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Exploring fatigue rules for timber structures in Eurocode 5

Kjell Arne Malo[1], Francesco Mirko Massaro and Haris Stamatopoulos

Abstract

The next generation of Eurocode 5 "Design of timber structures" is currently planned with normative rules for prevention of fatigue failures in timber structures. Probably only a few building structures like windmill towers will need evaluation with respect to high numbers of cyclic loading, and the proposed rules will most likely be used in timber bridge design. The proposed rules for fatigue in the second generation of the timber Eurocode are almost identical to the informative rules found in an annex to the current Eurocode 5 for timber bridges; EN1995-2. Although few new fields of applications or more comprehensive rules are brought into the new normative rules of the second generation, it is nevertheless worth to explore what is incorporated in the rules, and their possible limitations.

In the present paper, the rules limiting the applicable stress, or the number of cycles to failure, are mainly presented and commented. It is shown how experimental results have been used for calibration of expressions, using dowel type connections with slotted-in steel plates as case. Other effects of the formulations and calibrations will also be explored and commented.

1 Introduction

The second generation of Eurocodes is currently under development. A large amount of new design rules as well as fields of applications have been proposed and are under investigation. However, for timber structures exposed to loading with relatively low-intensity but high number of cycles, as for example traffic loading on road bridges, the existing informative annex (Annex A EN1995-2:2004) [1] is proposed to be kept approximately as it is without any major changes. The most significant changes are that the fatigue provisions are proposed to move to the main part of Eurocode 5 (EN1995-1-1) [2], and to make them normative. The proposed normative status in the Eurocode makes it more intrusive to explore the implications of the fatigue provisions. An approach for fatigue regulations based on integration of rate and time dependent effects is not relevant for the Eurocodes, as the time dependency of loading and loading models are absent in EN1990 and EN1991. Consequently, possible effects of time dependency or order of load appearance must be incorporated in an implicit way.

So far, no satisfactory analytical model for the prediction of the fatigue life of wood or other composites is known to the authors. The knowledge on fatigue behaviour of wood and connections in timber structures comes from experimental testing at various scales. Most experimental fatigue results have been derived from constant stress amplitude loading until failure. The parameters are commonly the maximum and minimum stress levels, and the experimental result is the number of cycles until failure. The experimental results are usually presented by use of Wöhler-curves (SN-curves), relating the stress level to the logarithm of the number of cycles to failure.

For most composites, wood included, the experimental results show a clear dependency of the mean stress level on the fatigue life. The approach used for components in steel, considering only the stress range (the variation in stresses), is therefore probably not satisfactory for wooden components. Moreover, there is a general agreement that increased moisture content and long duration of load interact with the fatigue life, making it shorter, but the experimental results are so sparse that hardly any general quantification can be made.

[1] Kjell Arne Malo, Professor, NTNU Norwegian Univ of Sci and Technology, Dep of Structural Engineering. Norway, Kjell.Malo@ntnu.no

2 Method

2.1 Fatigue loading

2.1.1 Load combinations

The proposed second generation of EN 1990, specifies the load combination for fatigue actions by:

$$\sum F_d = \sum_i G_{k,i} + \sum_j \psi_{2,j} Q_{k,j} + (P_k) + Q_{fat} \tag{1}$$

where Q_{fat} is the relevant fatigue load, giving cyclic stresses in a building structure. Note that the quasi-permanent part of the live load $\sum_j \psi_{2,j} Q_{k,j}$ shall probably not have a spatial variation between the load cases, it is merely an addition to the self-weight of the structure. For timber structures it might be recommended to evaluate several levels of density and quasi-permanent load levels, depending on the mean stress sign and level.

Note also that all load factors shall be set to unity ($\gamma_f = 1.0$), which indicate that all safety measures must be dealt with on the resistance side.

2.1.2 Stresses

The fatigue strength of wood is dependent on both mean stress σ_{mean} and alternating stress σ_a. All stress components have contributions from both quasi-static loading and cyclic loading.

The alternating stress from stress cycles can be determined by:

$$\sigma_a = \frac{1}{2}\Delta\sigma = \frac{1}{2}(\sigma_{max} - \sigma_{min}) \tag{2}$$

where σ_{max} is the numerical largest stress and σ_{min} the numerical smallest in representative stress cycles. Note that tensile stresses are defined positive, while compressive stresses are defined negative. The alternating stress amplitude σ_a corresponds to half of the stress range $\Delta\sigma$ and any effect of quasi-static loading is here cancelled out. Furthermore, the alternating stress σ_a is, by definition, positive.

The mean stress from stress cycles is calculated by:

$$\sigma_{mean} = \frac{1}{2}(\sigma_{max} + \sigma_{min}) \tag{3}$$

As an alternative to the use of mean stress and amplitude, the stress ratio R is commonly used in fatigue evaluations to characterize the stress situation, where R is defined by

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{4}$$

Note that the stresses can have any value and sign, and consequently R also can take on any value. For a pure alternating load with zero mean stress $R = -1$, while $R = 1$ indicates a pure static load without any change in stress. The use of the stress ratio R together with the maximum stress, or the use of alternating and mean stresses are two sides of the same story, i.e. they are interrelated in the following way:

$$\sigma_a = \tfrac{1}{2}\sigma_{max}(1 - R) \text{ and } \sigma_{mean} = \tfrac{1}{2}\sigma_{max}(1 + R) \tag{5}$$

When stress resultants, i.e. forces or moments, are used in fatigue strength evaluations, the stresses in the expressions above can be replaced by the corresponding stress resultants.

2.2 Constant life diagrams

For the evaluation of fatigue strength experimental results, it is very convenient to use constant life diagrams, confer for example [3] and [4]. For an easy understanding of the concept, we reformulate the maximum and minimum stresses to

$$\sigma_{max} = \sigma_a + \sigma_{mean} \text{ and } \sigma_{min} = -\sigma_a + \sigma_{mean} \tag{6}$$

Both static loading by σ_{mean} and cyclic loading by σ_a can independently lead to failure in a material. For most composites, also wood, it is generally found that the absolute stresses are more important for the fatigue life than the stress range $\Delta\sigma$. Considering Eq. (6), it is obvious that an increase in σ_{mean} will reduce the strength margin in case of tension (σ_{max}), while for compression (σ_{min}) a reduction of mean stresses will reduce the compressive strength margin. To take the combined effect into account, we can estimate the combined strength by, conservatively, applying a linear interaction between the two different failure modes, leading to

$$\frac{\sigma_a}{f_a} + \frac{\sigma_{mean}}{f_{mean}} = 1 \tag{7}$$

Note that the strength for alternating stress f_a is dependent on the number of cycles, and that the static strength can be the positive tensile strength, or the negative compression strength, for positive and negative mean stresses, respectively. A graphical representation of Eq. (7) for a given number of cycles is usually called a Goodman diagram. Since the alternating stress σ_a is, by definition, positive, we have only two quadrants in the stress space, one for positive and one for negative mean stresses; see visualization in Figure 1. A stress combination inside the triangle enclosed by Eq. (7) and the horizontal axes for mean stresses is considered safe, while the domain outside the triangle is considered unsafe. The Goodman constant life diagram is usually found either close to experimental results, or slightly conservative. More accurate results have been reported for some cases by letting the ratio σ_{mean}/f_{mean} be raised to the power $c \geq 1$, see Eq. (8), making the interaction curves slightly convex.

$$\frac{\sigma_a}{f_a} + \left(\frac{\sigma_{mean}}{f_{mean}}\right)^c = 1 \tag{8}$$

Letting the parameter $c = 2$ is known as a Gerber type diagram. Usually, timber structures will have c values somewhere in between 1 and 2. However, it is not possible that the slope of the strength interaction curve, Eq. (8), is positive for positive mean stress (or negative for negative mean stress), since this would imply that the strength limit increases for an increase of maximum stress.

The alternating stress σ_a and the mean stress σ_{mean} can also be related by use of the stress ratio R giving

$$\sigma_a = \frac{1-R}{1+R} \cdot \sigma_{mean} \tag{9}$$

In the stress space, this is the equation of a straight line from the origin with a slope given purely of the stress ratio R. Note that $R = +1$ corresponds to the horizontal axes for σ_{mean}, while $R = -1$ corresponds to the vertical axes for σ_a. An example (with units MPa) of a Goodman diagram using tensile static strength of 30, compression strength of -20, and alternating strength (depending of number of cycles) equal 10 is visualized in Figure 1. For a given stress ratio R, the combined strength can be estimated from the interception of the strength line given by Eq. (7) and the stress combination given by Eq. (9).

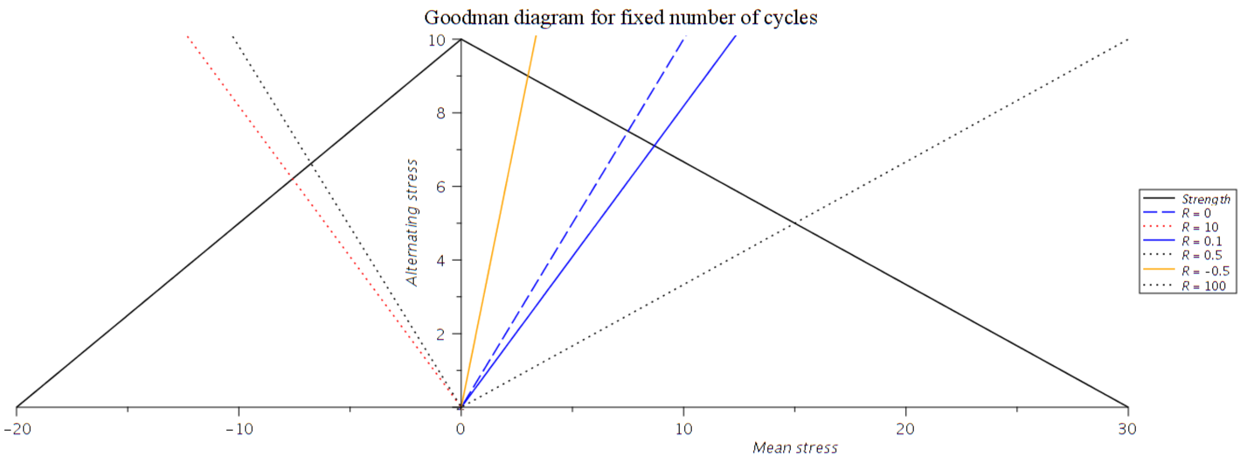

Figure 1: Example of a constant life diagram for a given number of cycles.

2.3 Fatigue strength and Eurocode 5

The degradation of strength due to cyclic stresses in wood is commonly represented by letting the strength level (SL) be reduced linearly with the base 10 logarithm of the number of cycles N (SN-curves).

$$SL = B - A \cdot Log_{10}(N) \tag{10}$$

The slope of the SN-curve is given by parameter A. The parameter A must be calibrated by experimental testing. The parameter B is the interception of the fitted straight line $A \cdot Log_{10}(N)$ with the stress axes (SL). The stress level can be either real stresses or dimensionless stress levels by scaling the stresses by some representative stress level.

In the annex A of EN 1995-2 (2004) [1] the design stress level is given by the parameter k_{fat}, where

$$k_{fat} = 1 - \frac{1-R}{a(b-R)} \mathrm{Log}(\beta \cdot N_{obs} \cdot t_L) \geq 0 \tag{11}$$

and the product $(\beta \cdot N_{obs} \cdot t_L)$ is the number of cycles to be used in the design [1]. This corresponds to a scaling of Eq. (10) by the static design strength, since

$$f_{\mathrm{fat,d}} = k_{\mathrm{fat}} \frac{f_{\mathrm{k}}}{\gamma_{\mathrm{M,fat}}} \tag{12}$$

A comparison of Eq. (10) to (11) gives $B = 1$ and implies that the design static strength is achieved for one full cycle. However, strictly speaking the static strength is determined at one quarter of a stress cycle, and hence B equal unity should correspond to $\mathrm{Log}(0.25) = -0.6$. The assumption $B = A \cdot Log_{10}(1) = f_{fat,d}$ is a convenient choice but does not necessary match experimental results. Usually, the slope of an SN curve is determined based on experimental mean values. Forcing a SN curve to pass through the point $(Log(1), f_{mean})$ puts a restriction on the determination of the slope of the SN curve.

By fitting the slope of the SN curve to experimental mean values both from static and cyclic results, and thereafter scaling the vertical axes of the SN curve by the ratio between the static design strength to mean experimental values, is the same as to rotate the whole SN curve about the point of interception between the SN-curve and the horizontal axes for number of cycles to failure with respect to absolute stresses. Hence, the characteristic values for low cycle fatigue strength are matching the static values, but it is implied that the standard deviation of the fatigue strength is linearly decreasing with the logarithmic number of cycles and ends up with zero standard deviation at the interception point. If this assumption is valid is not known to the authors.

The informative annex A in EN1995-2 [1] has in principle separate curves for each type of stress/or connection type and value of the ratio of min and max stresses (R-values).

By comparison of Eqs. (10) and (11), the slope A of the SN curves is given by

$$A = \frac{1 - R_T}{a \cdot (b - R_T)} \tag{13}$$

Note that the informative annex A in EN1995-2 has a special interpretation of the stress ratio R. To distinguish it from the usual definition given by Eq. (4), it is here (and in a proposal for new EN1995-1-1) denoted R_T. The use of R_T requires that the absolute values of the stresses govern what is used as minimum and maximum stresses. Here it is required that $\sigma_{d,min}$ is determined such that

$$|\sigma_{d,min}| \leq |\sigma_{d,max}| \tag{14}$$

Consequently, the value of R_T is limited to the range $-1 \leq R_T \leq +1$. Note that this choice also necessitates that the total variation of stresses must be subdivided into separate cases dependent on the mean value of σ_{mean}, i.e. a separate case for tensile stresses $\sigma_{mean} \geq 0$, which is different from the case of compression stresses where $\sigma_{mean} \leq 0$.

This is reflected in the various cases in EN 1995-2 with different sets of parameters for a and b in Eq. (13). The tabulated parameter values proposed for new EN1995-1-1 are given in Table 1. By the separation into two separate cases based on the mean stresses, only one quadrant of the stress space is needed for each case.

Table 1: Proposed values for SN curves in the new EN 1995-1-1

Stress type	Stress σ_d	Mean stress $\sigma_{d,mean}$	a	b
Normal; compression	$\sigma_{d,c,0}$, $\sigma_{d,c,90}$	≤ 0	2.0	9.0
Normal; tension parallel	$\sigma_{d,t,0}$	≥ 0	9.5	1.1
Normal; tension perpendicular	$\sigma_{d,t,90}$	≥ 0	4.7	2.1
Shear	τ_d		6.7	1.3
Connection, dowels 12 mm		≥ 0 or ≤ 0	6.0	2.0
Connection, nails		?	6.9	1.2

By applying the parameters in Table 1 and a stress ratio of $R_T = 0.1$, the SN-curves plotted in Figure 2 are obtained. For this stress ratio, tension parallel and perpendicular to the grain direction have practically the same relative strength reduction due to fatigue loading, see the two dotted lines in Figure 2.

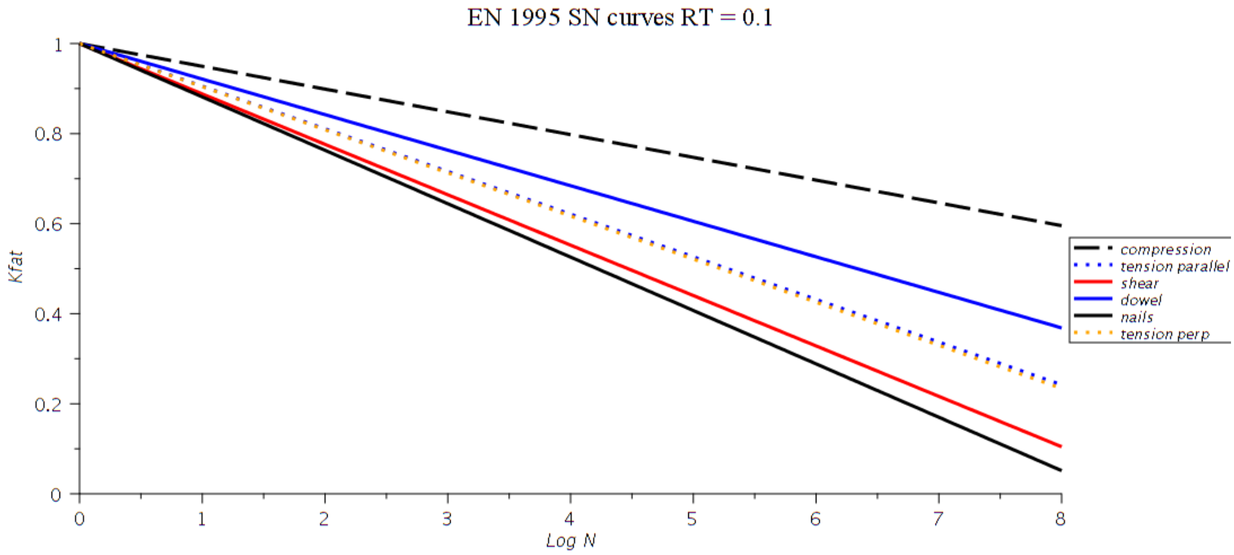

Figure 2: Proposed S-N curves for various cases with $R = 0.1$ for new EN1995-1-1.

The slopes of the curves are given by the value of A, Eq. (13), and a plot of A for the range of R_T shows considerable variation for the various values of R; confer Figure 3. From this plot we also see that the only value of the stress ratio giving equal strength reduction for tension parallel and perpendicular to the grain is approximately the value $R_T = 0.1$. The curves for compression and tension parallel to grain end up with the same value for $R_T = -1$ which is correct, since this is the same stress situation in both cases, having $\sigma_{max} = -\sigma_{min}$. For tension and compression perpendicular to grain, the curves do not end up with the same value for $R = -1$, and this is not satisfactory.

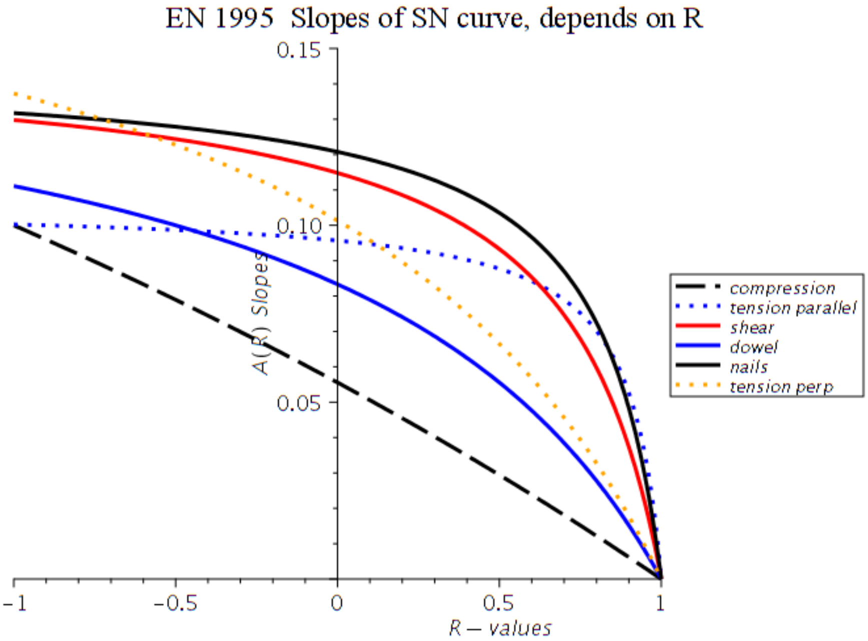

Figure 3: The slope parameter A for the EN 1995 S-N curves for various values of $R = R_T$.

2.4 Calibration of fatigue model for dowel connection

In Figure 4, the SN curves from EN 1995 for dowel connections for various R ratios are plotted. By reading the values for the various R ratios at a given number of cycles, for example 1 million cycles ($Log(N) = 6$), and plotting them in a constant life diagram, it will be visible how well they fit into a linear or nonlinear interaction between alternating and mean stresses.

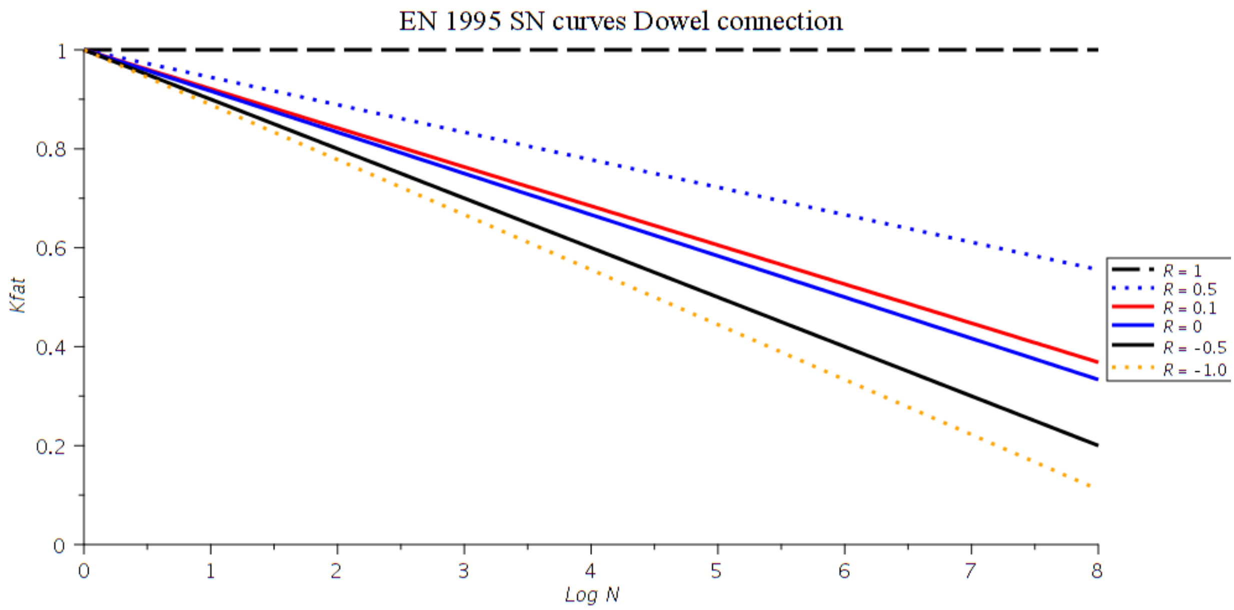

Figure 4: S-N curve for dowel connection

Few experimental test series have enough experimental results to cover the whole field of R values. For dowel connections with slotted-in steel plates, the experimental data used in the calibration are published in refs. [5] to [8], and depicted in Figure 5 and Figure 6. The slopes of the SN curves were determined to $A = 0.079$ and $A = 0.111$ for $R = 0.1$ and $R = -1$, respectively. Note that f_{max} is the available maximum relative strength based on mean values and has the same meaning here as the symbol k_{fat} used in EN 1995.

The maximum strength f_{max} (and k_{fat}) is a dimensionless parameter which relates the fatigue strength to the corresponding static strength and this strength should be compared to the maximum stress σ_{max}.

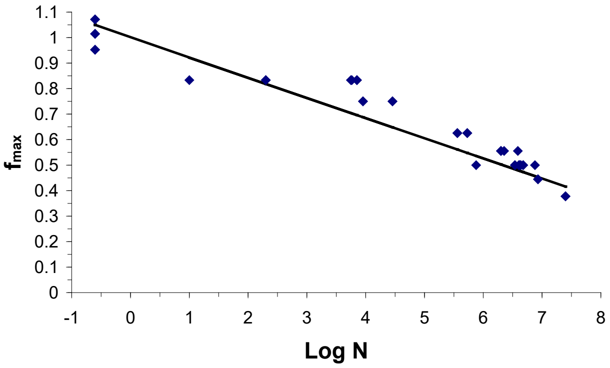

Figure 5: Maximum stress vs. cycles to failure, $R = 0.1$, EC5 compared to test results.

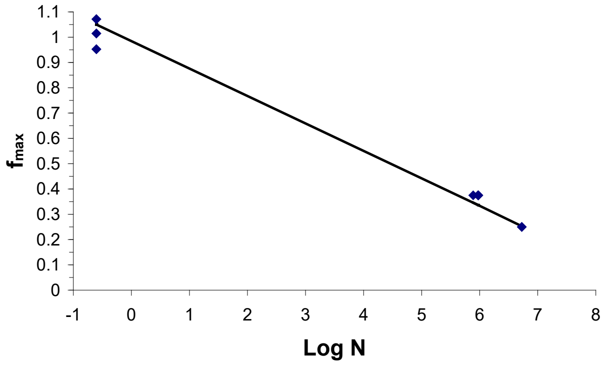

Figure 6: Maximum stress vs. cycles to failure, $R = -1$, EC5 compared to test results.

As an example on calibration, 1 million cycles ($Log(N) = 6$) will be used. For reversed loading $R = -1$, this gives

$$f_{max} = \frac{\sigma_{max}}{f_{mean}} = \frac{\sigma_a}{f_{mean}} \quad = 1 - 0.111 \cdot 6 \approx 1 - \frac{6}{9} = \frac{1}{3} \tag{15}$$

For loading with $R = 0.1$ is the following obtained

$$f_{max} = \frac{\sigma_{max}}{f_{mean}} = 1 - 0.079 \cdot 6 \approx 0.526 \tag{16}$$

and by use of Eq. (5):

$$\frac{\sigma_a}{f_{mean}} = 0.526 \cdot \frac{1}{2}(1 - 0.1) = 0.236 \text{ and } \frac{\sigma_{mean}}{f_{mean}} = 0.526 \cdot \frac{1}{2}(1 + 0.1) = 0.289 \tag{17}$$

Plotting this data into a linear constant life diagram (Goodman), the results show that a linear constant life diagram in this case fits the experimental results well.

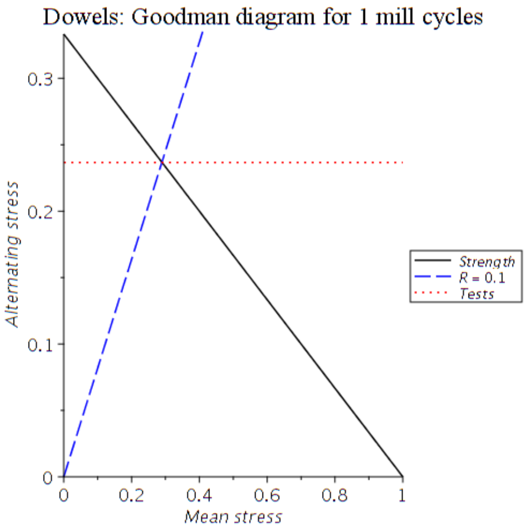

Figure 7: Constant life diagram for 1 million cycles for dowel connection

To generalize the results for other stress ratios $R = R_T$, we combine Eqs. (5) and (7), giving

$$\frac{\frac{1}{2}\sigma_{max}(1-R)}{f_a} + \frac{\frac{1}{2}\sigma_{max}(1+R)}{f_{mean}} = 1 \quad (18)$$

The strength for purely alternating load f_a is found by letting $R = -1$ and is determined by

$$f_a = f_{mean} \cdot (1 - A^* Log(N)) \quad (19)$$

where A^* means the slope of the SN-curve determined for $R = -1$. The maximum allowed stress σ_{max} is governed by

$$\sigma_{max} = f_{mean} \cdot (1 - A \cdot Log(N)) \quad (20)$$

Combining Eqs. (18), (19) and (20), the resulting equation is solved for A giving

$$A = \frac{(1-R) \cdot A^*}{2 - (1+R) \cdot A^* Log(N)} \quad (21)$$

Considering the expression for the generalized slope A, it is observed that it will not be possible to do this type of calibration independent of which number of cycles the calibration is made at. The slope A will always be dependent of the number of cycles used for calibration. If we choose to calibrate dowel connections at 1 million cycles, we will have $\text{Log}(N) = 6$ and $A^* = 0.111 \approx 1/9$, giving

$$A = \frac{(1-R)}{6(2-R)} \quad (22)$$

This result is identical with the use of Eq. (13) and the parameters for dowels in Table 1 and is the basis of the calibration performed for annex A in EN 1995-2 [1].

3 Results

In the following all calibrations given in EN 1995 are explored for various values of the stress ratio in the domain $-1 \le R_T \le 1$, and for various number of cycles to failure. The maximum stress σ_{max} is set equal to the fatigue strength and the alternating and mean stresses are calculated by Eq. (5) and plotted in a constant life diagram format.

3.1 Dowel connections

Considering Figure 8, the interaction line is straight for 1 million cycles, as it should be as this is the value used for the calibration. The calibration is probably satisfactory up to 10 mill cycles, but above it is obviously not working for all R_T ratios as the slope of the strength line then becomes positive. For smaller number of cycles, the calibration probably gives slightly conservative results as the curves appear somewhat concave.

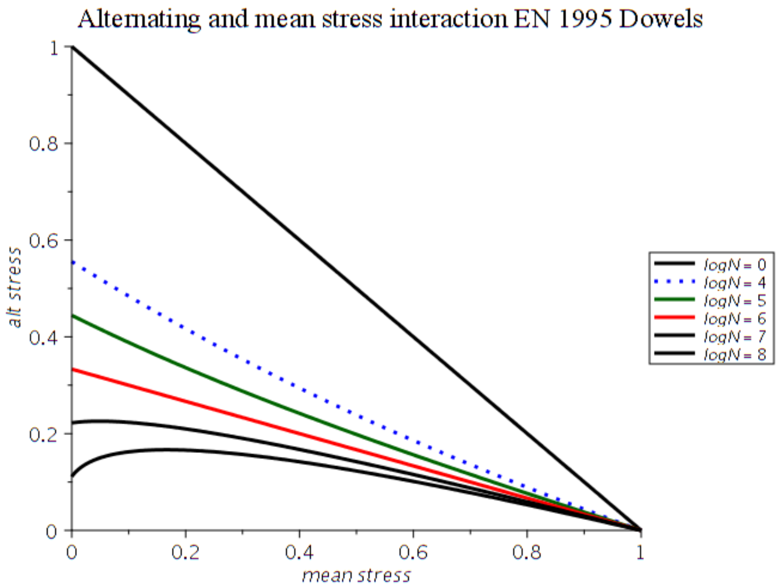

Figure 8: Constant Life diagrams for dowel connections

3.2 Compression parallel and perpendicular to grain

The calibration made for compression parallel and perpendicular to grain, see Figure 9, gives only a straight line for one cycle, while more cycles lead to convex curves. The calibration might be acceptable up to 100000 cycles for the full range of R_T, but above the calibration does not seem to work, at least not for the full range of the stress ratios.

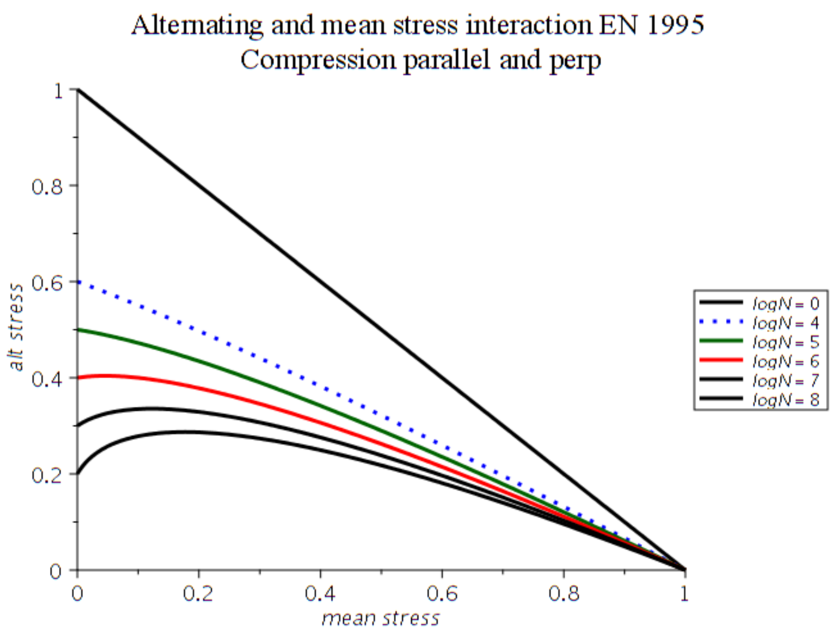

Figure 9: Constant Life diagrams for compression parallel or perpendicular to grain

3.3 Tension parallel to grain

The strength interaction curves are all strongly concave (except for one cycle) for tension parallel to grain, see Figure 10. It is noted that the calibration gives the same values as for compression parallel to grain for purely alternating loads ($R_T = -1$), as it should, as this loading situation is identical both for compression and tension. This property is also visual from the SN-curve plots for alternating loads ($R_T = -1$) in Figure 11, where the compression and the tension parallel curves practically coincide. However, it is hard to find any physical reason for the excessive concave shape of the strength curves in Figure 10 and this effect is likely to be caused by improper calibration or experimental data.

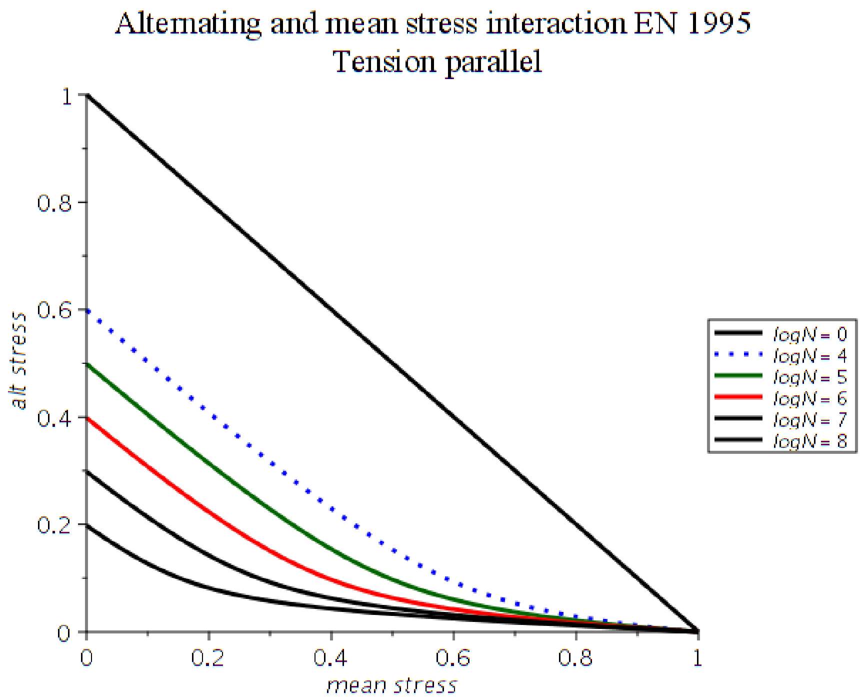

Figure 10: Constant Life diagrams for tensile stresses parallel to grain

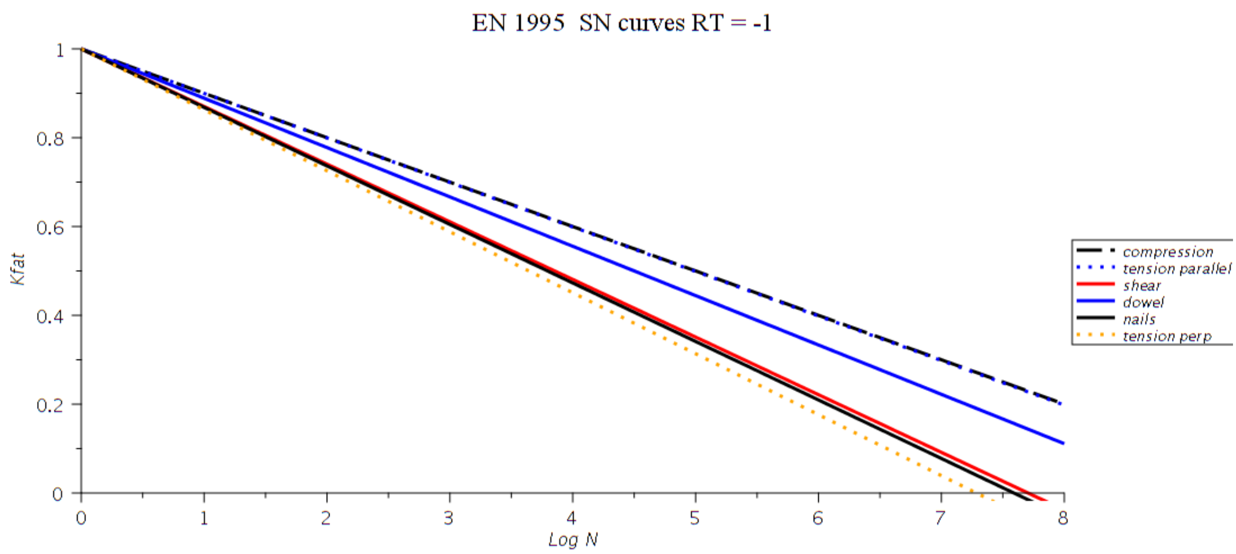

Figure 11: S-N curves for alternating loads $R_T = -1$ in EN 1995

3.4 Tension perpendicular to grain

By comparing the SN-curves for alternating loads ($R_T = -1$) in Figure 11, it is obvious that either the compression curve is not valid for $R_T = -1$, or the tension curve is not valid for $R_T = -1$, as purely alternating loads have the same stresses regardless of whether the stress quadrant is denoted compression or tension. Considering the strength curves in Figure 12, they are hardly valid for cycles above 100000 cycles, at least not for R_T values less than 0.5.

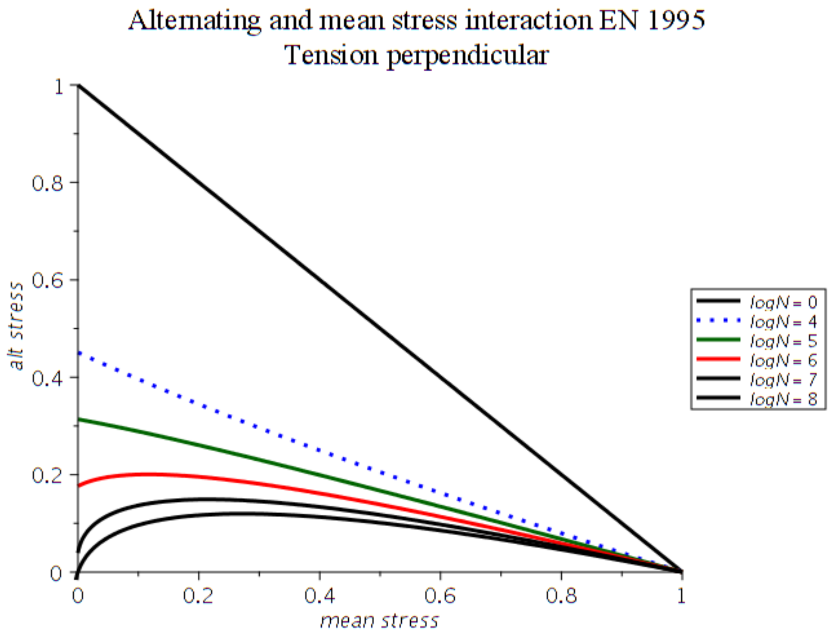

Figure 12: Constant Life diagrams for stresses perpendicular to grain

3.5 Shear

The strength curves for shear are presented in Figure 13. The calibration of fatigue shear strength seems inconsistent as they are strongly concave up to one million cycles. Probably, the calibration suffers from lack of consistent experimental results.

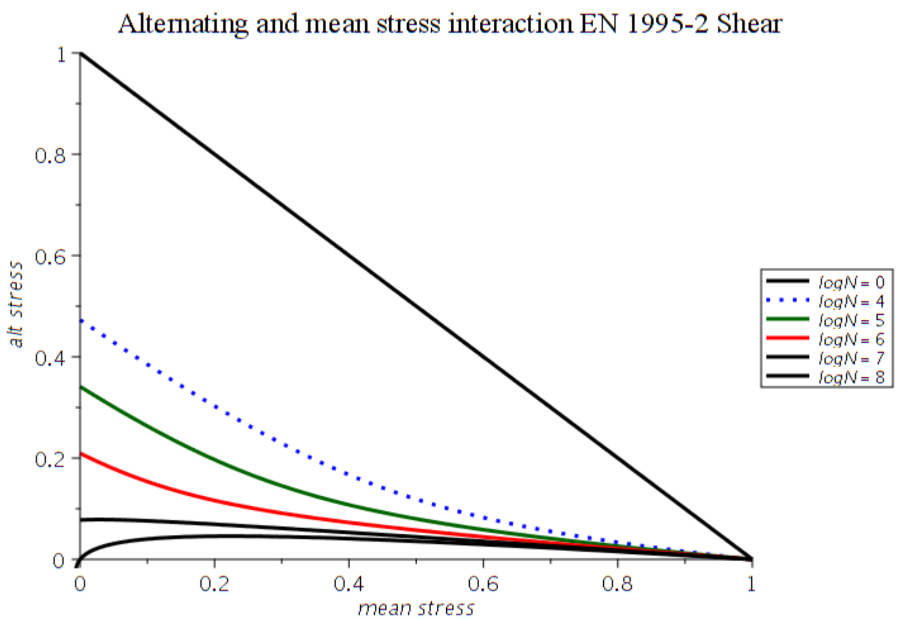

Figure 13: Constant Life diagrams for shear stresses

3.6 Nails

The strength curves for nails are presented in Figure 14. This calibration has approximately the same parameters as shear, and no further comments are made here.

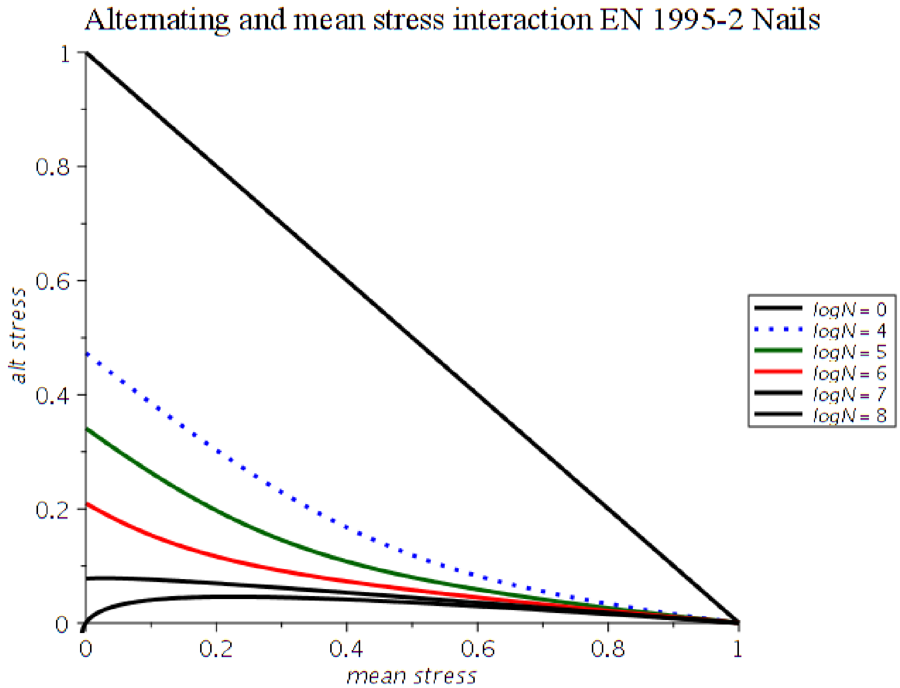

Figure 14: Constant Life diagrams for dowel connections

4 Concluding Remarks

Some aspects of the predictive rules for fatigue life of wooden structures in the present and future version of the Eurocode EN1995 have been explored and commented in the present paper. It has been shown that the general expression for determination of the slopes of the SN curves has limited generality and gives values which are obviously erroneous in some ranges. Especially for stress ratios R_T less than 0.5 and high number of cycles the fatigue strength appears to be wrongly estimated. Possible causes for this defect might be lack of experimental data, or calibration based on only a narrow band of stress ratios. A re-evaluation and possibly a recalibration of the strength parameters are recommended.

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