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Fatigue behaviour of composite girders with composite dowels assuming randomly distributed input parameters

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The fatigue design of shear connectors for composite girders is based on fatigue strength curves (with 95 % survival probability) derived from tests with one or just a few connectors. According to the Eurocodes, the lifetime of a girder can then be limited by failure of the shear connector with the highest fatigue utilization. The failure probability of a component is thus determined by the failure probability of one shear stud or composite dowel, although a composite girder is an internally highly statically indeterminate system with the capability of redistributing forces in the composite joint. This paper outlines how considering crack propagation, the residual capacity of shear connectors with cracks and the redistribution of forces towards less stressed and damaged connectors can have positive effects on the lifetime of a girder. The failure probability of a girder is determined by several Monte Carlo simulations using a simplified FE lamella model with incremental calculation of the degradation of the connectors. The input parameters with the greatest influence on the fatigue behaviour of the girder are evaluated. Furthermore, the results show the economic potential of a future global safety concept for composite girders, especially those with composite dowels.

Keywords composite dowels; fatigue; crack propagation; probabilistic design

1 Introduction

Statistics on German highway bridges show that almost 12 % of those bridges will need to be replaced in the short to medium term, since they are in a poor condition due to their age or increasing traffic loads [1]. In absolute numbers, more than 4000 bridges need to be rebuilt in the near future. Obviously, there is a great demand for safe, economical and durable bridge solutions that can also be erected quickly. In recent years, composite bridges have been built more and more often for the medium span range, fulfilling the aforementioned requirements very well [2]. Modern composite structures, especially in combination with high-strength materials, also offer promising solutions in terms of sustainability and material savings [3].

Owing to their favourable fatigue behaviour, composite dowels have been used more and more often [4] instead of the typical shear studs according to Eurocode 4 [5].

Composite dowels were introduced in Germany by way of a technical approval [6] in 2013 (extended in 2018), which expires in 2023. Currently, a European Technical Specification (CEN-TS) is in preparation to allow the continued use of composite dowels throughout Europe. This will certainly increase the number of bridges built with composite dowels. In Poland especially, numerous new bridges are already being built with composite dowels, some with innovative composite or hybrid cross-sections [7].

The current fatigue design concept for composite dowels is based on fatigue strength curves with a detail category up to 140, see section 2.1. Hence, composite dowels are often more favourable for fatigue design than shear studs. Nevertheless, the concept is based on the design of a critical shear connector, using a fatigue strength curve that indicates the 95 % survival probability of crack initiation determined from load-controlled model tests (with constant shear forces) on only one or just a few connectors. The fatigue design of the whole steel/concrete interface is broken down to the design of one critical connector. This circumstance disregards the fact that

- other shear connectors are still intact or have longer service lives, and
- crack growth at a connector leads to a decrease in stiffness and thus to a decrease in the shear force transmitted, provided surrounding dowels show less damage (displacement-controlled behaviour).

Excessively damaged connectors are thus unloaded and their service life is extended, provided the crack propagation phase is also considered. This applies, in particular, to composite dowels because of their phase until crack initiation, see Fig. 1.

The slip δ between steel and concrete (Fig. 1a) depends on the loading, the stiffness of the connectors and cross-sectional values. During the lifetime of a girder, the maximum slip increases due to inelastic concrete strains (creep effects) [8] and the decreasing stiffness of connectors with cracks. Whereas with headed studs crack initiation is assumed to occur with the beginning of the fatigue load [9], composite dowels have an additional phase of load cycles until cracks initiate (Fig. 1b, 1c). Assuming randomly distributed values for the number of load cycles N_{crack} until crack initiation, there will be cracked dowels with a redistribution of shear forces to adjacent uncracked dowels [10–12]. Other input parameters can also

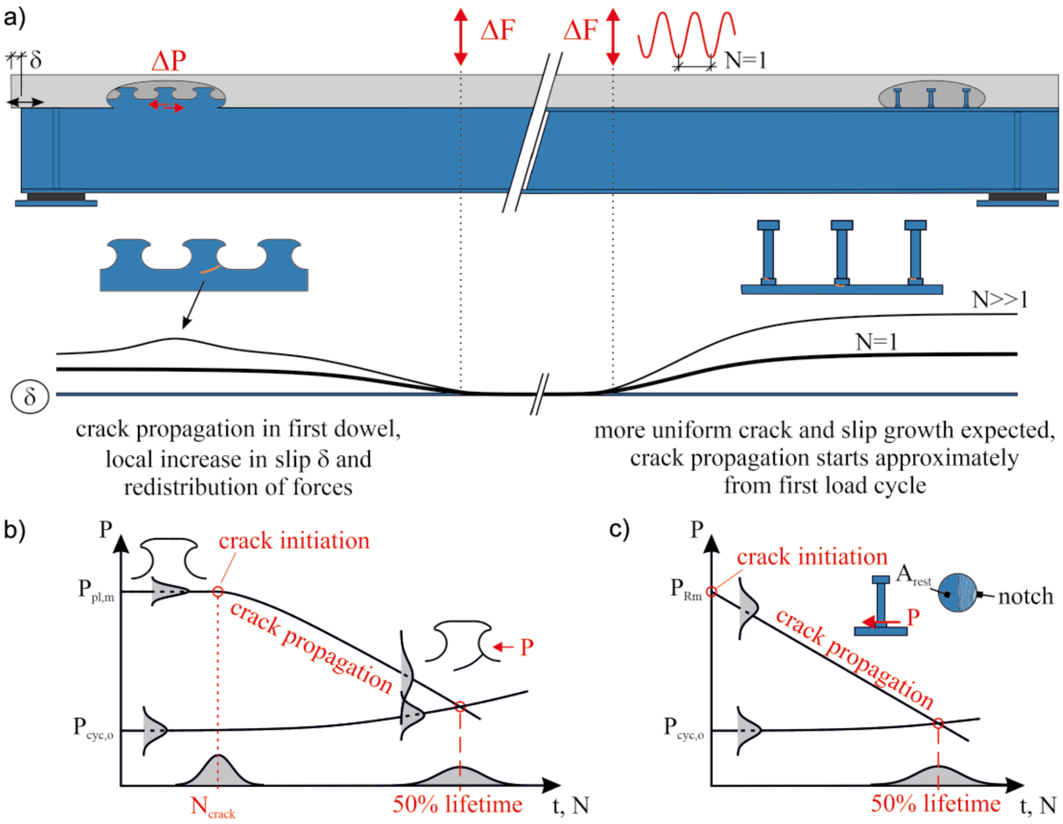


Fig. 1 a) Slip behaviour at steel/concrete interface due to inelastic concrete strains and crack propagation at shear connectors, and typical lifetime prediction for b) one composite dowel and c) one shear stud with fatigue crack growth [9]

be considered as randomly distributed values, e.g. steel capacity, location of crack initiation, rate of crack propagation, residual capacity and external loading.

This paper deals with a probabilistic view of the steel/concrete interface with composite dowels as a whole, considering randomly distributed input parameters and redistributing forces. The influence of single parameters on the fatigue behaviour of the whole girder is evaluated in several Monte Carlo simulations.

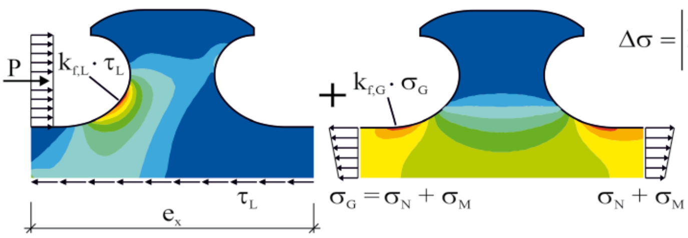
2 Fatigue behaviour of composite dowels

2.1 Fatigue design according to the German technical approval

The Wöhler curve for shear studs (detail category $\Delta\tau_c = 90$ N/mm^2 and $\Delta\sigma_c = 80$ N/mm^2 for a flange in tension, for rules of interaction see [13]) to apply the nominal stress concept from EN 1993-1-9 [14] was derived in [15] using the load cycles until the studs are sheared off. In contrast, no new detail category was derived for composite dowels and the fatigue strength curves for machine flame-cutting are used (category 125 without and 140 with post-treatment of the cut edge).

According to [6], a nominal stress range is calculated using stress concentration factors k_f, internal beam forces and cross-sectional values, see Fig. 2. Furthermore, the maximum cyclic load is limited to 70 % of the static characteristic capacity of the concrete dowel to avoid cyclic concrete failure in the form of a steady increase in inelastic slip growth up to concrete pry-outs, see [6].

This concept allows the hot-spot stresses due to local shear forces in the dowel (tensile stresses) and global notch effects due to bending and normal forces in the steel beam (usually compressive stresses in single-span girders) to be superposed despite their different locations.



$$\Delta\sigma = \left| k_{f,L}\cdot \underbrace{\frac{\Delta V\cdot S_y}{I_y\cdot t_w}}_{\tau_L}\right| + \left| k_{f,G}\cdot\left(\underbrace{\frac{\Delta N}{A}}_{\sigma_N} + \underbrace{\frac{\Delta M}{I_y}\cdot z_D}_{\sigma_M}\right)\right|$$

	$k_{f,L}$	$k_{f,G}$
clothoid shape	7.3	1.5
puzzle shape	8.6	1.9

Fig. 2 Principal tensile stress distributions due to local shear and global forces for clothoid-shaped dowels, stress concentration factors k_f for different dowel shapes and determination of the nominal stress range $\Delta\sigma$ according to [6]

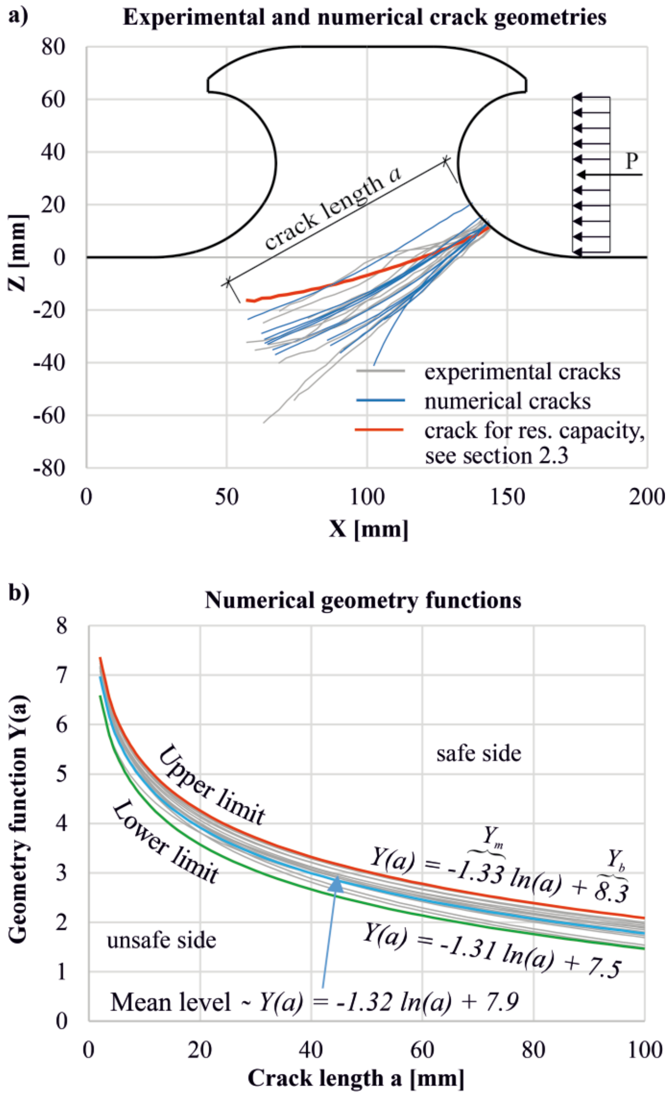


Fig. 3 a) Scatter of all crack geometries determined numerically and experimentally, and b) scatter of the 15 numerically determined geometry functions with limits [12]

Therefore, this concept lies well on the safe side and even the calculation of the phase until crack initiation can be optimized in the future. A more sophisticated evaluation of the crack initiation employing the strain-life approach is currently in preparation [16].

2.2 Crack propagation

The phase of crack propagation in the steel teeth of composite dowels was evaluated in a recent research project [10–12, 16]. Using well-known approaches from linear elastic fracture mechanics, experimental tests and numerical parametrical studies, a concept for calculating rates of crack propagation was developed, see Fig. 3.

In a medium load range, the rate of crack propagation can be determined using the Paris Law [18] with material parameters C and m.

$$da/dN = C \cdot (\Delta K)^{m} \tag{1}$$

where ΔK is the range of the stress intensity factor at the crack tip and parameter a is the crack length. In fracture mechanics, ΔK is usually calculated using nominal stresses $\Delta\sigma$ and geometry functions Y, which can be found in the literature, e.g. [19]. For composite dowels, the proposal is to use the nominal shear stress $\Delta\tau$, which can be determined by the dowel force ΔP, the dowel spacing e_x and dowel thickness t_w:

$$\Delta K = \frac{\Delta P}{e_x \cdot t_w} \cdot \sqrt{\pi \cdot a} \cdot Y(a) \tag{2}$$

Applying this approach, the geometry function $Y(a)$ was recalculated using calibrated FE models with incrementally increasing crack lengths a, where stress intensity factors can be output by the finite element software Abaqus [20]. The experimental cracks in Fig. 3a as well as automatically simulated cracks with different boundary conditions were evaluated to obtain the geometry functions in Fig. 3b. Effects of stresses due to global internal forces ($\Delta\sigma_N$, $\Delta\sigma_M$) are thus taken into account indirectly. The red curve can be seen as an upper limit for a design on the safe side, leading to faster crack propagation. The scatter of the functions will be considered as distributed values later in this paper, see sections 4.4 and 5.

2.3 Steel capacity and residual loadbearing behaviour

The steel capacity P_{pl} of composite dowels due to longitudinal shear can be calculated according to [6] and depends on the dowel spacing e_x, the dowel thickness t_w and the characteristic yield strength f_{yk}. The formula was derived from a determination of the critical cross-section, see Fig. 4a or [4] for further information.

$$P_{pl,k} = 0.25 \cdot e_x \cdot t_w \cdot f_{yk} \tag{3}$$

In simplified numerical simulations, using elastic material for concrete, ideal elastic-plastic material behaviour for steel (with f_{yk} as the yield strength) and pure shear loading as a boundary condition, it can be shown that the maximum shear forces fit almost perfectly with Eq. (3). The simulation was then repeated for different crack lengths using the red crack path of Fig. 3a [12]. Fig. 4b shows the results of these simplified numerical simulations.

$$P_{pl}(a) = \psi(a) \cdot 0.25 \cdot e_x \cdot t_w \cdot f_{yk} \tag{4a}$$

$$\text{with } \psi(a) = -0.0088a + 1 = -1.766\frac{a}{e_x} + 1; \frac{a}{e_x} \leq 0.5 \tag{4b}$$

In the recent project, test specimens with cracks up to a = 90 mm still failed due to concrete pry-outs because a low rotational stiffness of the cracked steel tooth led to a punching force acting on the concrete cover. The experimental validation of the residual steel capacity and the influences on the concrete capacity will be part of future research.

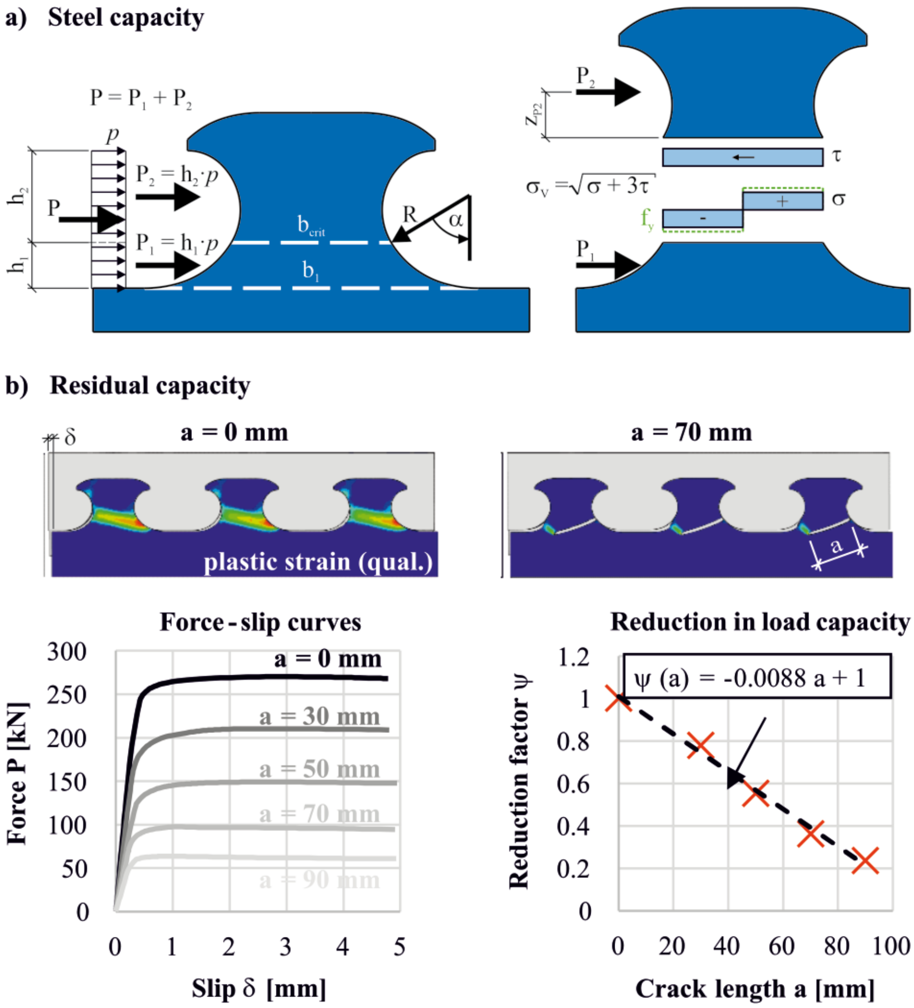


Fig. 4 a) Approach for determining the longitudinal shear strength due to steel failure according to [6], and b) reduction factor for residual loadbearing capacity derived numerically with ideal elastic-plastic material behaviour (steel) for clothoid-shaped dowels, $e_x = 200$ mm

3 Probabilistic design

3.1 First-order reliability method (FORM)

Reliability theory is usually classified into five levels 0 to 4 depending on the degree of accuracy and complexity. The semi-probabilistic safety concept of the Eurocodes with the application of partial safety factors and combination factors corresponds to level 1 of this classification. More complex and exact methods are level 2 (probabilistic approximations), level 3 (probabilistic “exact” solutions) and level 4 methods (with additional optimization; level 0: deterministic concept with global safety factor).

In the semi-probabilistic concept, the two randomly distributed variables “action” (stress S) and “resistance” (R) are evaluated via a limit state equation Z, where $Z < 0$ means failure.

$$Z = R - S, \text{ or better based on density functions:} \quad f_Z(x) = f_R(x) - f_S(x) \qquad (5)$$

The probability of failure P_f is equal to the area or integral of $f_Z(x)$ for $x < 0$.

Several methods have been developed for the evaluation of the limit state equation, whereby the first-order reliability method (FORM, level 2) with a limit state equation linearized at the design point is probably the most common method. The method can always be applied when a limit state equation is given. The number of randomly distributed values in this equation is not limited. Regarding fatigue, probabilistic approaches for the calculation of the residual lifetime of steel bridges exist in the literature [21]. An example is shown in Eq. (6), considering distributed values for loading (Weibull distribution with collective H and shape coefficient ν), fatigue resistance ($\Delta\sigma_D$, N_D, m) and damage parameter (Palmgren-Miner rule with failure at D_{limit}).

$$Z = D_{limit} - \frac{\Gamma(m/\upsilon)}{ln(H)^{m/\upsilon}} \cdot \frac{H}{N_D} \cdot \left(\frac{\Delta\sigma_{max}}{\Delta\sigma_D}\right)^m \qquad (6)$$

Eq. (6) can be adopted for a connector at the steel/concrete interface, the decreasing forces could be considered by H and ν, but it is not possible to consider sequence effects along the steel/concrete interface, the additional crack propagation phase or interaction effects between steel and concrete. Therefore, incremental calculations considering the whole steel/concrete interface are used instead in the following sections.

3.2 Monte Carlo method

As seen before, the FORM provides a limit state equation for a certain failure mode. If a problem is too complex and no limit state equation is given, numerical simulations can be performed with distributed input parameters. By repeating the simulation several thousand times (each simulation with new random input values), it is possible to estimate the distribution of an output, e.g. the number of load cycles until an abort criterion is reached.

In the Monte Carlo method (MCM) in its original meaning, the probability of failure P_f for a given load or load cycle number is calculated by the quotient of simulations where the failure criterion is reached divided by the total number of simulations [22]. This basic idea or method is complicated by the small probabilities of failure required for building structures. A first estimation of simulations N needed for a requested failure probability P_f with an error in estimation α is given in Eq. (7) [22]. For very small failure probabilities, e.g. $P_f = 10^{-5}$, correspondingly very high numbers of simulations are necessary, e.g. 10^7 simulations for a 10 % error in the estimation of P_f, 10^9 simulations for 1 %. This entails a high computational effort and requires very fast simulations.

$$N = \frac{1 - P_f}{P_f \cdot (\alpha\,[\%]/100)^2} \tag{7}$$

There are more sophisticated methods such as the importance sampling method, which is an MCM with randomly distributed values near the design point, but here it is difficult to estimate the failure probability since the quotient mentioned above (N_{fail}/N) must be weighted appropriately. In this paper a more practical way is used by determining the distribution of the output value "Number of load cycles until failure N_{ab}" after thousands of simulations, see section 5. For a given number of load cycles, the safety factor β can then be estimated.

4 Lamella model and input parameters

4.1 The model

The need for and importance of fast simulations for gaining thousands of simulation results and an estimation of the distribution of a result parameter with an acceptable computational effort was shown in the previous section. The use of 3D FE calculations is therefore almost impossible, at least at the present time.

For investigations of the complex interactions between steel girder, concrete slab and shear connectors in combination with the degradation of the steel/concrete interface due to fatigue loading, a beam-spring lamella model has been developed with Matlab. Steel girder and concrete slab are discretized as beam elements, and both can be divided into an arbitrary number of lamella over the depth, see Fig. 5. A division into several lamella leads to an increased calculation time, but increases the accuracy and enables subsequent investigations of the residual loadbearing capacity of the beam assuming plastic material behaviour for the steel beam and concrete slab. Over the length, the lamella are connected with stiff coupling elements at the same spacing as the connectors. Each composite dowel or row of shear studs can be modelled by a non-linear spring element, which has information about current crack length a, stiffness, residual capacity, inelastic concrete deformation and other factors. Several input parameters are summarized in Fig. 5 and section 4.2. The focus in this paper will be on composite dowels only. Approaches for shear studs can be found in [22, 23].

In the Matlab code the basic input information about girder length, cross-sectional values and positions of shear connectors is translated into the beam-spring model shown in Fig. 5. Therefore, nodes with two translational and one rotational degree of freedom are introduced and connected by 1D beam or spring elements. An element stiffness matrix is created for each beam, spring and coupling element and assembled into a global stiffness matrix K. The external loads are input as nodal forces into a load vector p. The deformation vector u is calculated considering the boundary conditions, Eq. (8), see [10].

$$\underline{K} \cdot u = p \Leftrightarrow u = \underline{K}^{-1} \cdot p \tag{8}$$

The deformation vector u contains all translational and rotational node deformations. The internal forces in the beam elements can be calculated using the deformations of both nodes of an element and the element stiffness matrix. Furthermore, the slip and shear forces at each shear connector are calculated by evaluating the spring elements. More information about this method can be found in [10]. In contrast to FE simulations with volume elements, e.g. using Abaqus, the calculation can be completed in less than a second, depending on the discretization. This allows for incremental calculations in steps of ΔN load cycles, where crack propagation and redistribution of forces can be considered over time or load cycle number.

4.2 The input parameters

At the beginning of a fatigue simulation, fixed or distributed values are assigned to each spring element. The parameters can be set as local random values (for each dowel) or global random values (for the girder in each simulation). Input parameters that can be described by mean value and variance for composite dowels in the Monte Carlo Method are:

- Material properties such as the yield strength of steel f_y for the steel capacity of the steel teeth, see Eq. (3).
- Paris Law material parameters C and m_{Paris} for the rate of crack propagation, see Eq. (1).

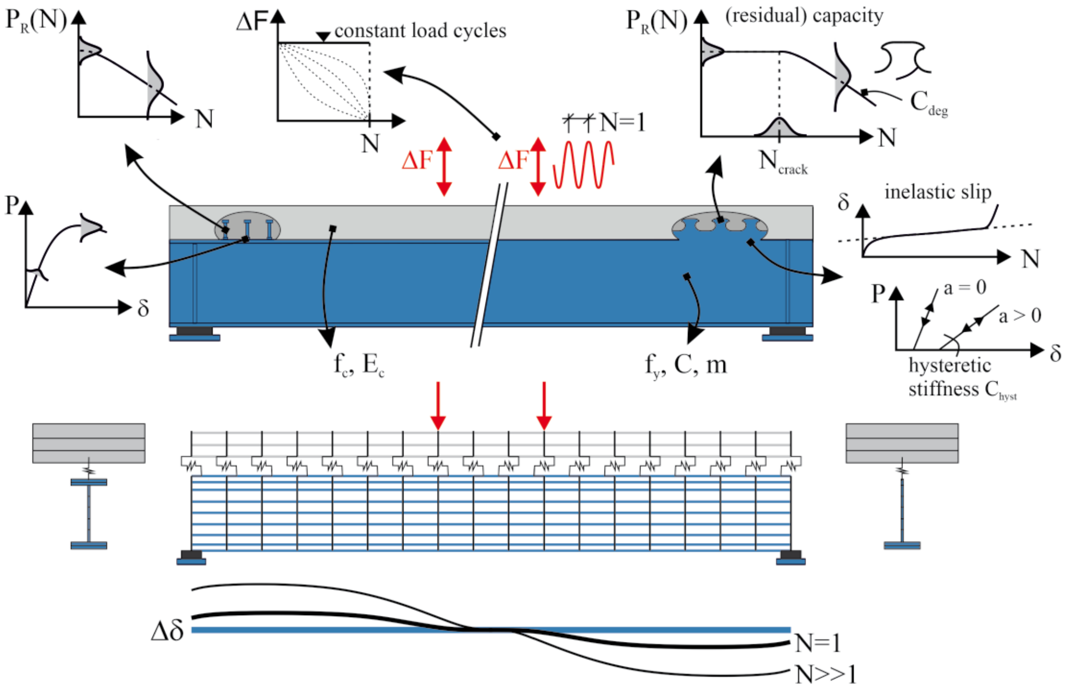


Fig. 5 Input parameters to be considered in the beam-spring lamella model of the composite girder

- Fatigue strength properties until crack initiation such as the Wöhler exponent $m_{\text{Wöhler}}$ and the base value of a distributed Wöhler curve $\Delta\sigma_D$, see Eq. (6).
- Model uncertainty of the Palmgren-Miner rule via a randomly distributed value D_{limit}, see Eq. (6).
- Geometry function parameters for $Y(a)$ to calculate the stress intensity factors ΔK, see Fig. 3b and Eq. (2).
- Hysteretic stiffness of a dowel C_{hyst} for the spring stiffness in the model.
- Reduction in the steel capacity C_{deg} due to increasing crack length, see Eqs. (4a) and (4b).

The fatigue behaviour of concrete (increasing slip due to creep effects and pulverization of concrete in front of the steel teeth) will be implemented in the future. Furthermore, the loading is assumed to be deterministic and constant for all simulations. The implementation of varying loads or even axle loads crossing the girder is also easily possible but not considered here. Instead of – or alternative to – the fatigue strength curves, the strain-life approach will be implemented as a next step for the determination of crack initiation.

4.3 The calculation procedure

Slip and dowel forces are calculated for each incremental load cycle number $N+\Delta N$ and each connector. After crack initiation, when a dowel has reached its (random) D_{limit}, Eqs. (1) and (2) are used to calculate the additional crack length Δa caused by ΔN. Stiffness and residual capacity are calculated depending on the current crack length in each dowel. The calculation continues in steps of ΔN until an abort criterion is reached. This can be defined in different ways:

- A critical crack length a_{crit}
- Reaching the residual capacity in one dowel
- Reaching the shear capacity of the whole composite joint
- Reaching the moment capacity of the composite girder (increasing partial shear connection)

The number of load cycles until an abort criterion is reached N_{ab} is saved to a list. After thousands of fatigue simulations, the distribution of N_{ab} is determined approximately, see section 5.

4.4 Example of a fatigue simulation with mean values

The lamella model was validated against experimental girder tests. In three girder tests, three steel teeth were notched with a handsaw at their hot-spot to achieve a quick and targeted initiation of crack growth. As already mentioned, the investigations focused on the crack propagation phase. Crack gauges were fitted in front of the notch to measure the first 5 mm of crack propagation. Further information about testing and validation can be found in [12].

Fig. 6 shows the results of a fatigue simulation with fixed (mean) values. The notches were considered by setting the crack length a to 1 mm from the first load cycle at dowels 3 to 5 on both ends of the girder. For other dowels, the damage until crack initiation is calculated using the Palmgren-Miner rule with $D_{\text{limit}} = 1$.

External load cycles $\Delta F = 120$ kN are applied. According to the fatigue concept in [6], this would lead to a design value of 2 million load cycles until crack initiation, which

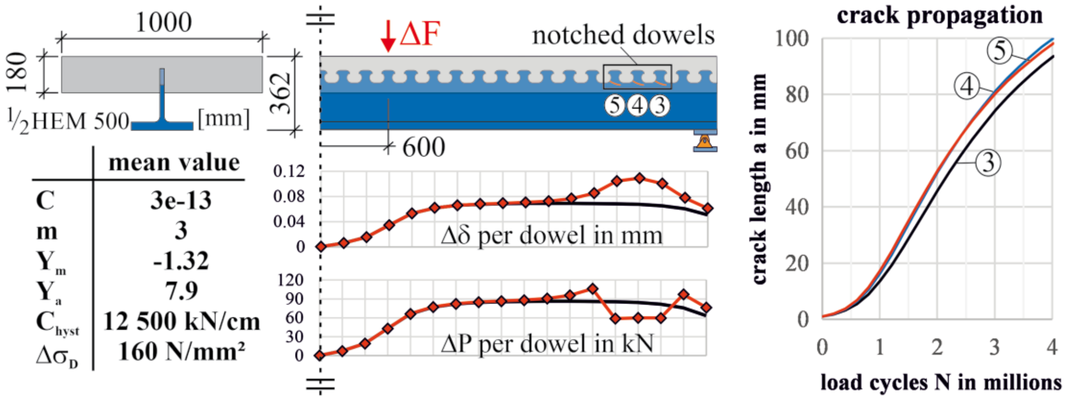


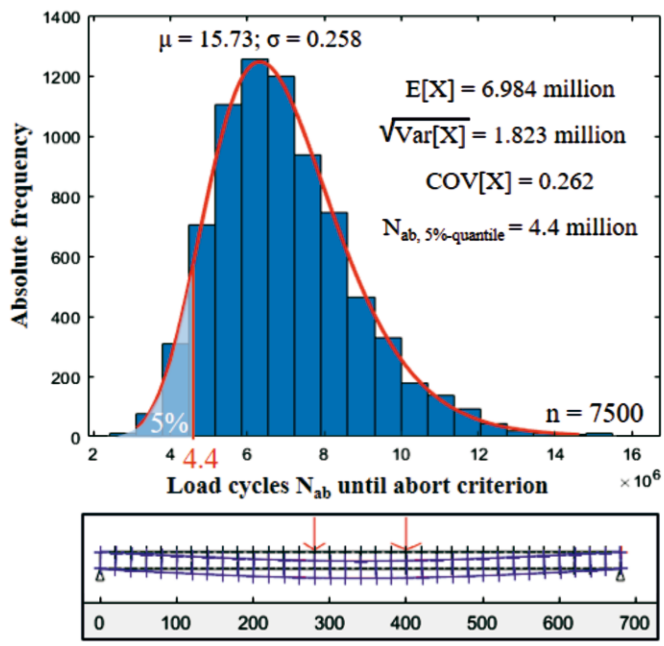
Fig. 6 Girder of length 6.8 m under four-point bending loading for parameter studies, with composite dowels and three notched dowels at each end following the experimental tests; mean values for input parameters leading to hysteretic slip $\Delta\delta$ and shear forces ΔP (black: first load cycle; red: last load cycle) and development of crack lengths for the three dowels

in [6] is considered as termination of lifetime. The abort criterion is set to a critical crack length of 100 mm in one dowel. The example in Fig. 6 shows a crack propagation phase of 4 million further load cycles until the critical crack length is reached. Considering crack initiation and propagation, the service life of the girder is tripled. Furthermore, Fig. 6 shows the redistribution of shear forces from cracked to adjacent dowels. The slip grows locally, see also Fig. 1a, while the forces decrease with increasing crack lengths. As seen in the experimental tests with strain gauges fitted at the hot-spots, dowels 1, 2, 6 and 7 carry higher forces, leading to a constant sum of shear forces. This simulation and the result for N_{ab} can serve as a reference for the Monte Carlo simulations in the next section.

5 Probabilistic simulations of the fatigue behaviour at the steel-concrete interface

One fatigue simulation with elastic beam elements and elastic but degrading spring elements takes about 2–3 s. In the model it is possible to consider reinforcement in zones with concrete in tension. Additionally, inelastic behaviour can be considered. In that case, however, iterative calculations are necessary, which is more time-consuming and requires greater computational power. These functions are neglected in the following studies because of concrete in compression and load cycles in the elastic range.

For a probabilistic study or Monte Carlo simulation described in section 3.2, the girder described in section 4.4 and Fig. 6 was simulated without notches and with randomly distributed input values, see Fig. 7. In 7500 simulations, the Paris parameters C and m, the stress intensity factor via the geometry function $Y(a)$ (Y_m and Y_b, see Fig. 3b) and the gradient of the stiffness degradation C_{deg} were considered as the randomly distributed values shown in the table in Fig. 7. A crack length of 100 mm was again chosen as the abort criterion. The load cycles N_{ab} until the critical crack length is reached exhibit a log-normal distribution with an expected value of about 7 million load cycles and a coefficient of variation of 0.262. These results allow other quantiles to be determined, e.g. the 5 % quantile at 4.4 million load cycles. Compared with a lifetime of 2 million load cycles when using the traditional approach [6], this is a considerable improvement. In other words, there are significant fatigue reserves that have not been utilized so far.



parameter	distribution	μ	σ	COV
C	lognorm.	3e-13	6e-14	0.2
m	determ.	2.88	0	0
Y_m	normal	-1.325	0.005	0.004
Y_b	normal	8.1	0,1	0.012
C_{deg}	normal	0.56	0.01	0.018

Fig. 7 Statistical distribution and evaluation of the number of load cycles until the abort criterion N_{ab} is reached for the example calculation (7500 simulations) with assumed distributions of the input variables [12]

The method works very well, but the critical points are reasonable assumptions of the input values: mean value, coefficient of variation (COV), type of distribution and correlation between two or more parameters. For realistic

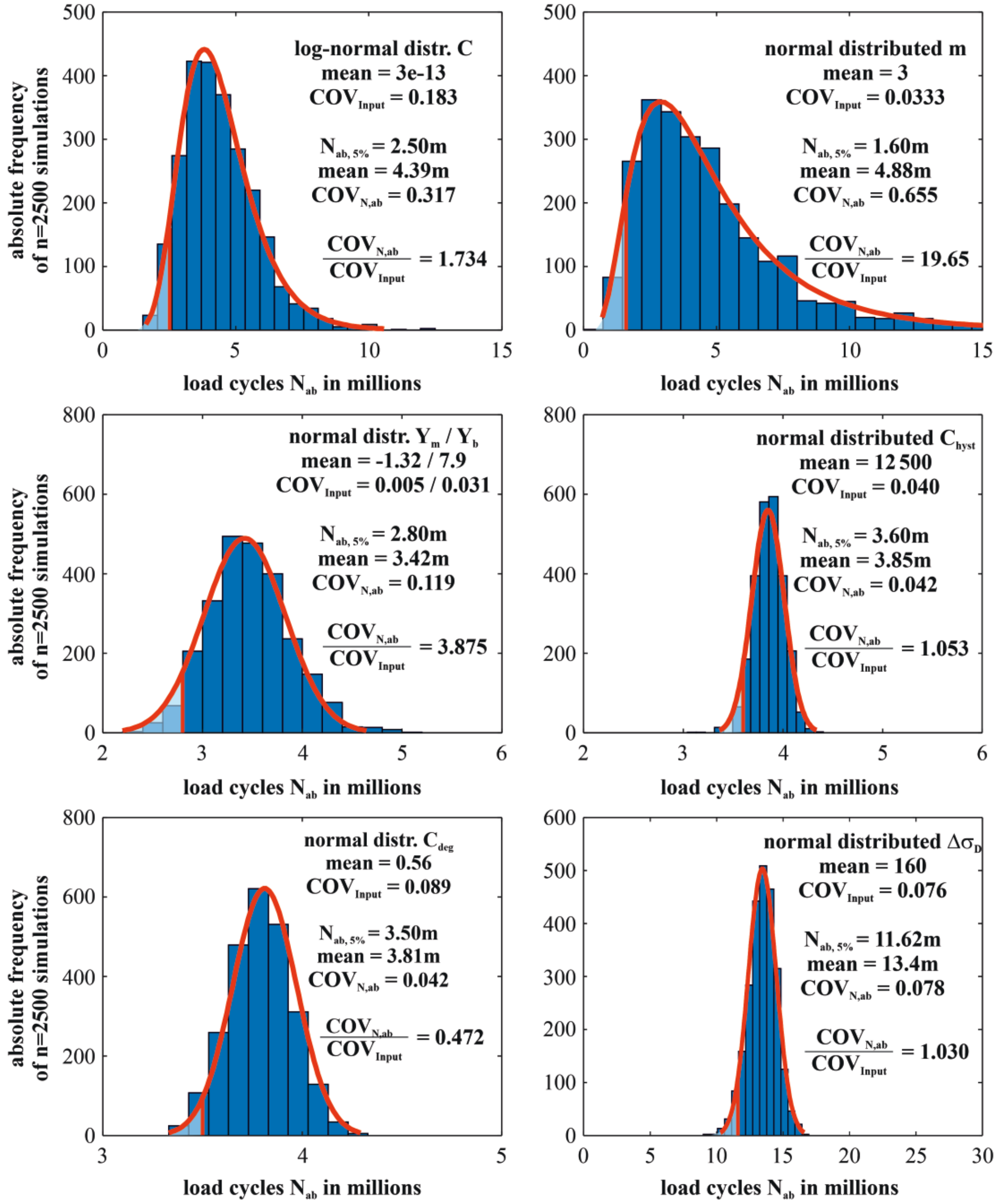


Fig. 8 Results of Monte Carlo simulations for different influence parameters with load cycle number N_{ab} until the abort criterion "critical crack length 100 mm" is reached; comparison of coefficients of variation (COV) for N_{ab} and input parameter to show effects of distributed input parameters

assumptions, the experimental database for composite dowels is still too small.

Nevertheless, the lamella model is very useful for checking the significance of single input values. Therefore, each individual input parameter was checked using 2500 incremental simulations with randomly distributed values, whereas others were taken to be deterministic. Only Y_m and Y_b were as assumed to be fully correlated. The COVs of input and result distribution were then compared. Fig. 8 summarizes the results of several Monte Carlo simulations. A quotient of 1.0 shows that the distribution of the input parameter leads to a similar COV of load cycle numbers until "failure". Quotients > 1.0 indicate an increase in the effects of random input parameters. The most important findings of these MC simulations are:

– The Paris parameter m has a huge influence on the results. Even a small COV leads to a large range of results. The COV of N_{ab} is 20 times higher than the variance of input m. In [25], m is assumed to be deterministic, which is helpful for calculation but still questionable. The parameter C has a lower but significant influence on the results.
– The geometry function *Y(a)* has a big influence too. Therefore, the function must be chosen carefully for manual calculations.
– The other input parameters (hysteretic stiffness C_{hyst}, gradient of stiffness degradation C_{deg} and base value of Wöhler curve $\Delta\sigma_D$) show less influence.

Future studies will concentrate on reasonable values for C and m, extending the experimental database for the geometry function Y and the development of new abort criteria mentioned in section 4.3. As mentioned in section 4.2, concrete degradation, the strain-life approach and axle loads will be implemented as well. Effects on the global behaviour of the steel-concrete interface will then be checked in similar Monte Carlo simulations. Finally, the method can be used for a probabilistic design of the whole composite girder including all degradation effects and redistribution along the steel-concrete interface.

6 Conclusions and outlook

Experimental tests and numerical studies have confirmed a favourable fatigue behaviour for composite dowels. Compared with shear studs, they have the advantage of a significant phase until crack initiation with subsequent crack propagation. Another factor is that the current fatigue design in the Eurocodes and the technical approval does not account for the probabilistic effect of the number of shear connectors combined with the internal load redistribution effects during damage processes in studs or dowels. Traditional design is based on a single connector and its probability of failure, and neglects other connectors that are still intact. However, considering the whole composite shear gap along the beam with possibilities to redistribute shear forces from damaged to undamaged connectors will lead to a more realistic fatigue design associated with clear economic benefits.

Using the example of a composite section, probabilistic studies and Monte Carlo simulations have shown that lifetime improvements exceeding a factor of 2 can be achieved while maintaining the target safety level. Such simulations can be considered as a first step towards estimating the influences of the input values and will help to develop a new design concept. This concept must be determined in further probability studies. Therefore, the experimental database has to be widened in the future. Questions about inelastic concrete strains under variable loads plus the residual steel and combined steel-concrete capacity of cracked dowels will be investigated.

Acknowledgements

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