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Fatigue strength of axially loaded steel rods bonded in European ash glulam

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Abstract

Bonded-in profiled rods are among the most efficient fasteners in modern timber construction. Especially under axial loading, they are characterised by high load-carrying capacity and high stiffness. In addition, connections with steel rods can be designed to exhibit ductile failure, so that the brittle failure modes of wood in connections and reinforcements are excluded. For bridges, fatigue can be a critical ultimate limit state. Starting from the desired design value of a rod in practice, in this paper the required load level for the typical connection configuration is derived. Based on experiments, it is shown how the undesired mixed failure modes can be avoided. The effect of the loading frequency and the corresponding temperature rise in the specimen are presented and discussed. The results of the experimental campaign confirm the appropriate performance of the bonded-in rod system under the tested conditions.

1 Introduction

1.1 Background

The GSA Technology is a practice-proven system for bonding steel rods with metric thread into timber members. The German Technical Approval (Z-9.1-778) as well as the European Technical Assessment (ETA-19/0752) confirm the suitability of the applied epoxy adhesive (EPX) and provide confidence in the practical application of these high-performance joints to all parties involved in a project. Both approval documents mention softwoods as substrates and load-bearing structures with mainly static loading as the scope of application. The reason for these restrictions is that no fatigue tests had been carried out during the development of these approvals and fatigue design rules for such type of connections are missing in the currently applicable standards (e.g. EN 1995).

For structures or structural components that are frequently exposed to cyclic loading with large amplitudes, fatigue verifications are required. It shall be verified that no failure or major damage occurs due to fatigue, i.e. the weakening of the bond or any component caused by cyclic loading. Various verification methods are described in literature and some of them have found their way into standardisation, for example into the Swiss standard SIA 265:2003 [1] and into Eurocode 5 (EN 1995-2:2004 [2] and later versions). The methods differ considerably, especially with regard to involving different parameters in the design equations: For instance, the verification method in SIA 265 is based on the stress range whereas the one in EN 1995-2 uses stress ratios and maximum stresses. The latter procedure is nowadays, considered more suitable and reliable for timber structures [3]. An overview of this verification method can be found in the papers of the recent ICTB [4]. For the interested reader, publications [5] and [6] (in German) are also recommended. In the current version of Eurocode 5 [2], the fatigue coefficients (*a* and *b*) are specified only for connections with dowel-type fasteners. From published work within the project "TACITUS" it can be concluded that an extension of the verification method to bonded-in rods is possible [7].

In December 2019, the first fatigue tests on specimens with bonded-in rods applying the GSA Technology were successfully conducted at the Structural Engineering Research Laboratory of the Swiss Federal Laboratories for Materials Science and Technology, Empa. Specimens with identical end grain connections made of 2 steel rods with metric thread M16 bonded into European ash (*Fraxinus excelsior*) glulam were tested in a pull-pull setup. In this first test series, the rods were pre-stressed against the end grain with a controlled torque. With this procedure and by using duplex stainless steel threaded rods, the specimen could be subjected to $2{\cdot}10^6$ stress cycles without occurrence of fatigue failure. The frequency of the sinusoidal loading was increased step by step starting from 5 Hz. Finally, most of the cycles were tested at a frequency of 12 Hz, which led to a welcome reduction of the test duration. One specimen was even subjected to 50'000 stress cycles both at frequencies of 15 and 20 Hz. The four temperature sensors installed in the bond lines (one on each rod) recorded only moderate temperature rises of less than 2 °C throughout the test duration. In the summer of 2021, further specimens were tested at the Empa. Besides the omission of the pre-stressing, the edge distances and spacings were slightly reduced. The objective of these tests was to investigate the performance of the GSA adhesive and to compare it with test results published in literature.

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1.2 Failure modes

The design approach in EN 1995-2:2004 is considered appropriate to design for fatigue of wood itself. Difficulties are encountered, however, in the case of combined wood and steel configurations. Depending on the failure mode - wood failure or steel failure - different types of verification apply (Figure 1). In the given example, the failure mode changes from wood to steel failure in the range of 10^4 to 10^5 stress cycles.

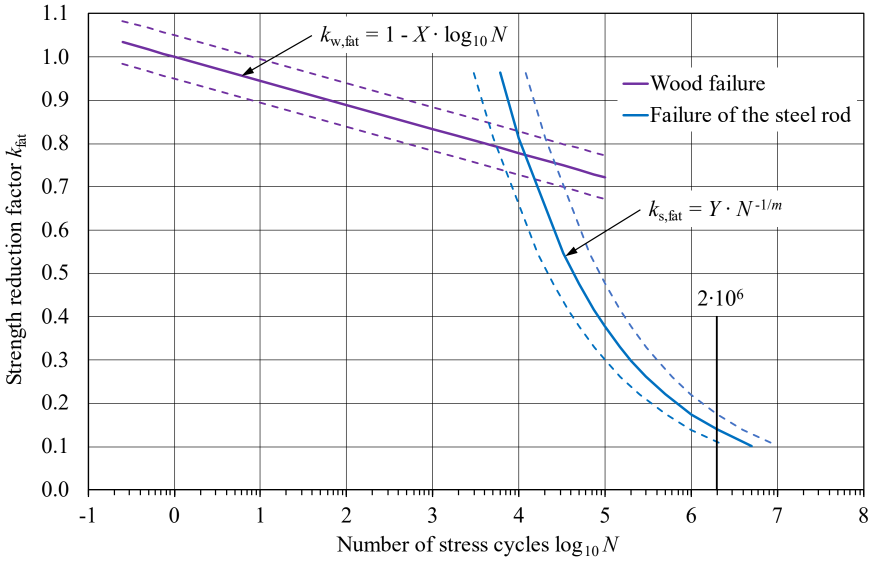


Figure 1: Strength reduction factor for fatigue loading k_{fat} considering two different failure modes

For lower numbers of stress cycles, **pull-out failure of the bonded-in rod** occurs; with EPX bonding, i.e. shear failure in the wood. According to the design approach in EN 1995-2:2004, the decrease in load-carrying capacity can be described as a linear function of the logarithm of the number of stress cycles (Figure 1). The parameter X is a function of the stress ratio R ($= F_{min,fat} / F_{max,fat}$), of the configuration of the structural element or connection and of the wood species. Its definition is identical with the slope parameter A according to [4].

With higher numbers of stress cycles, a **fatigue fracture occurs in the threaded steel rod**; the decrease in load-carrying capacity can be described here as a function of the difference in force or stress $\Delta\sigma_{fat}$, which is also called the stress range. The common approach for fatigue design of steel members is adopted here. In this case, the parameter Y is a function of the shape of the thread i.e. the sharpness of the indentation (which is different for cut threads, and cold-rolled or warm-rolled threads), the configuration of the structural element or connections, as well as the mechanical properties of the steel (grade). In steel design (e.g. [8]), usually a value of 3 is adopted for the parameter m in stress ranges below $5 \cdot 10^6$ stress cycles.

By optimising the connection and test parameters, the range of stress cycles where wood failure changes to steel failure can be shifted, e.g. up to about 10^7 stress cycles. This makes a separate evaluation of the two failure modes possible.

1.3 Target values

The design of the specimens was based on the characteristic withdrawal resistance $F_{w,k}$ of 100 kN for a GSA fastener M16 bonded in hardwood parallel to the grain. Hardwood was chosen because with an identical configuration, significantly higher forces can be applied here than in softwood and thus the bond line is subjected to higher stresses. The high strength of the rod material used requires a substantial reduction of the cross-section to ensure ductility in the ultimate limit state. Based on the rod's tensile strength of $f_u = 1000$ N/mm² determined in tests, a reduced diameter of 11.5 mm ($A_C = 104$ mm²) would be chosen for practical applications. According to standard SIA 263 [9], this would result in a design load-carrying capacity of $F_{t,Rd} = 74.8$ kN of the steel rod. The design value of the withdrawal resistance would therefore still be decisive with 100/1.5 = 66.7 kN and a smaller steel cross-section would therefore be possible. Assuming a partial factor of $\gamma_Q = 1.5$, the rod could be expected to be able to carry a variable live load of almost 45 kN. For the configuration to be tested, this results in the target load value of 45 kN per rod. For the stress ratio R a value of 0.1 was chosen. This ratio is considered to be relevant in practice for a lightweight structure with a large cyclic live load. In addition, this choice allows a comparison with results from literature [7]. The target value for the test duration was fixed at $2{\cdot}10^6$ stress cycles, because steel design codes also refer to this number for defining their detail categories [8], usually.

2 Material and method

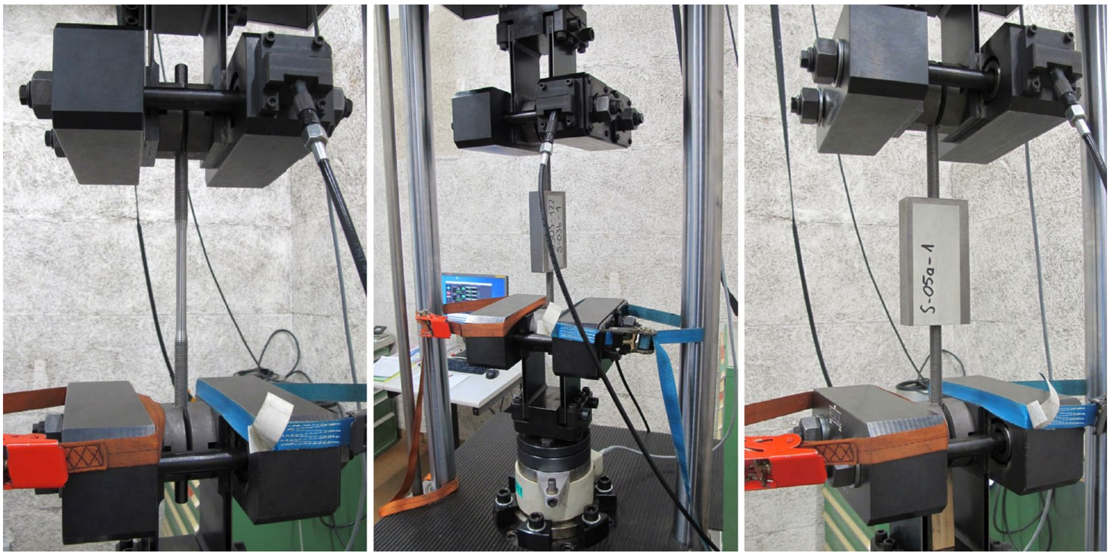
2.1 Tests on steel rods and internal threads

By previously determining the factor Y (Figure 1), mixed mode failures in the main test series should largely be avoided. Therefore, a first test series was carried out on pure steel specimens without adhesive bonding. In order to determine the fatigue strength, the "Mechanical Systems Engineering" laboratory at the Empa carried out single-step fatigue tests and load increase tests on M16 threaded rods and their connection to a steel part. (Figure 2).

Figure 2: Steel specimens; connection with internal thread (top) and machined threaded rods (bottom)

For the connection, a metric internal thread was chosen, which was cut into the narrow side of a 30 mm thick plate made of steel S355J2. The threaded rods made of duplex stainless steel were machined to a defined diameter over a certain length in accordance with the building practice when bonding-in according to the standard of the GSA Technology [10]. This zone, called "constriction zone" was 110 mm long with linear transitions to the full rod diameter over a length of 15 mm on both sides. Specimens with constriction zones of three different diameters (11.5 mm, 12.0 mm, 12.5 mm) were prepared. Finally, only the specimens with the smallest constriction diameter were tested because these three specimens already exceeded all expectations. Also in terms of connections, four different variants were planned to be tested. But even here, the most economical option already provided satisfying results.

For the fatigue tests, an electrodynamic high-frequency resonance testing machine ("HFP") of type Russenberger, *Rumul Testronic 8601.11-1* (150 kN) was employed. The machine has hydraulic grips ("Hydrogrip") in which the ends of the threaded rods of the specimens were clamped directly. Stainless steel shims were used to apply the external load evenly via shear to the threads of the M16 threaded rod. The free length between the 80 mm long grips was 270 mm. Figure 3 shows three different specimens during the fatigue tests under cyclic tensile loading.



(a) (b) (c)

Figure 3: Installed specimens; (a) threaded rod machined to ø11.5 mm, (b) connection "S-03b-1", (c) connection "S-05a-1"

Three threaded rods with a machined centre zone were tested. The stress ratio R (= $F_{\min}$ / $F_{\max}$) was kept constant at a value of 0.2 and the frequency was about 72 Hz for all specimens of this series. For the first specimen, the maximum load $F_{\max}$ was increased by 5 kN every 10^6 stress cycles (block programme). A total of $4{\cdot}10^6$ stress cycles with a final maximum load $F_{\max}$ of 65 kN were imposed to this specimen. The two other specimens were tested at this highest load level up to $5{\cdot}10^6$ stress cycles. The duplex stainless steel of these threaded rods thus carried a tension-tension stress range $\Delta\sigma$ of 500 N/mm².

The first connection tested was specimen “S-03b-1” with a conservative thread length. After this specimen had survived 10^6 stress cycles to $F_{\max}$ = 65 kN with R = 0.2, the specimens detailed as considered optimal were installed. Three specimens were tested to 10^6 stress cycles under identical loading. As the threaded rods no longer had any constriction, the load can be related to the stressed cross-section A_s of 157 mm², resulting in a stress range $\Delta\sigma$ of 255 N/mm². Here, the frequency was around 80 Hz.

Another specimen was successfully tested during $5{\cdot}10^6$ stress cycles with $F_{\max}$ = 50 kN and a reduced stress ratio of R = 0.1. Finally, again a block programme was defined for specimen “S-05a-1”. This started with $F_{\max}$ = 55 kN. Again, the maximum load was increased by 5 kN every 10^6 stress cycles, at a constant stress ratio R of 0.1. After a total of $5{\cdot}10^6$ stress cycles with a stress range in the last block of $\Delta\sigma$ = 430 N/mm², this test was also completed without failure.

During these tests, the temperatures of the specimens were monitored periodically with an infrared thermometer (especially in the clamping area and at the internal threads). A temperature rise could have been an indication of frictional fatigue or friction corrosion. The temperatures generally remained below 50 °C. The maximum of 56 °C was measured during the second test on a machined rod.

2.2 Tests on rods bonded in European ash glulam

For the tests on bonded-in rods, four identical specimens were designed and produced. They were made of European ash glulam of strength class GL40h. The ash (*Fraxinus excelsior*) lamellas were graded with the Timber Grader MTG (device for strength grading of wood based on the determination of the dynamic modulus of elasticity from the measurement of the eigenfrequency and the density) in such a way that the moduli of elasticity and the densities of the specimens had a uniform distribution. Two threaded rods M16 were bonded in parallel to the grain direction of the wood, according to the standard of the GSA Technology into both end faces of the glulam members, each consisting of four bonded lamellas. The adhesive used was a 2-component EPX resin and the drill hole diameter was 18 mm. The bond length was 290 mm (i.e. $16.1{\cdot}d_{\text{drill}}$) with a recess (not bonded length) of 70 mm. To apply the force from the testing machine to the specimen, 30 mm thick steel plates of grade S355J2 were used. The connection detail to the two threaded rods corresponded to the previously tested variant (see section 2.1). In addition, the specimens had two holes each, which allowed the installation of temperature sensors into two bond lines. The geometric dimensions of the specimens are shown in Figure 4.

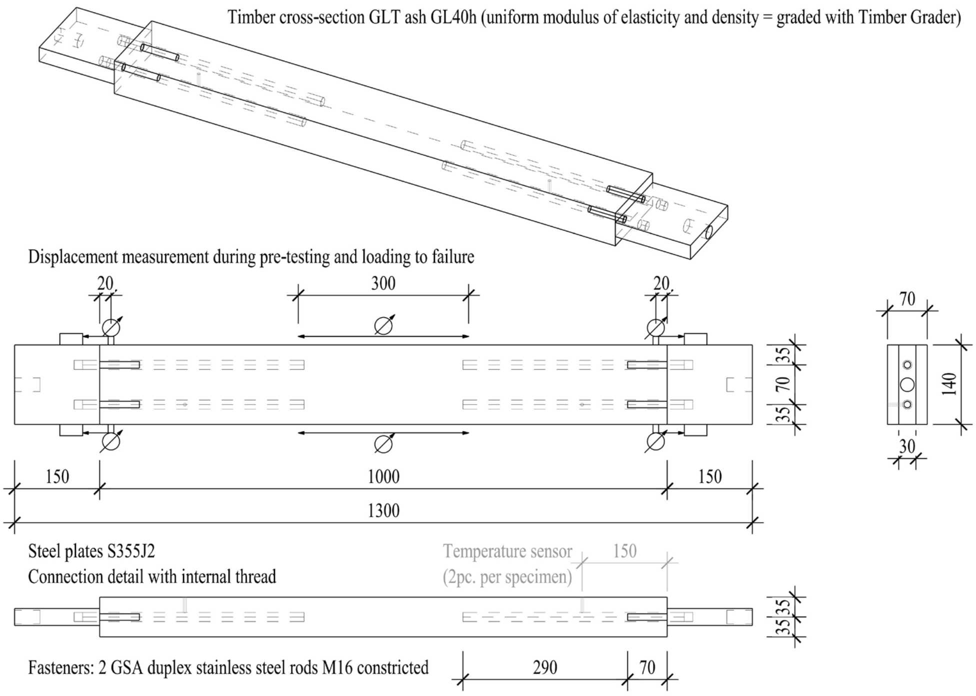


Figure 4: Design and dimensions (in mm) of the four timber specimens subjected to fatigue testing

The specimens were produced by the neue Holzbau AG (n'H) and then proof-loaded almost to their characteristic withdrawal resistance (185 kN) in order to confirm proper production and curing. In this pre-testing, the displacements depicted with a ∅ symbol in Figure 4 were measured. The static modulus of elasticity of the timber was determined based on the measurement in the centre of the member. Then the Structural Engineering Research Laboratory of Empa carried out the main series of tests. For this purpose, a servohydraulic fatigue testing machine of type Walter & Bai, *LFV-500* (500 kN) was used. The machine has hydraulic grips in which the steel plates are directly clamped over a length of 90 mm. The displacements in the direction of the longitudinal axis of the specimens were recorded by the crosshead gauge installed in the testing machine (stroke). In addition to the readings of the climate logger in the hall (air temperature and relative humidity), a third temperature sensor was placed near the testing machine.

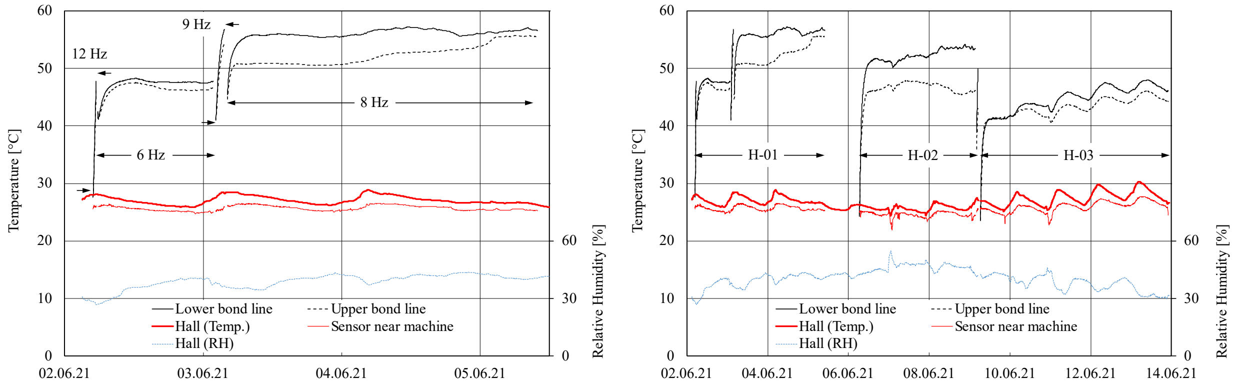
Of the four test specimens, three could be tested within the available (time) budget. Initially, each specimen was statically loaded in tension up to the maximum load $F_{\max}$ of 100 kN (loading rate 2 kN/s, force-controlled) in order to determine the stiffness of the system. For the following fatigue tests, a sinusoidal waveform with constant amplitude and a stress ratio R of 0.1, with force-controlled loading was applied. Looking at the cross-section area of the constriction zone ($2 \cdot A_C = 265$ mm²), this resulted in a tension-tension stress range $\Delta\sigma$ of 340 N/mm². The specification for the frequency was: As high as possible without however, provoking the temperature in a bond line to exceed 55 °C.

After successful fatigue testing, one specimen was finally tested to static tension failure by the n'H at their own laboratories. The specimens “H-01” and “H-03” were cut open after the fatigue test to evaluate the state of the bond lines. Based on the central part of each specimen, the density was determined and two samples were taken to assess the moisture content of the wood using the kiln-drying method.

3 Results and discussion

3.1 Frequencies and temperatures

For the first specimen “H-01” with GSA rods bonded in ash glulam, the loading frequency was initially set to 12 Hz. However, as shown in Figure 5a, within short time (i.e. 30 minutes) a considerable temperature rise occurred in the bond lines, and hence, the frequency was halved for the next phase (i.e. 6 Hz). After a total of about 455’000 stress cycles, the frequency was increased to 9 Hz. In this phase, a ventilator was placed on the floor next to the testing machine in order to cool the specimen. Since the desired effect did not occur and the temperatures continued to rise, the ventilator was removed after a while. Due to a new excessive rise of the temperature in the bond lines, the frequency was set to 8 Hz after a total of approximately 505’000 stress cycles.



(a) (b)

Figure 5: Temperatures in the bond lines and in the ambient air, as well as the relative humidity of the air in the testing hall as a function of time; (a) specimen “H-01”, (b) compilation of all specimens

For the specimen “H-02”, the frequency of 8 Hz was adopted and maintained throughout the $2 \cdot 10^6$ stress cycles. The fatigue test had to be restarted shortly before its end because a breakdown of the power supply of the hydraulic pumps had occurred. The curves of the temperature measurements in the bond lines therefore show a second rise. Because these values in the second specimen were around 50 °C, a frequency of only 5 Hz was chosen for testing specimen “H-03”. Here, the variation in ambient temperature was clearly visible in the temperatures measured in the bond lines. Reducing the loading frequency by 3 Hz led to a

5 °C lower average bond line temperature (48.3 °C in H-02, 43.3 °C in H-03), although the ambient temperature was considerably higher during the third test. The temperatures recorded by the sensor next to the machine were on average 1.2 °C higher, the testing hall was on average 1.8 °C warmer. These differences, however, are in the range of the precision in temperature measurements.

3.2 Ultimate resistance and stiffness

The moduli of elasticity derived from the displacement measurements in the preliminary tests are shown in Table 1. The determination of the ultimate tensile force F_u after the fatigue test showed no change in the measured static modulus of elasticity of the timber E_{timber}. The specimen failed in a brittle mode at a force of 246 kN, which is 23 % above the characteristic value found in static short-term tests of GSA rods bonded in hardwood. Since the constriction diameter of 13.0 mm chosen for the fatigue tests was intentionally not designed to get ductile failure, the observed failure mode, i.e. pull-out failure and splitting of timber, was as expected.

Table 1: Properties and number of stress cycles in fatigue testing for the specimens made of European ash glulam

Label	Density [kg/m³]	MC [%]	E_{timber} [N/mm²]	Number of cycles, N	F_u [kN]
H-01	702	8.0	15’000	2’054’712	not determined
H-02	679	7.7	13’000	2’010’000	246
H-03	696	8.2	16’900	2’010’000	not determined

The crosshead stroke rose with increasing number of stress cycles, whereas the measured displacement developed consistently with the temperature of the bond lines. The effect of the temperature is superposed by the different stiffnesses of the timber members (Figure 6).

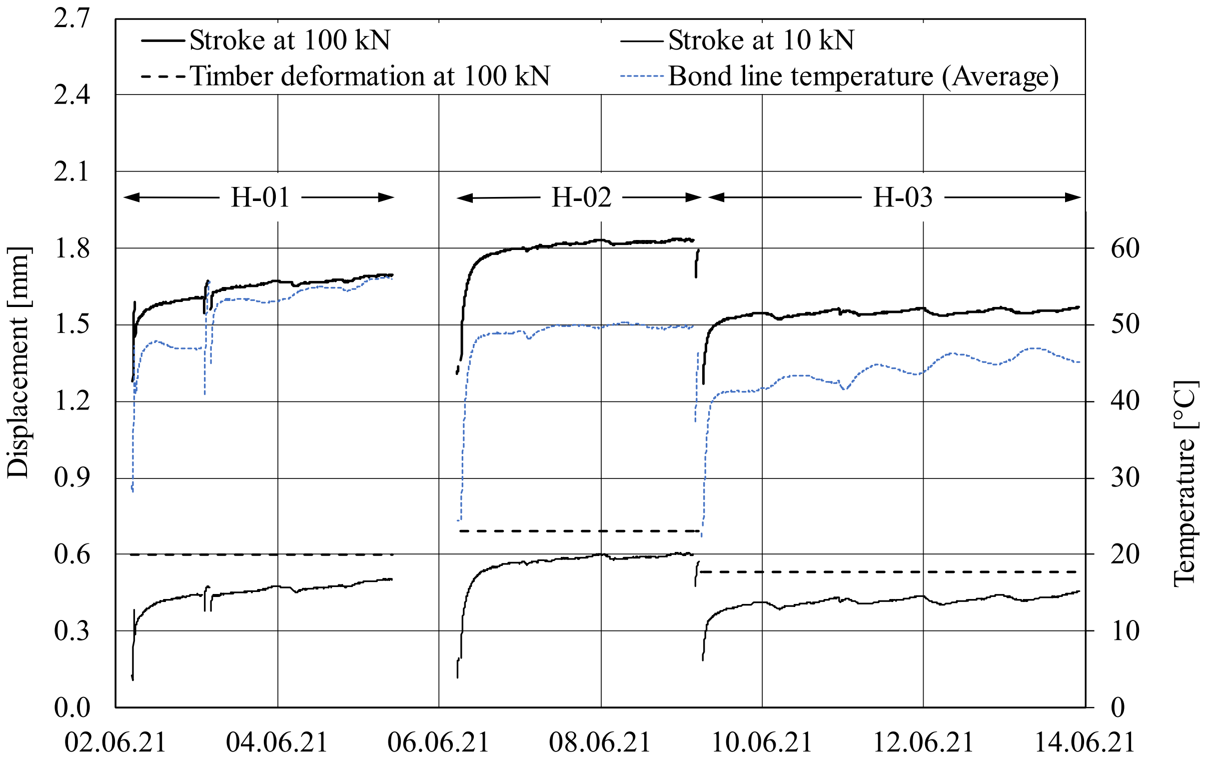


Figure 6: Crosshead stroke and average of the bond line temperature as a function of time; all specimens with displacement share of the timber member

These differences are not large enough to explain the differences between the specimens. Therefore, an attempt was made to model the measured crosshead strokes by shares of linear-elastic displacement in steel and timber. In addition, the temperature rise of the threaded rod was taken into account with a constant thermal expansion coefficient. Figure 7 shows that this worked well for the specimen “H-03”. On the other hand, the specimen “H-02” shows a difference between the measured values and the analytical model, which is similar for the minimum and the maximum load. Heating the bond lines to about 50 °C seems to cause an additional, small, but irreversible displacement share. This displacement very likely originates from the adhesive.

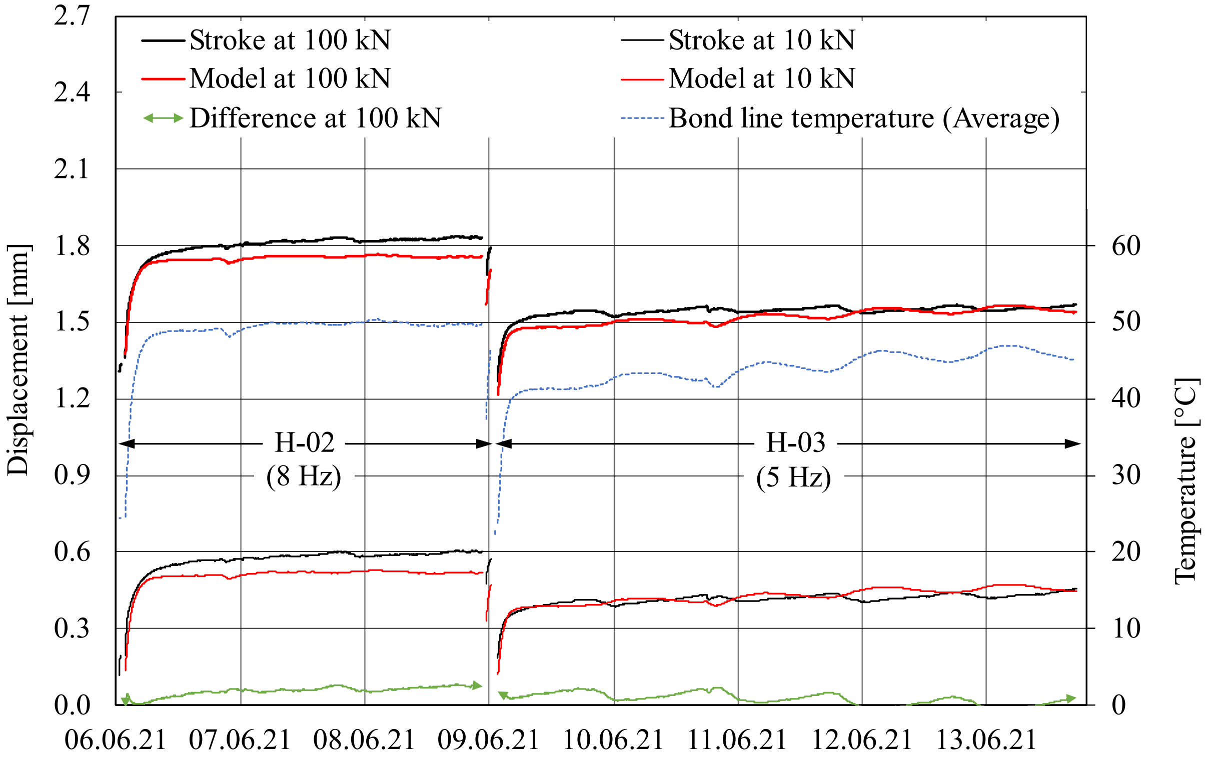


Figure 7: Crosshead stroke and average of the bond line temperature as a function of time; specimens “H-02” and “H-03” with analytical stiffness model

In the visual inspection of the specimens after the fatigue test, a gap between the steel plate and the end grain was noticed on specimen “H-02”. On the third specimen, such a gap was only barely apparent.

3.3 Fatigue strength

The tests carried out on machined threaded steel rods, internal threads and rods bonded in European ash glulam did not lead to fatigue failure in any case. Because only one load level with one stress ratio was tested, a relationship valid for design can hardly be derived from this investigation. However, a comparison with the “Inoxripp” proposal according to Myslicki et al. [7] shows that the performance of the tested system is well within the range of other test results (Figure 8). In the past, comparisons of fasteners were made based only on the slope of the curve describing the strength reduction factor k_{fat} [4]. Graphing the test data in form of axial load-carrying capacity per rod reveals that the slope parameter X should always be rated in conjunction with the quasi-static resistance $F_{\mathrm{w,k}}$. In addition, the various differences in the connection configuration, such as the area of the bonding surface A_{b}, have to be taken into account. The question might be raised if the extrapolation based on a tested bond line shear strength as usually done in common design methods is conservative enough with regard to fatigue. The results of the present investigation are considered to be more reliable in this respect, because the tested configuration (bond length, edge distance, etc.) and the chosen pull-pull setup correspond very closely to the actual reality in building practice.

Figure 8 also shows possible fatigue resistance curves of the steel components in the connection. To represent the threaded rods made of duplex stainless steel, a value of 5 was chosen for the parameter m. For comparison, a curve is drawn as it could apply for a threaded steel rod of grade 8.8. This curve corresponds to the detail category 50 according to Eurocode 3 [8]. For the GSA Technology, the stress cross-section of the threaded rod A_{s} is replaced by the cross-section area of the constriction A_{C}. For both rod types, a value for A_{C} was assumed that is deemed a realistic value for building practice.

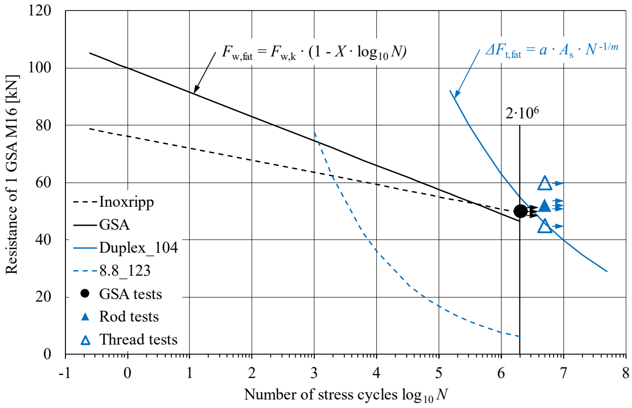


Figure 8: Fatigue resistance of an axially loaded GSA M16 in hardwood also considering the steel components (R = 0.1)

Table 2: Parameters of the curves describing the fatigue resistance

Curve	$F_{w,k}$ **[kN]**	X **[-]**	A_b **[mm²]**
Inoxripp	76.16	0.056	10’050
GSA	100.00	0.085	16’400

	a **[-]**	A_C **[mm²]**	m **[-]**
Duplex	9.62	104	5
8.8	6.30	123	3

4 Conclusion

The experimental investigation presented in this paper was intended as a contribution to the development of a practical verification method for connections with bonded-in profiled rods in timber structures subject to fatigue loading. Suitable threaded rods and an appropriate connection detail with regard to the steel part could be found, allowing passing fatigue tests with more than $2 \cdot 10^6$ stress cycles without failure. Loading frequencies exceeding 5 Hz caused the bond line temperatures to rise above 45 °C. This is considered unfavourable because it resulted in irreversible displacements suggesting assuming that changes in the adhesive occurred due to elevated temperatures. Nevertheless, the stiffness of the connections remained very high during the entire tests. The final loading to failure in a static test also indicated a high consistency of the load-carrying capacity. The results of this investigation provide additional arguments that the GSA Technology is very suitable for the realisation of reliable and durable structures also in the case of fatigue loading.

5 Acknowledgement

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