high stress concentration, the tensile residual stresses are also redistributed in samples not subject to thermal stress relief and a benefit from the treatment does not result. As under variable amplitude loading the stress levels are high, due to local plasticity effects, a significant benefit of the thermal treatment is also not observed here.

When stress concentration at weld toes is not as high as in the previous example, a benefit from thermal stress relief can be drawn along the whole Woehler-curve as well as under variable amplitude loading, Fig. 23, /28/. But, under spectrum loading, the increase of fatigue strength is not as large as under constant amplitude loading, because of plasticity effects.

Also, these examples reveal clearly that improvements observed under constant amplitude loading cannot be assumed to be the same under variable amplitude loading.

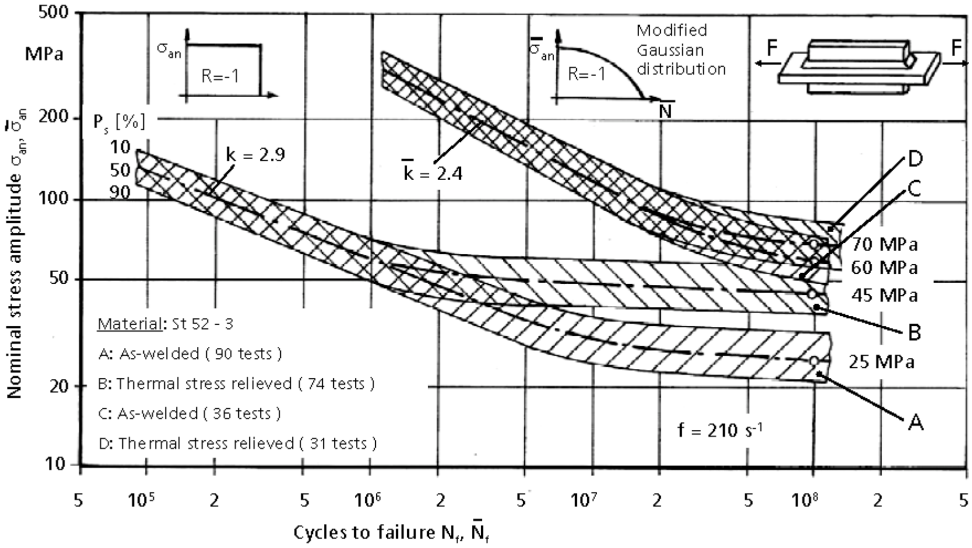

Figure 22. Fatigue life curves under constant and variable amplitude loading.
Slika 22. Krive veka zamaranja pod konstantnim opterećenjem i sa promenljivom amplitudom

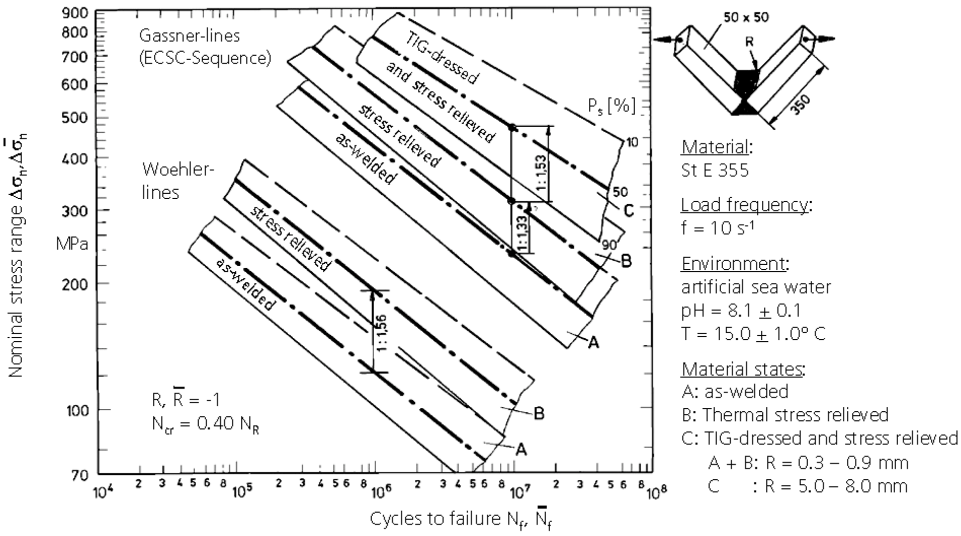

Figure 23. Fatigue behaviour of V-shaped specimens under constant and variable amplitude loading.
Slika 23. Ponašanje zamora kod epruveta oblika V pod konstantnim opterećenjem i sa promenljivom amplitudom

CORROSION FATIGUE

In the following, some examples from environmental and fretting corrosion are addressed. From Fig. 24, it can be seen that cyclic salt spray corrosion of an automotive cast aluminium rear axle carrier decreases the fatigue strength in the constant amplitude high-cycle regime significantly more than under variable amplitude loading, /29/. If the observed reduction under constant amplitude loading had been taken into account rather than the smaller decrease under variable amplitude loading, the component thickness and weight would have been much higher.

Also, under fretting corrosion, the fatigue strength response to variable amplitude loading is much more favourable than to constant amplitude loading, Fig. 25, /30/. The decrease of fatigue strength in the high-cycle regime, especially under surface pressure of p_A = 100 MPa, for the investigated cast nodular iron EN-GJS-400-15 is about 15% under spectrum loading while the decrease is about 35% under constant amplitude. Here, it should be mentioned that the graphite in the microstructure has a retardant influence with regard to the fatigue strength decrease. In case of steel, the observed decrease is also about 35% under spectrum loading, /30/.

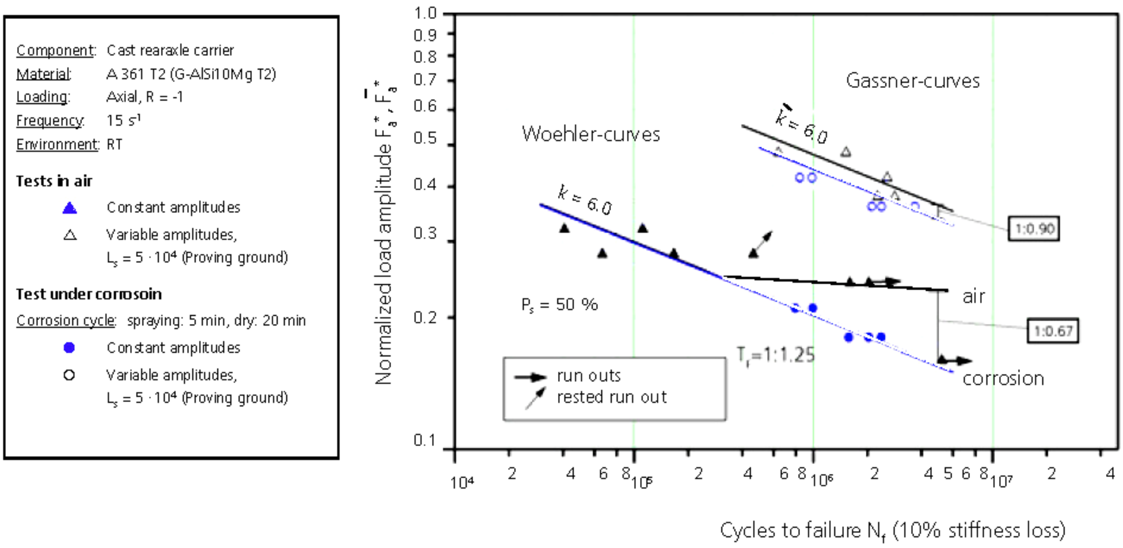

Figure 24. Fatigue strength of cast rear axle carriers in air and under corrosion.
Slika 24. Zamorna čvrstoća izlivenih nosača zadnje osovine na vazduhu i pod uticajem korozije

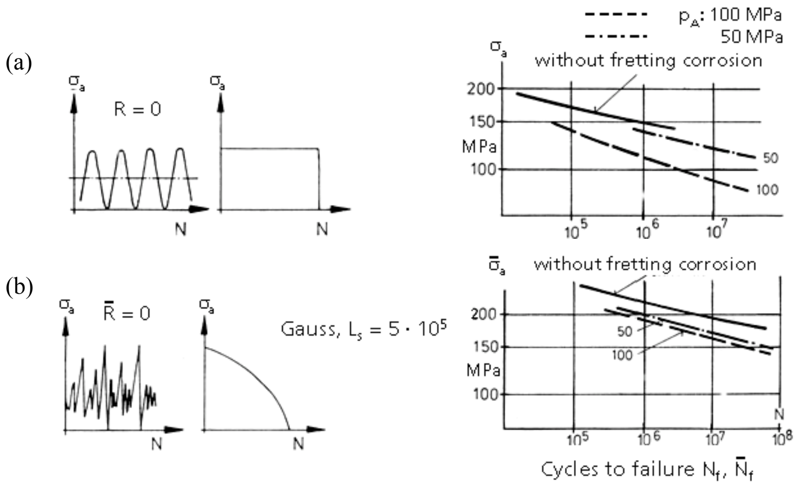

Figure 25. Influence of fretting corrosion and surface pressure on fatigue strength of a cast nodular iron. Material: EN-GJS-400-15
(a) Constant amplitude loading, (b) Random loading.
Slika 25. Uticaj freting korozije i površinskog pritiska na zamornu čvrstoću odlivka od nodularnog liva. Materijal: EN-GJS-400-15
(a) opterećenje konstantne amplitude, (b) proizvoljno opterećenje

TEST SPECTRA FOR TIME REDUCTION

As variable amplitude testing is too time consuming, possibilities for the reduction of test time are continuously in discussion. The main possibilities are summarized in Fig. 26, /31/, The recommendation is not to exceed the maximum loads of the spectrum, not to perform a simple omission, but to consider the possible damaging effect of omitted small load amplitudes by a damage equivalent increase of loads between the maximum spectrum load and the omission level.

For test time reduction, the omission of loads under a certain level, e.g. half of the so-called endurance limit or a smaller percentage, is often suggested /3, 4, 8, 32, 33/. On one hand, as an endurance limit does not exist /34/ or, on the other hand, even if a structure is operated in a non-aggressive ambient, as a corrosive environmental attack cannot be excluded during long fatigue lives, an omission without a damage compensation should never be applied. Figure 27 shows how sensitive the fatigue life response to different uncompensated omission levels may be /3/, i.e. the effect of such an omission can be assessed by experimental verification only /35/.

As indicated in Fig. 27, despite the damage compensation, there is still a physical limitation, which should be strongly considered when a testing time reduction is introduced. If, in the testing, corrosion is involved, a fretting or an environmental corrosion, enough time should be given for the development of the corrosive attack, i.e. the tests should be run between $2 \cdot 10^6$ to $5 \cdot 10^6$ cycles.

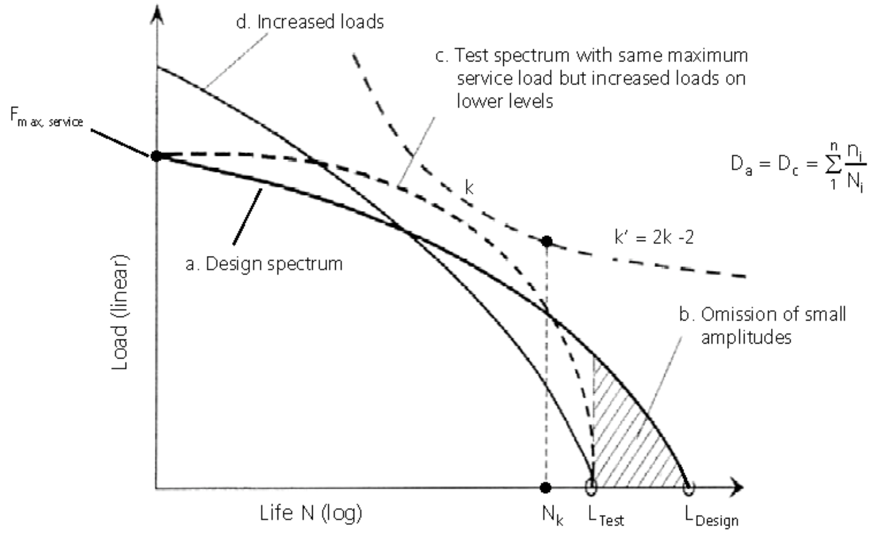

Figure 26. Possibilities for reduction of testing time, /31/.
Slika 26. Mogućnosti za smanjenje vremena ispitivanja, /31/

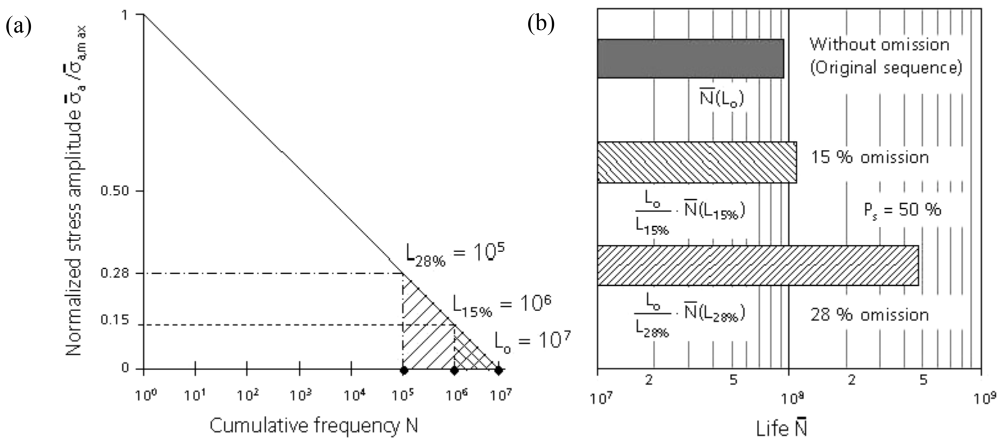

Figure 27. Influence of different omission levels on fatigue life. (a) Amplitude distribution, (b) Fatigue life.
Slika 27. Uticaj različitih nivoa izostavljanja na zamorni vek, (a) raspodela amplitude, (b) zamorni vek

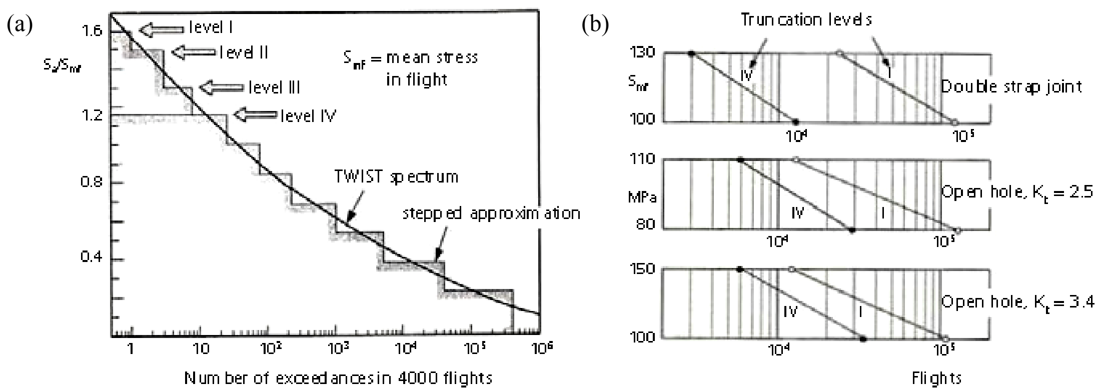

Figure 28. Effect of truncation of the TWIST load spectrum on fatigue life. (a) Stress amplitude distribution of the TWIST load spectrum, (b) Truncation levels and test results, /16/.
Slika 28. Uticaj skraćenja TWIST spektra opterećenja na zamorni vek (a) raspodela amplitude napona TWIST spektra opterećenja, (b) nivoi skraćenja i rezultati ispitivanja, /16/

Despite the recommendation not to exceed the maximum loads of a spectrum, there are some exceptions for which an increase of the loads can be tolerated. If the increased load still lies below the structural yield point and new residual stress systems do not result from this, testing time can be also reduced by this measure. The increase of loads can also be used for simulating the strength reduction by corrosion without applying a corrosive environment, /29/.

For some applications, a truncation is proposed /16, 36/, for obtaining conservative fatigue lives. Even if theoretically, according to the linear damage accumulation hypothesis, an increase of fatigue life should result, in some cases, contrary to expectations, a reduction is observed /4, 8, 16, 36/, Fig. 28. This is especially the case for straight-line or concave spectra, /16/.

The truncation leads to different large decreases of fatigue life depending on stress concentration and load level. These result a comprise of crack initiation as well as propagation life. Obviously, by truncation, a lower life to crack initiation and afterwards a higher crack propagation rate is permitted; otherwise, the fatigue life to crack initiation is increased by compressive residual stresses and then the crack propagation rate is lowered by plasticity at the crack tip due to the high spectrum loads, /8/.

This example shows again the importance of variable amplitude tests with original load sequences before introducing test time affecting modifications.

CONCLUSIONS

The examples discussed display the complexity of variable amplitude loading and the diversity of parameters, which determine fatigue life. From this, it becomes obvious that not only the estimation of fatigue life but also the performance of tests under spectrum loading require experience, especially when test time reductions have to be introduced. Also the often desired substitution of variable amplitude loading by constant amplitudes requires the consideration of a lot of details, such as the estimation of the right failure location, assumption of the appropriate real damage sums and other parameters, that influence the fatigue life.

This complexity reveals that variable amplitude testing, especially for safety components, is indispensable, In this context, not only laboratory and numerical experiences are required, but also the observation of components and structures in service and the feedback from failure cases. Only by this interaction, can the reliability of experimental and numerical assessments be increased.

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REFERENCES

1. Gassner, E., *Festigkeitsversuche mit wiederholter Beanspruchung im Flugzeugbau Luftwissen*, (1939) 6, pp.61-64.
2. Heuler, P., Klätschke, H., *Generation and Use of Standardized Load Spectra and Load-Time Histories*, Int. J Fatigue 27, (2005), pp.974-990.
3. Sonsino, C.M., *Fatigue Testing under Variable Amplitude Loading*, Int. J Fatigue 29, (2007), pp.1080-1089.
4. Buxbaum, O., Betriebsfestigkeit – Sichere und wirtschaftliche Bemessung schwingbruchgefährdeter Bauteile Verlag Stahleisen, Düsseldorf, 2nd Edition, 1992.
5. Dowling, N.E., *A Review of Fatigue Life Prediction Methods*, SAE Paper No. 871966, SAE Passenger Car Meeting and Exposition, Dearborn, Michigan, Oct. 19-22, 1987.
6. Chaboche, J.L., Lesne, P.M., *A Non-linear Continuous Fatigue Damage Model*, Fatigue and Fracture of Eng. Mat. and Structures 11 (1988) 1, pp.1-7.
7. Fatemi, A., Yang, L., *Cumulative Fatigue Damage and Life Prediction Theories: A Survey of the State of the Art for Homogeneous Materials*, Int. J Fatigue 20 (1998) 1, pp.9-34.
8. Haibach, E., Betriebsfestigkeit – Verfahren und Daten zur Berechnung Springer Verlag, Düsseldorf, 2nd Edition, 2002.
9. Eulitz, K.-G., Kotte, K.L., *Damage Accumulation-Limitations and Perspectives for Fatigue Life Assessment*, Materials Week 2000–Proceedings, Ed. and Organiser: Werkstoffwoche-Partnerschaft, Frankfurt, 25-28 Sep. 2000, URL: www.materialsweek.org/proceedings
10. Grubisic, V., Rupp, A., *Gegenüberstellung der experimentell und rechnerisch bestimmten Lebensdauer von Bauteilen und Probestäben*, Deutscher Verband für Materialforschung und –prüfung (DVM), Berlin DVM-Report AKBF (1993), pp.271-291.
11. Sonsino, C.M., Kaufmann, H., Grubisic, V., *Transferability of Material Data for the Example of a Randomly Forged Truck Stub Axle*, SAE Transaction Section 5, Journal of Materials and Manufacturing 106, 1997, pp.649-670.
12. Vormwald, M., Anrisslebensdauervorhersage auf der Basis der Schwingbruchmechanik für kurze Risse (Crack Initiation Life Prediction on the Basis of Fracture Mechanics for Short Cracks) Veröffentlichung des Instituts für Stahlbau und Werkstoffmechanik der Technischen Hochschule Darmstadt, Heft 47, 1989.
13. Sonsino, C.M. et al., *Structural Durability Criteria for Commercial Vehicle Components from the Self Strengthening Cast Ausferrite Nodular Iron EN-GJS¬800-8 (ADI) in Comparison to the Ferrite EN-GJS-400-15*, Mat. wiss. u. Werkstofftechn 39 (2008), 10, pp.761-768.
14. Henkel, S., Hübner, P., Pusch, G., *Cyclic Crack Growth Behaviour of Cast Iron – Analytic and Statistic for Usage with the Esacrack Model*, Deutscher Verband für Materialforschung und prüfung (DVM), Berlin DVM-Report No. 240 (2008), pp.251-259.
15. Vlasveld, J.A., Schijve, J., *Tongue-Shaped Crack Extension During Fatigue of High Strength Aluminium Alloys*, Fatigue of Engn. Mat. And Struct. 3 (1980), pp.129-145.
16. Schijve, J., Fatigue of Structures and Materials, Kluwer Academic Publishers, AH Dordrecht, 2001.
17. Hänel, B., Haibach, E., Seeger, T., Wirthgen, G., Zenner, H., Rechnerischer Festigkeitsnachweis für Maschinenbauteile FKM-Richtlinie, VDMA Verlag, Frankfurt, 2002.
18. Hobbacher, A. (Ed.), *Recommendations for Fatigue Design of Welded Joints and Components*, IIW Document No.XIII-1823-07 (2007), update July 2008.
19. Gassner, E., Kreuz, P., Bedeutung des Programmbelastungsversuchs als einfachere Form der Simulation zufallsartiger Beanspruchungen, VDI-Verlag, Düsseldorf, 1984.

20. Buxbaum, O., Klätschke, H., Oppermann, H., *Effect of Loading Sequence on the Fatigue Life of Notched Specimens Made from Steel and Aluminium Alloys*, Applies Mechanics Reviews 44 (1991) 1, Engineering Materials Advisory Services (EMAS), Warley, 1987, pp.355-401.
21. Lowak, H., Grubisic, V., Möglichkeiten zur Lebensdauervorhersage für Bauteile aus Aluminiumlegierungen Materialprüfung 27 (1985) 11, pp.337-343.
22. Fischer, G., Grubisic, V., *Dimensioning of Wheelset Axles*, Fraunhofer Institute for Structural Durability and System Reliability LBF Report No. FB-226e (2005), Darmstadt.
23. Kalinowski, B., Morgenstern, C., Ditzer, B., Hicker, A., *Structural Durability Improvement of Stabiliser Bars under Variable Amplitude Loading with Heat Treatment and Tooling Optimization*, In: Proceedings of the 2nd Int. Conf. on Material and Component Performance under Variable Amplitude Loading, March 23-26, 2009, Darmstadt, DVM-Report No. 136 (2009).
24. Schijve, J., Broek, D., de Rijk, P., Nederveen, A., Sevenhuysen, P., *Fatigue Tests with Random and Programmed Load Sequences with and without Ground-to-Air Cycles. A Comparative Study on Full-Scale Wing Center Sections*, National Aerospace Laboratory (NLR), Amsterdam Report No. NLR-TR S. 613 (1965).
25. Oppermann, H., Oberflächennachbehandlung – Steigern der Betriebsfestigkeit zufallsartiger wechselbiegebelasteter Kerbstäbe aus Stahl Materialprüfung 37 (1995) 3, pp.82-85.
26. Jung, L., Esderts, A., Zenner, H., Betriebsfeste Bemessung antriebstechnischer Komponenten Antriebstechnisches Kolloquium 1993, Aachen, Verlag TUV Rheinland, Köln, pp.313-335.
27. Radaj, D., Heat Effects of Welding, Springer-Verlag, Berlin/ Heidelberg, 1992.
28. Sonsino, C.M., *Effect of Residual Stresses on the Fatigue Behaviour of Welded Joints Depending on Loading Conditions and Weld Geometry*, Int. J Fatigue 31 (2009), pp.88-101, Special Issue Welded Joints, Ed.: L. Susmel.
29. Sonsino, C.M., Berg-Pollack, A., Grubisic, V., *Structural Durability Proof of Automotive Aluminium Safety Components – Present State of the Art*, SEA Paper No.2005-01-0800 (2005), Warrendale, PA/USA.
30. Buxbaum, O., Fischer, G., Zum Einfluß der Reiskorrosion auf das Festigkeitsverhalten unter sinusförmiger und zufallsartiger Belastung Konstruktion 40 (1988) 9, pp.333-338.
31. Grubisic, V., *Determination of Load Spectra for Design and Testing*, Int. J of Vehicle Design 15 (1994) 1/2, pp.8-26.
32. Schütz, D., Heuler, P., *The Significance of Variable Amplitude Fatigue Testing*, In: ASTM STP 1231 (1994), pp.201-220 (Ed.: C. Amzallog).
33. Sonsino, C.M., *Principles of Variable Amplitude Fatigue Design and Testing*, ASTM STP 1439 (2005), pp.3-23, Eds.: P.C. McKeighan and N. Ranganathan.
34. Sonsino, C.M., *Course of SN-Curves Especially in the High-Cycle Fatigue Regime with Regard to Component Design and Safety*, Int. J Fatigue 29 (2007), pp.2246-2258.
35. Sonsino, C.M., *Versuchszeitverkürzung in der Betriebsfestigkeitsprüfung – Methoden und Kompromisse*, Materialprüfung 45 (2003) 4, pp.133-144.
36. Schütz, D., Lowak, H., *Zur Verwendung von Bemessungsunterlagen aus Versuchen mit betriebsähnlichen Lastfolgen zur Lebensdauerabschätzung*, Fraunhofer-Institut für Betriebsfestigkeit LBF, Darmstadt LBF-Report No. FB-109 (1976).
37. Sonsino, C.M., *Effects on Lifetime under Spectrum Loading*, In: Proc. Sec. Int. Conf. On Material and Component Performance under Variable Amplitude Loading, Vol. I (2009), pp.93-118; MP Materials Testing 52 (2010) 7-8, pp.440-451.