TRANSIENT TEMPERATURE EVOLUTION IN GLULAM WITH HIDDEN AND NON-HIDDEN GLUED-IN STEEL RODS

TRANSIENTE TEMPERATURENTWICKLUNG IN BRETTSCHICHT-HOLZ MIT VERDECKT UND NICHT VERDECKT EINGEKLEBTEN STAHLSTANGEN

EVOLUTION TRANSITOIRE DE LA TEMPERATURE DANS DU LAMELLE COLLE COMPORTANT DES GOUJONS COLLES EN ACIER, APPARENTS OU NON

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SUMMARY

A recently terminated European research project on glued-in steel rods in timber structures (GIROD) – with participation of Timber Department of Otto-Graf-Institute – revealed a strong strength reducing influence of elevated temperatures, not expected to that extent. This affects especially the duration of load behavior of the connections. The maximum temperature level acting in service on the glued-in rod connections thus sets performance requirements on the shear modulus-temperature relationship and on the glass transition temperature of appropriate adhesives.

Today’s prevailing intuitive conviction of practitioners is, that rods bonded hidden in the interior of glulam cross-sections experience, due to the low thermal conductivity and specific heat of wood, considerable lower temperatures compared to ambient climate. The paper gives some experimental and computational results proving, depending on cross-sectional width, only a moderate reduction of peak temperatures combined with a pronounced phase shift vs. ambient temperature varying roughly sinusoidally during a day.

ZUSAMMENFASSUNG

Ein kürzlich abgeschlossenes Europäisches Forschungsvorhaben betreffend in Holz eingeklebter Stahlstangen (GIROD) – mit Beteiligung des Fachbereichs Holz des Otto-Graf-Instituts – zeigte einen in dieser Ausprägung nicht erwarteten großen festigkeitsmindernden Einfluss erhöhter Temperaturen. Dies beeinflusst insbesondere auch das Zeitstandverhalten der Verbindungen. Das maximale Temperaturniveau, das im Gebrauchszustand auf Verbindungen mit eingeklebten Stangen einwirkt, definiert somit Leistungsanforderungen an die Schubmodul-Temperaturbeziehung und an die Glasübergangstemperatur geeigneter Klebstoffe.

Die heute in der Praxis vorherrschende Meinung ist, dass verdeckt in das Innere eines Brettschichtholzquerschnitts eingeklebte Stangen infolge der niedrigen Wärmeleitfähigkeit und Wärmekapazität von Holz beträchtlich niedrigeren Temperaturen im Vergleich zum einwirkenden Umgebungsklima ausgesetzt sind. Der Aufsatz berichtet über einige experimentelle und rechnerische Ergebnisse, die belegen, dass abhängig von der Querschnittsdicke lediglich eine schwache Reduzierung der Spitzentemperaturen verbunden mit einer ausgeprägten Phasenverschiebung gegenüber den Außentemperaturen, die näherungsweise sinusförmig über den Tag variieren, vorliegt.

RESUME

Un projet de recherche Européen portant sur les goujons collés en acier dans les structures en bois (GIROD) récemment achevé – auquel participait le département bois de l’Otto-Graf Institute – a mis en évidence un effet négatif marqué de températures élevées sur la résistance, qui affecte principalement la durée de vie des joints. La température maximale agissant sur les joints en service impose donc des exigences de performance sur la relation température – module de cisaillement et la température de transition vitreuse des adhésifs appropriés.

La conviction intuitive des praticiens aujourd’hui est de penser que les goujons collés cachés à l’intérieur des sections de lamellé collé sont soumis, du fait de la faible conductivité thermique et chaleur spécifique du bois, à des températures considérablement plus faibles que celles du climat ambiant. Cet article présente des résultats expérimentaux et numériques montrant, selon la largeur de la section, une faible réduction seulement des températures de pic combinée à une transition de phase prononcée, par rapport à la température ambiante qui varie grossièrement de manière sinusoïdale au cours d’une journée.

KEYWORDS: glued-in rods, glulam, elevated temperatures, transient temperature evolution

1. INTRODUCTION

Today's prevailing conviction of practitioners is, that steel rods bonded hidden in the interior of glulam cross-sections experience, due to the low thermal conductivity and specific heat of wood, considerable lower temperatures compared to ambient climate. A European research project on glued-in rods in timber structures (GIROD) revealed an unexpected strong strength reducing influence of elevated temperatures in duration of load tests with connections bonded by epoxy and polyurethane adhesives [BENGTSSON, JOHANSSON, 2002; AICHER, 2002].

In the performed tests the temperature increase was applied after mechanical loading thus suppressing positive post-curing effects. The experiments revealed clearly the crucial importance of a sufficiently high glass transition temperature. Performance requirements on temperature stability – especially shear modulus-temperature relationships and/or glass transition temperature – have to be set in view of realistic temperature loading scenarios. Eventually the temperature loading should also be considered in probabilistic manner, in case a specific adhesive shows high post-curing potential.

The reported experimental investigations were performed in first instance to substantiate the GIROD results. In addition thereto a major point of interest was the transient temperature evolution in the timber-bond line interface.

2. TEST PROGRAM

In order to verify the different temperature-strength behavior of glued-in steel rods either protruding or fully hidden in the wood, two types of specimens shown in Fig. 1 were investigated. The performed experiments concerned the strength verification at variable temperature and static long term loads and furthermore the temperature evolution in the bond lines. This paper reports on the temperature evolution.

The temperatures in the bond line were measured with thermo-elements consisting of copper/constantan (Cu/Cu-Ni) wires. In order to measure the temperatures in the bond line with little interfering influences of leakages to ambient climate, the application of the thermo-element wires to the bond line was performed as following: first an oversized specimen was sawn up lengthwise with a saw blade thickness of 2 mm. Then the two parts were clamped together and a hole with a diameter of 13 mm for the glued-in rod was drilled. The thermowires were glued into small notches as shown in Fig. 2a. The end or actual measuring point of the thermo-wire was flush with the surface of the drilled hole. Then the two parts of the specimen were glued together again. In a second step the steel rod (Ø 12 mm) was glued into the wooden piece (see Fig. 2b). All gluing were performed with a special epoxy adhesive.

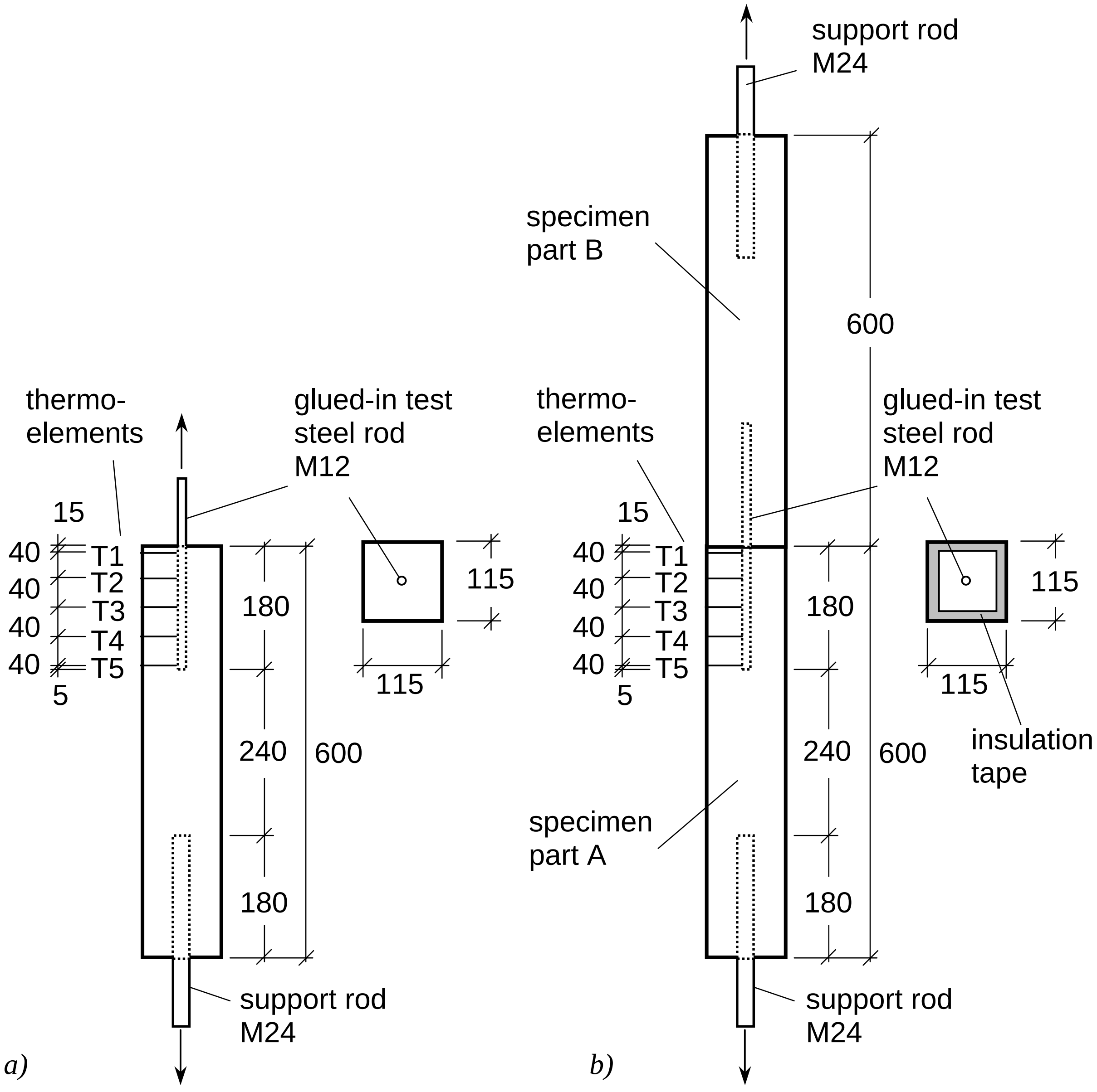
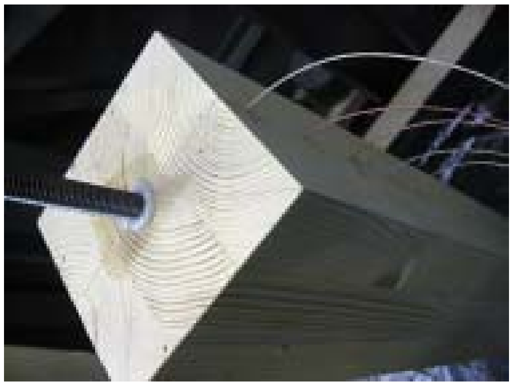


Fig. 1a,b: Geometry and schematic test set-up of
a) specimen No. I with protruding steel rod and
b) specimen No. II with hidden steel rod

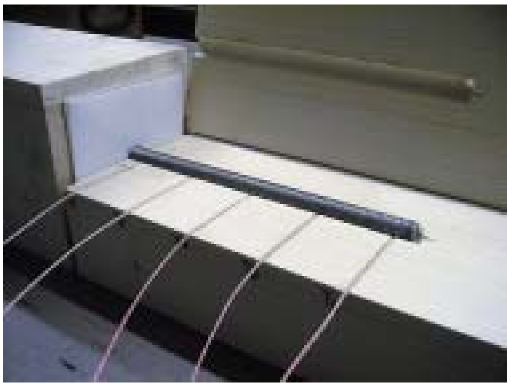
In order to obtain a specimen with a fully hidden rod which could be subjected to temperature and mechanical loads, specimen No. II, shown in Fig. 1b, was used. First, specimen part A was manufactured as specified above and after curing of the adhesive, part A incorporating the protruding test rod was glued into the rod hole of specimen part B. In order to enforce exclusively load transfer between the specimen parts A and B via the glued-in rods, a Teflon sheet with a thickness of 0.5 mm was inserted between the two parts of the specimen (see Fig. 2c) . The surrounding edge of 10 mm width and 2 mm depth of the two specimen parts was sealed with an elastic insulation tape compressed to 0.5 mm (see Fig. 1b and 2d).

a)

b)



c)



d)

Fig. 2a-d: Views of the specimens No. I (a,b) and No. II (c,d)

3. TEMPERATURE LOADING

As in the GIROD project a cyclic sinusoidal variation of warm and dry climate was applied [AICHER ET AL., 2002]. Contrary to GIROD, where a full temperature cycle consisted of 8 hours, now a practically relevant cycle length of 24 hours was chosen. A sinusoidal variation of temperature within a time span of 24 hours represents a very good approximation of daily temperature courses. This is shown exemplarily in Fig. 3 with recorded temperature data (sheltered outdoor, well ventilated shed in Stuttgart) for a period of three successive days.

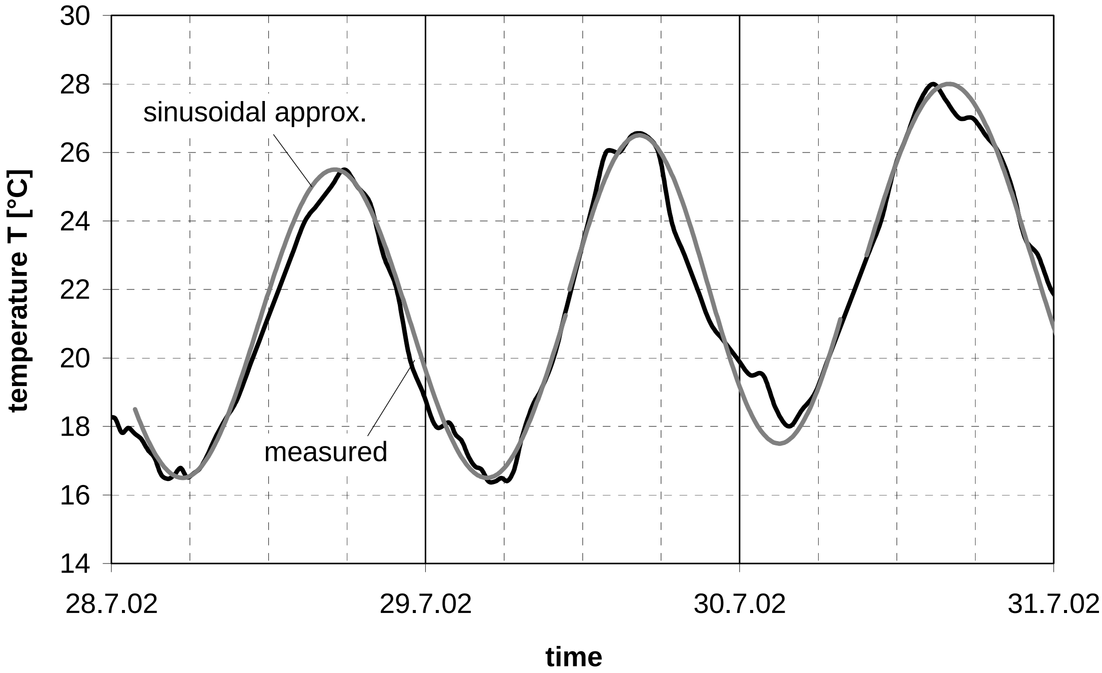


Fig. 3: Course of temperature (sheltered outdoor conditions) of typical summer days and sinusoidal approximation of the temperature

As in the GIROD project the minimum and maximum set temperatures were chosen as 25°C and 55°C, resulting in a peak-to-peak temperature amplitude of 30 K. These temperature boundaries might be regarded as an upper, yet realistic temperature range, which can occur under a dark, little ventilated roof in very warm summers in the Southern part of Europe. The course of the applied temperature and of the relative humidity is given in Fig. 4. The controlling of the relative humidity was limited, due to technical restrictions of the climate chamber, to 45% RH during a time of 6.5 h of a full cycle of 24 h, as shown in Fig. 4.

The actual temperatures obtained in the climate chamber showed a minimum and maximum of 24.9°C and 54.7°C, respectively, with a peak-to-peak temperature amplitude of 29.8 K. The relative humidity roughly ranged from 5 to 50 %, exceptionally temporary up to 67 % for about 0.5 hours.

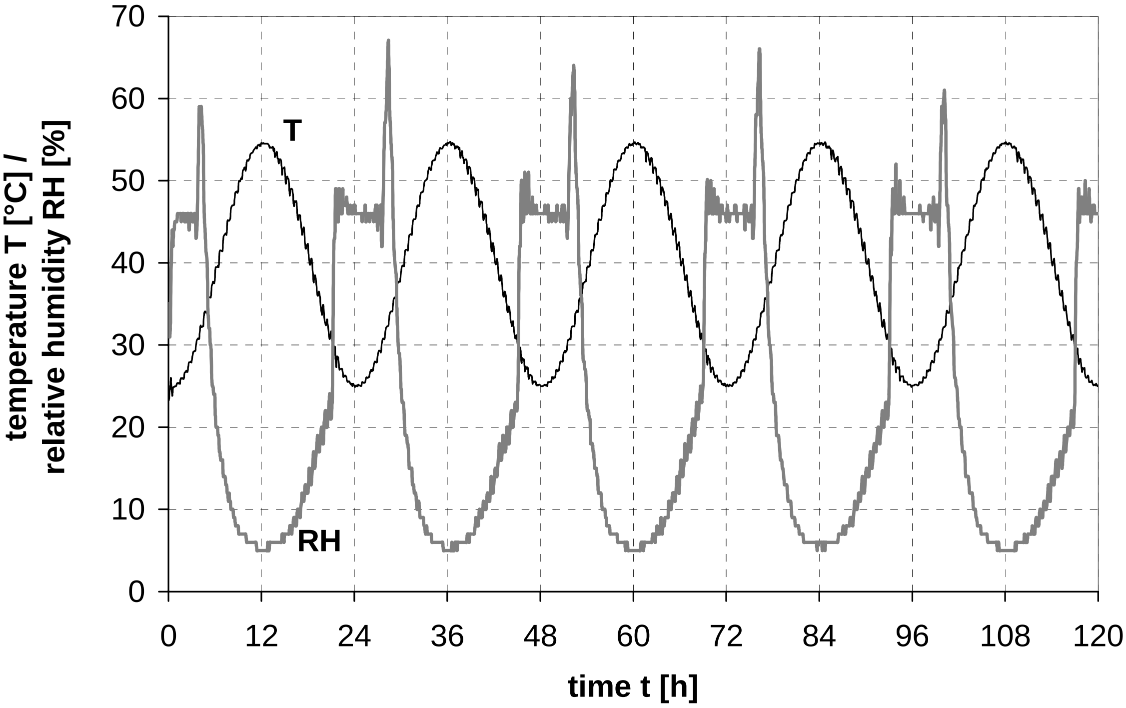


Fig. 4: Course of the applied ambient temperature and relative humidity variation in the climate chamber

4. NUMERICAL INVESTIGATIONS

In an early paper the evolution of temperature in a specimen with a glued-in rod protruding into ambient air was investigated numerically and experimentally [AICHER ET AL, 1998], taking into account the timber, the adhesive layer and the steel. An additional fourth layer, representing a steel/adhesive interface, was introduced in order to account for the problem that the used FE-code does not enable the specification of contact conductance of inner surfaces. By means of the interface layer a good agreement of measured and calculated transient temperatures was obtained.

In this paper the preliminary numerical study is exclusively related to specimen No. II with the hidden rod. In a first crude approximation the inner steel rod was omitted, so only the heat transfer through a quadratic block of timber was regarded in a 2 dimensional analysis. The cross-sectional dimensions of the timber, a = 115 mm, were reduced by the hole diameter of 13 mm (rod diameter + 1 mm) to 102 mm.

In the calculations a constant thermal diffusivity perpendicular to grain of

$$D_{\perp} = \frac{k_{\perp}}{C_P \cdot \rho} = 700 \frac{mm^2}{h}$$

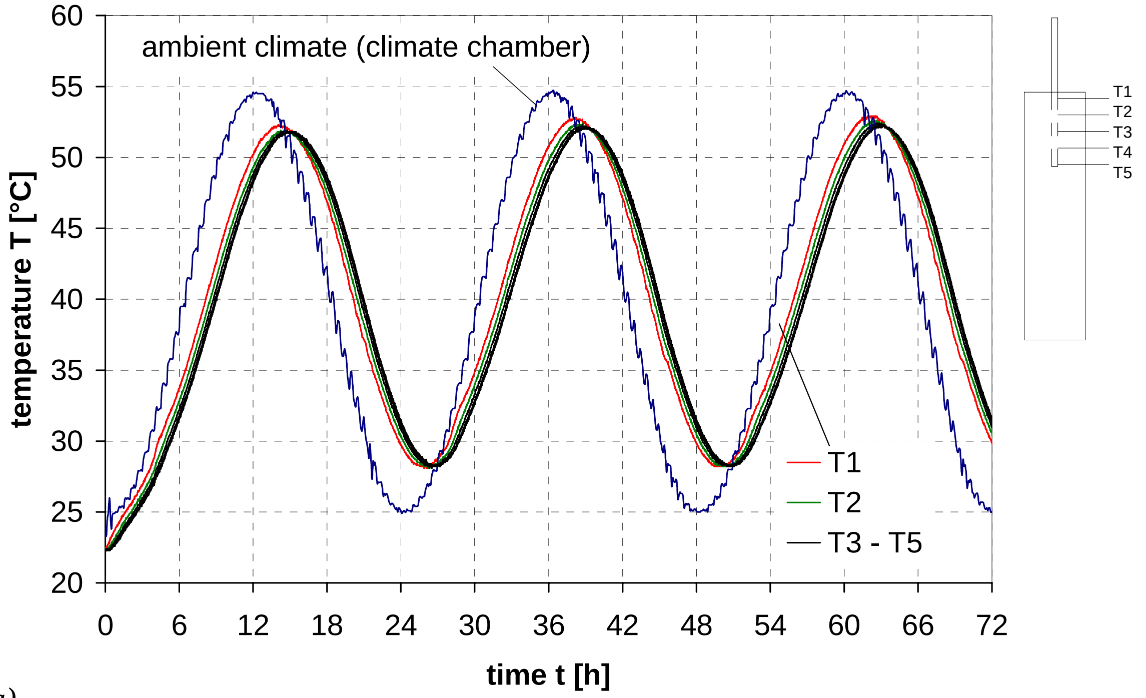
was employed. Hereby $k_{\perp}$, C_P and ρ were assumed as

$k_{\perp} = 0.13 \frac{W}{m \cdot K}$	thermal conductivity perpendicular to fiber acc. to DIN 4108, part 4
$C_P = 1.6 \frac{kJ}{kg \cdot K}$	specific heat [BATZER, 1985]
$\rho = 420 \frac{kg}{m^3}$	mass density of glulam at dry status of about u = 7 %

The convection heat transfer coefficient h was chosen as a fitting parameter in the range of 10 to 20 $W/(m^2 \cdot K)$. Literature data for forced convection of gas media vary roughly between 10 and 100 $W/(m^2 \cdot K)$; a value of 25 $W/(m^2 \cdot K)$ is assumed for convection at exterior walls in DIN 4108, part 4.

5. TEMPERATURE EVOLUTION IN CYCLIC CLIMATE

Figs. 5a,b show the temperature evolution of both specimen types I and II at different thermo-element positions. The evolution of the ambient temperature in the climate chamber is given, too. For a better visualization of phase shift and differences in amplitudes Figs. 6a and b show the temperature evolution at a cycle length of 24 hours; additionally finite element computed temperature evolutions based on the revealed approach are specified in case of specimen type II with a hidden rod.



a)

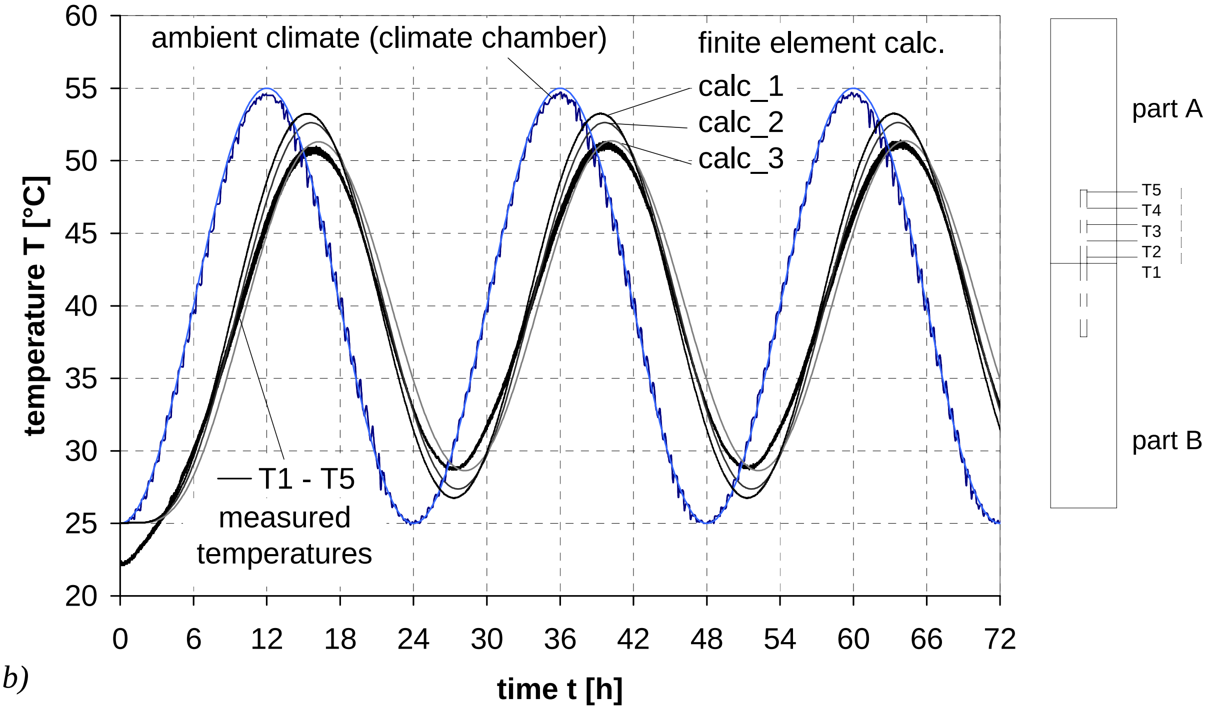


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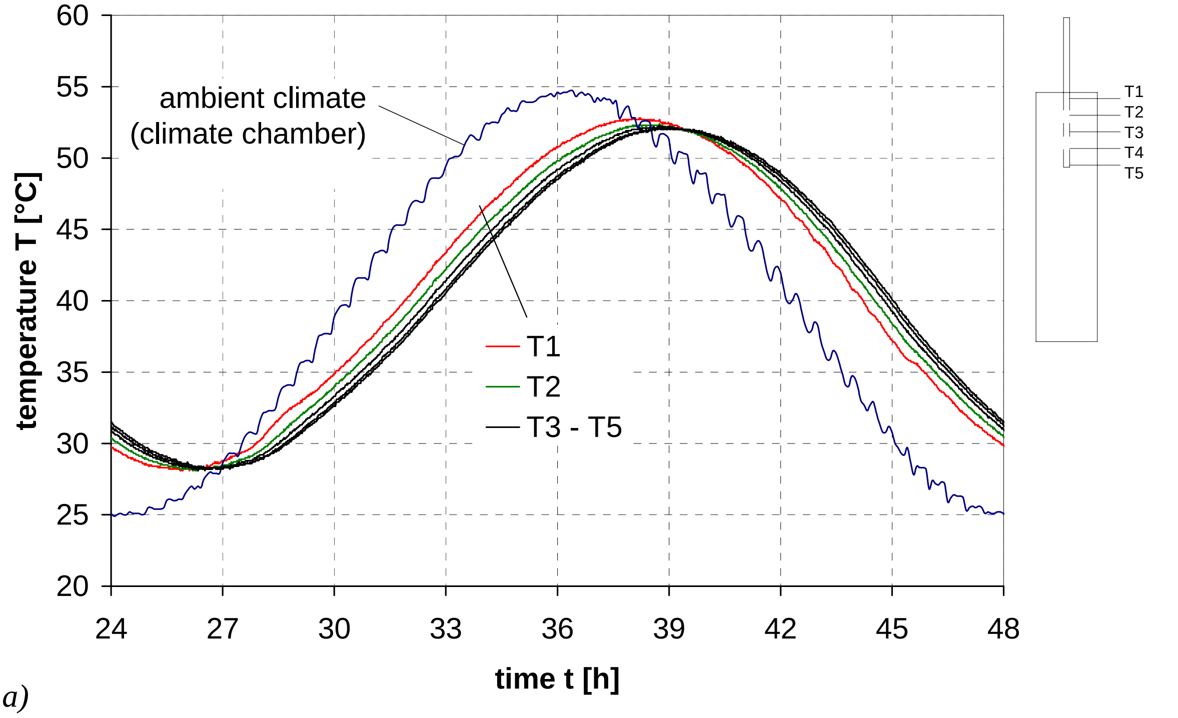
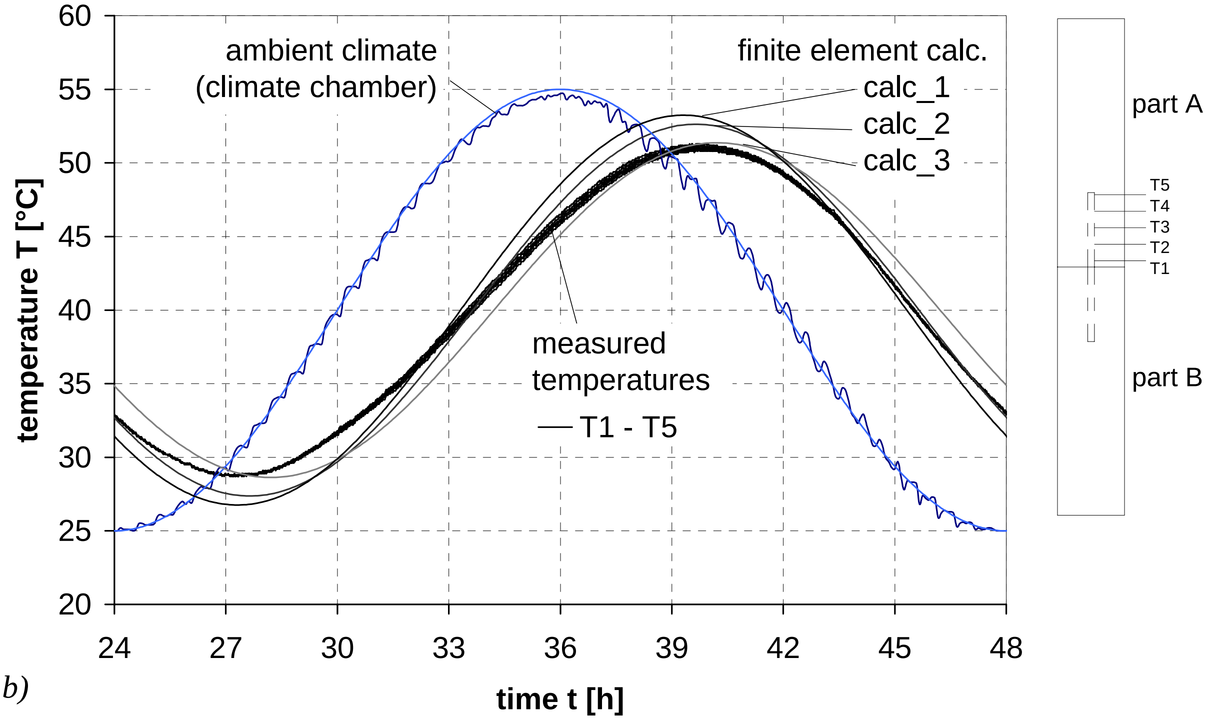
Fig. 5a,b: Temperature evolution over 3 days at the positions of the thermo-elements
a) specimen No. I with protruding steel rod
b) specimen No. II with hidden steel rod



a)



b)

Fig. 6a,b: Temperature evolution over 1 day at a cycle length of 24 hours
a) specimen No. I with protruding steel rod
b) specimen No. II with hidden steel rod

The differences between the two specimen types are rather small. Purely qualitatively the temperature in the wood-bond line interface of specimen No. II shows slightly decreased amplitudes and a slightly more pronounced phase shift vs. ambient climate when compared to specimen No. I with the protruding rod. Quantitatively the results are specified in Tab. 1.

Tab. 1: Temperature evolution in the wood-adhesive interface of specimens No. I and No. II at thermo-element positions T1 and T5

	thermo-element T1 ("protruding" end of steel rod)				thermo-element T5 (embedded end of steel rod)			
	maximum temperature T_{max} [°C]	minimum temperature T_{min} [°C]	peak-to-peak amplitude ΔT [K]	phase shift Δt [h]	maximum temperature T_{max} [°C]	minimum temperature T_{min} [°C]	peak-to-peak amplitude ΔT [K]	phase shift Δt [h]
ambient climate	54.7	24.9	29.8	-	54.7	24.9	29.8	-
experimental results:								
specimen No. I (protruding rod)	53.4	28.1	25.3	1.7	52.6	28.2	24.4	2.4
specimen No. II (hidden rod)	51.2	28.7	22.5	3.3	51.6	28.8	22.8	3.2

It can be seen that the maximum temperatures at the embedded ends of the rods (thermo-element T5 for specimens No. I and No. II) differ only very little by about 1°C. The reduction of maximum temperature vs. ambient climate in case of specimen No. II (hidden rod) was only 3 K. The phase shift between the maximum temperature of the ambient climate and the maximum of recorded temperatures was 2.4 and 3.2 hours in case of specimens No. I and No. II, respectively.

In case of specimen No. II no difference of temperature amplitudes, peak temperatures and phase shifts between thermo-element T1 close to the sealed joint of both specimen parts A and B as compared to the embedded end (thermo-element T5) was observed. In case of leakages at the sealing of the joint of the parts A and B a different result should be obtained. This is substantiated by the calculations.

Table 2 represents the results of the rough finite element calculation compared to the experimental results of specimen type II and the applied ambient climate. It can be seen that either the maximum and minimum temperatures T_{max} and T_{min} (result calc_1) or the phase shift Δt (result calc_3) of the measured experimental results can be fitted by tuning of the convection heat transfer coefficient h. A roughly acceptable approximation of both , the temperatures and the phase shift, is obtained with a convection heat transfer coefficient of h = 15 W/(m²·K). This number is within the plausible range.

Tab. 2: Maximum temperatures and phase shift for specimen No. II according to experimental test results and finite element calculation

	calculation result	convection heat transfer coefficient h [W/(m²·K)]	maximum temperature T_{max} [°C]	minimum temperature T_{min} [°C]	peak-to-peak amplitude $\Delta T = T_{min}-T_{max}$ [K]	phase shift Δt [h]
ambient climate	-	-	54.7	24.9	29.8	-
experimental results	-	-	51.2	28.7	22.5	3.3
2D finite element calculation	calc_1	10	51.4	28.6	22.8	4.2
	calc_2	15	52.6	27.4	25.2	3.6
	calc_3	20	53.2	26.8	26.4	3.3

6. INFLUENCE OF TIMBER THICKNESS

The presented test results and hereby the small damping of the temperature maxima is obviously related to the cross-sectional dimensions of the specimens (quadratic cross-section of 115 mm · 115 mm). In order to verify the influence of an increased timber thickness some more calculations similar to those outlined in chapter 4 were performed. The convection heat transfer coefficient was chosen as h = 15 W/(m²·K) being the value which forwarded a reasonable good agreement of the simplified analysis with the hidden rod specimen No. II. The imposed temperature varies again sinusoidally between 25 and 55°C with a phase length of 24 hours.

Fig. 7 gives the temperature courses for square cross-sectional dimensions with thicknesses of a = 50, 102, 150 and 200 mm. The value a = 102 mm relates to the discussed results of specimen No. II, whereby the reduction of the real thickness of 115 mm to 102 mm is bound to the simplified approach of omitted rod cross-section. The graph shows the qualitatively somewhat trivial result of a decreasing temperature amplitude and an increasing phase shift with growing cross-sectional dimensions.

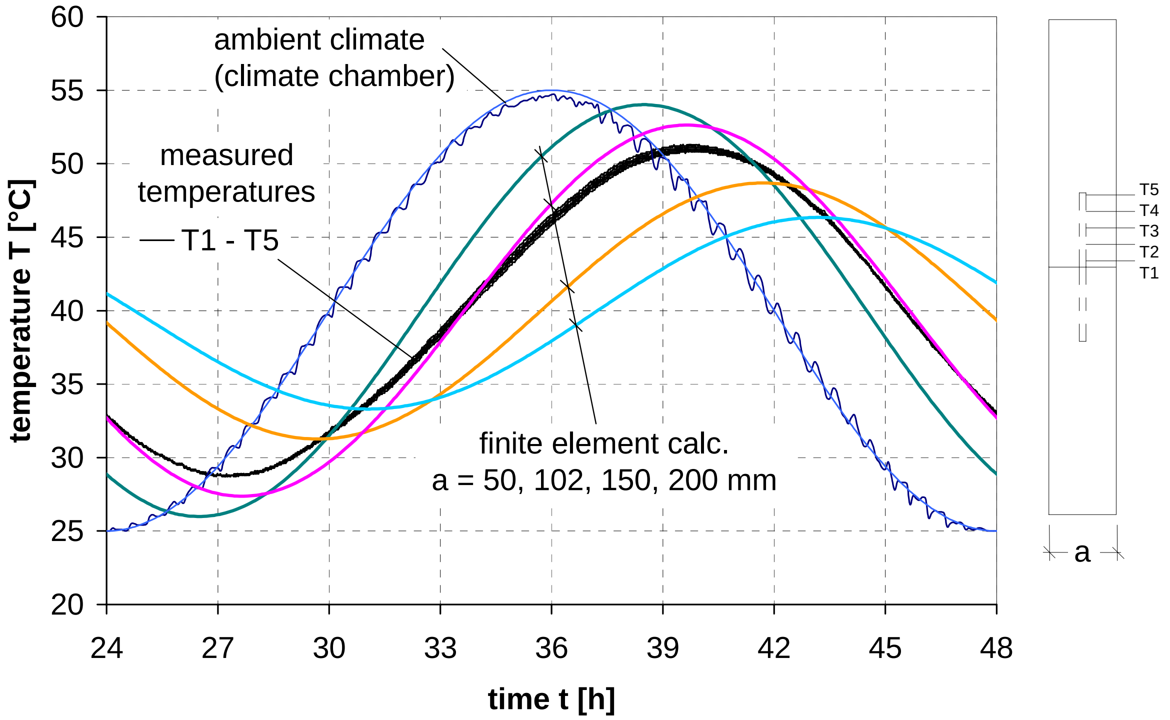


Fig. 7: Temperature evolution at a cycle length of 24 hours for finite element calculations with varying timber thicknesses compared to experimental results (specimen No. II with hidden rod)

A quantitative summary of the results is given in Tab. 3. In detail the changes of minimum and maximum temperature, the peak-to-peak amplitude $\Delta T = T_{max}-T_{min}$ and the phase shift Δt are specified. It can be seen that the reduction of the maximum temperature in the regarded range of cross-sectional dimensions is rather moderate. For a medium sized glulam thickness of 150 mm the maximum value is still rather close to 50°C, which marks the limit of type I adhesives acc. to EN 301.

The quantitative results of the very rough approximation of the problem shall be regarded with a more refined modeling considering the true build-ups.

Tab. 3: Extreme temperatures, temperature differences and shifts of phase depending on timber thickness according to a simplified calculation

	calculation result	cross-sectional thickness a [mm]	maximum temperature T_{max} [°C]	minimum temperature T_{min} [°C]	peak-to-peak amplitude $\Delta T = T_{min}-T_{max}$ [K]	phase shift Δt [h]
ambient climate	-	-	54.7	24.9	29.8	-
experimental results	-	-	51.2	28.7	22.5	3.3
2D finite element calculation	calc_1	50	54.0	26.0	28.0	2.5
	calc_2	102	52.6	27.4	25.2	3.6
	calc_3	150	48.7	31.3	17.4	5.7
	calc_4	200	46.3	33.6	12.7	7.2

7. CONCLUSIONS

The performed experiments on transient temperatures in glue-line/wood interfaces of steel rods bonded into glulam and subjected to cyclically varying ambient climate revealed

- relatively low damping of maximum temperatures for a cross-sectional thickness of 115 mm,
- pronounced phase shifts and
- only minor differences between the cases of protruding or hidden rods.

The results were extrapolated to different cross-sectional thicknesses by means of numerical calculations with a simplified model. The calculation results yielded rather moderate damping within the typical range of glulam thicknesses up to 200 mm. Roughly it can be concluded that the maximum ambient temperature level acting in service on the glued-in rod connections sets the performance requirements on the shear modulus/temperature relationship resp. on the glass transition temperature of appropriate adhesives.

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