Retrofitting of fully stressed roof structures for increased wind loads due to inclined solar panels using CFRP composite systems

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1. General objectives

Given the steady increase of live loads, climatic changes, as well as the installation of innovative technologies such as photovoltaics (PV), todays civil infrastructure is continuously being exposed to higher structural demands. For a typical PV application, the solar panels are mounted on flat or low inclined roofs of warehouses or other commercial buildings with comparable dimensions, whose structural support is often provided by glued laminated timber (glulam). As most situations require solar panels to be mounted at an angle of roughly 30 to 35 degrees off horiztonal, the area exposed to wind and thus the wind loading acting on the supporting structure may increase significantly. On fully stressed roof designs, the static system must often be modified to withstand the new loading situation. Figure 1 illustrates a typical installation concept on flat roof structures.

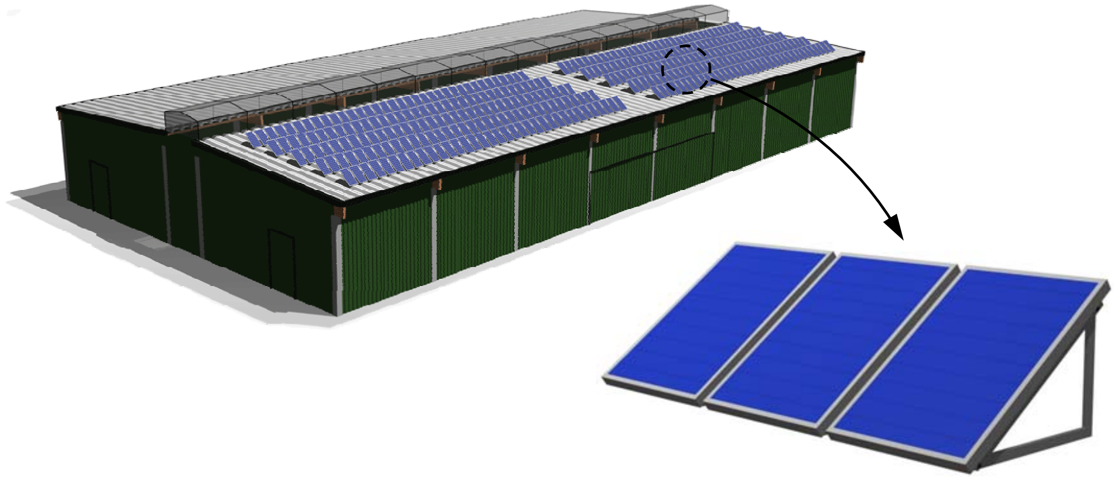


Figure 1: *Installation of inclined solar panels on roof structures*

When strengthening existing structures, the use of conventional materials such as steel or timber can result in either a considerable increase in the self-weight of the structure or the need for extensive cross-sectional areas. To account for these shortcomings, the use of carbon fiber reinforced polymers (CFRP) has found wide acceptance in recent years. Their excellent mechanical properties, high durablity, and relatively low self-weight make CFRP highly feasible for a large number of structural applications.

To date, general technical approvals *(allgemeine bauaufsichtliche Zulassung, abZ)* required for using CFRP as a structural strengthening material in practical applications in Germany have been limited to reinforced concrete structures [Deu02, Deu04]. In recent years, the use of CFRP has been established as a state-of-the-art technology for such applications. However, a number of research reports have outlined the high potential of CFRP materials for increasing the load-bearing capacity of timber structures [Tri97, Lug01, Bla03, Bru05, Mic05, and Joh07].

Since no German standard for the application of CFRP on timber structures has been made available, the retrofitting of such designs usually requires official authorization in each individual case. Consequently, the logistical and financial burden involved may yield an otherwise feasible project unattractive. Therefore, the availability of a general technical approval for use of CFRP in timber structures could strongly promote the use of PV systems on roof structures. However, general technical standards and design guidelines for CFRP strengthened timber structures must first be established through extensive analytical and experimantal work. Due to an increase in the horizontal wind loading, additional bracing of the roof structure itself may also be required. For this, diagonal ties made from lightweight and high-strength CFRP materials could provide an efficient solution.

The primary objective of this research project was the experimental and analytical investigation of CFRP laminates for structural strengthening of glulam beams in large-span structures. Furthermore, a general bracing system for timber roof structures was proposed and verified through experiments. Ultimately, a novel and practical design concept for timber roof structures using CFRP materials was introduced.

2. Implementation of research tasks

Given the results of previous studies [Bla01, Sch05, Kli08], preference was given to the use of near-surface mounted (NSM) reinforcement. Besides aspects of fire-protection and visual appearance of the strengthened structure, NSM reinforcement allows for a better introduction of bondline stresses between the joined materials.

In summary, the following tasks were established:

- Experimental and analytical investigation of the bond-stress distribution between near-surface mounted CFRP laminates and timber
- Derivation of a design concept for calculating the maximum transferable bond force between near-surface mounted CFRP laminates and timber
- Experimental and analytical investigation of the load-bearing capacity of CFRP-strengthened glulam beams
- Formulation of a practical design concept for strengthening glulam beams using CFRP
- Investigation of a roof bracing system to account for additional horizontal wind loading

Pull-out tests

Based on previous research results [Hol94, Bla01, Lug01, and Bla03], the bond-stress distribution and maximum pull-out force between CFRP and timber were investigated using a special pull-out test with a vertically mounted compression-tension specimen. To study the effect of different parameters such as bond length l_v, laminate width b_L, groove width b_s, or hygrothermal factors, a comprehensive test program with a total of 122 pull-out tests was established. Table 1 gives a summary of the most important experimental parameters. The general test setup is shown in Figure 2.

For fabrication of the test specimens, solid spruce of sorting grade S10 and pine glulam of grade GL24h were selected. As strengthening material, the unidirectional CFRP laminate Sika CarboDur S manufactured by Sika Deuschland GmbH was chosen. Two different laminates with a constant thickness of 2,5 mm were used, varying between 15 mm (S1.525/60) and 20 mm (S2.025/80) in width. Bonding of the CFRP laminates was performed using the epoxy adhesive systems Sikadur 30 DUE and Sikadur 330 of the same manufacturer. The essential mechanical peoperties of both adhesive systems are presented in Table 2.

Figure 2: *Pull-out test on a wood/CFRP-composite test specimen*

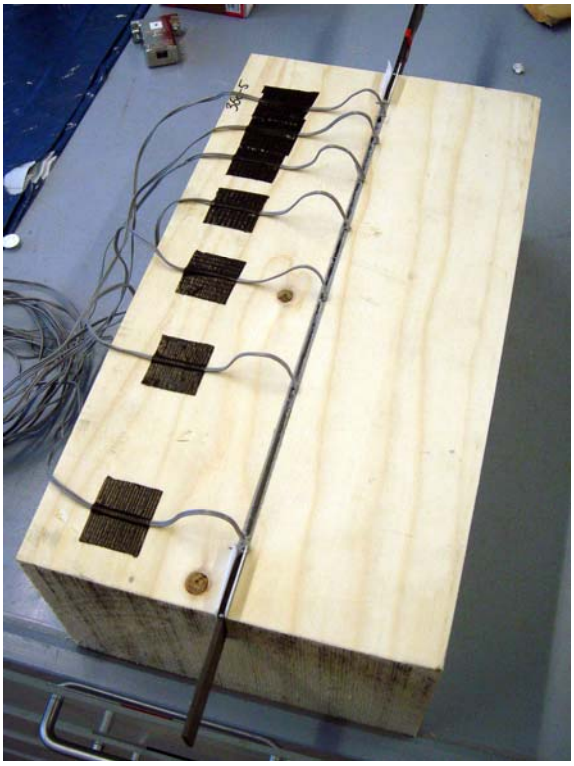


Figure 3: *Test specimen with strain gauges*

To allow for both experimental and analytical investigation of the bond behavior, a total of up to eight strain gauges was placed along the length of the laminate of various specimens (Figure 3). Also, the relative displacement (slippage) between CFRP and timber was measured at the stressed and unstressed ends of the specimen using three linear variable displacement transducers (LVDT). Given the relative displacement and discrete strain values along the laminate, the shear-slip relationship, subsequently referred to as τ(s)-relationship, could be derived analytically.

Table 1: *Summary of pull-out tests*

Test specimens	**Bond length l_v [mm]**	**Groove width b_s [mm]**	**Description and test parameters**
21	70	4.0 - 6.3	Preliminary evaluation of test arrangement. Comparison of bond behavior for external and NSM laminates
45	50 - 1,000	4.5	Effect of bond length and evaluation of strain distribution along the bondline using strain gauges
10	100 - 300	9.0	Effect of groove width
6	100	4.5	Distance of NSM to beam edge (ledge width: 10 to 40 mm)
9	100 - 300	4.5	Comparison of wood type: spruce (solid structural timber) vs. pine (glulam)
15	100 - 300	4.5	Hygrothermal effects (70°C, 95% RH)
16	100 - 300	3.2 - 4.5	Modeling of bond behavior

Table 2: *Mechanical properties of strengthening materials according to [Sik09a, Sik09b, Sik09c]*

Property	**Sika® CarboDur S**	**Sikadur® 30 DUE**	**Sikadur® 330**
Tensile strength	> 2,800 N/mm^2	≥ 21 N/mm^2	30 N/mm^2
E-Modulus	170,000 N/mm^2	11,200 N/mm^2	4,500 N/mm^2

Modeling of bond behavior

After completion of the pull-out tests, a second order differential equation describing the interfacial bond-slip behavior of NSM reinforcement in timber was used to numerically simulate the experimental results. To obtain a suitable mathematical model, the experimental $\tau(s)$-relationships were first derived by discretization of the differential equation. In a second step, the experimental $\tau(s)$-relationships were substituted by an appropriate bond-slip model. Finally, the second order differential equation was solved by numerical approximation.

Following the above methodology, a parametric study was performed to investigate the effects of different factors on the maximum pull-out strength. Ultimately, a practical design equation was established by combining the results from both numerical and experimental studies.

Flexural beam tests

Given the design equation for maximum pull-out strength, the load bearing behavior of CFRP reinforced glulam beams was studied. For this, a total of 26 finger joint pine glulam beams of grade GL24h with a cross-sectional area of 120 x 360 mm and a span of 5,500 mm were tested in 4-point bending. The majority of all beams were strengthened using different arrangements of the Sika CarboDur S2.025/80 laminate. For comparison, the surface mounted laminate Sika CarboDur S812 with a width of 80 mm and a thickness of 1,2 mm was also used on selected specimens. Table 3 shows the essential test parameters and a short description of the strengthening scheme.

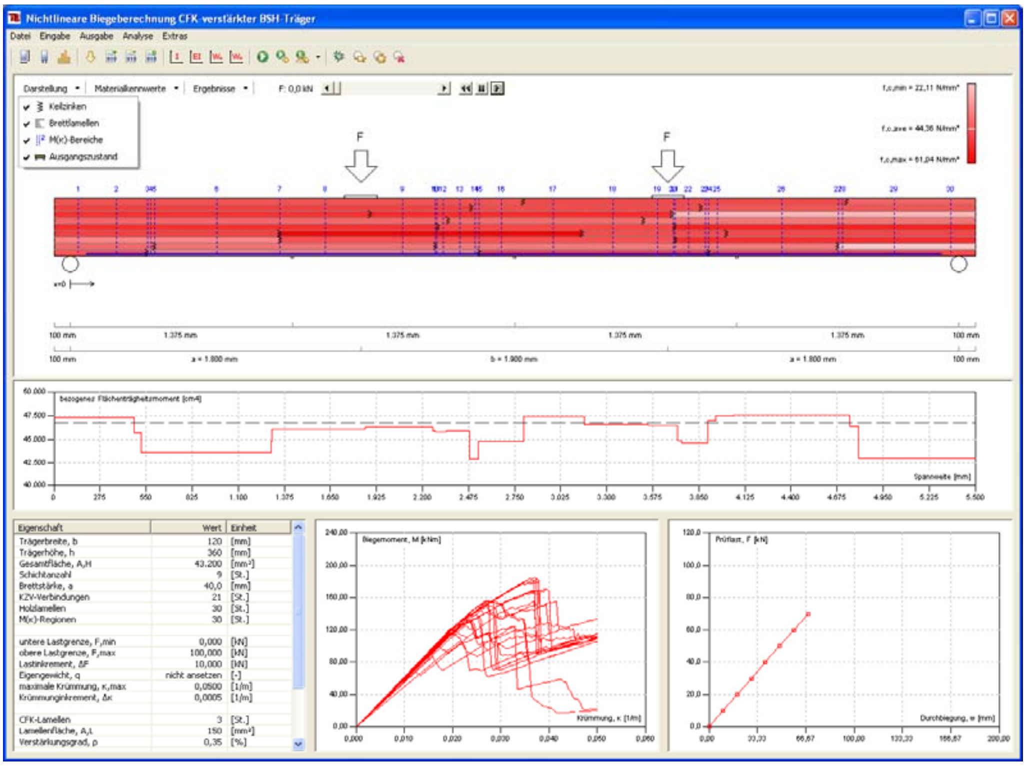
Table 3: *Summary of flexural beam tests*

Test series	**n**	**Laminate-length l_L**	**Laminate-area A_L**	**Strengthening ratio $\rho = A_L/A_H$**	**Description**
trv_REF	7	-	-	0.00%	reference specimens (unstrengthened)
trv_0.22	2	5,300 mm	96 mm^2	0.22%	external laminate (S812) on bottom
trv_0.23	3	5,300 mm	100 mm^2	0.23%	NSM laminate (S2.025) on beam sides
trv_0.35	3	5,300 mm	150 mm^3	0.35%	NSM laminate (S2.025) on bottom
trv_0.35_VGS	3	5,300 mm	150 mm^2	0.35% + VGS	NSM laminate (S2.025) on bottom + fully threaded screws (VGS)
trv_0.35_K	3	3,120 mm	150 mm^2	0.35% (short)	NSM laminate (S2.025) on bottom, local strengthening in max. moment region
trv_0.81	2	5,300 mm	350 mm^2	0.81%	NSM laminate (S2.025) on bottom + beam sides
trv_0.91	3	5,300 mm	392 mm^2	0.91%	external laminate (S812) on bottom + NSM laminate (S2.025) on beam sides

To obtain reference values for the flexural capacity and bending stiffness, a total of 7 unreinforced beams were tested to failure. Following these tests, reinforcement ratios between 0.22% and 0.91% relative to the beam cross-sectional area were investigated. Except for test series trv_0,35_K, all laminates were extended over a distance 100 mm short of either support. On specimens trv_0,35_K, the effects of local reinforcement were studied by terminating the laminate just outside the maximum moment region, which results in a significant increase in the bond stress near the laminate ends. Also, the effect of additional shear strengthening was investigated on specimens trv_0,35_VGS. For this, two rows of full-threaded screws by Würth GmbH & Co. KG with a diameter of 8 mm were placed at a distance of d = h = 360 mm throughout the entire span.

Stochastic simulation of flexural behavior

Due to the elaborate manufacturing process involved in the preparation of large-scale specimens, only a relatively small number of experiments could be conducted. To increase the sample size and allow for testing of further CFRP arrangements, a stochastic computer model of the 4-point-bending test was implemented. The suitability of the numerical model, which was based on the Monte Carlo method, was assessed by recalculating all experimental tests using the computer software shown in Figure 4. Subsequently, the effect of numerous parameters such as constituent material properties, dimensional composition of glulam beams, or CFRP arrangement on the bearing capacity of the beams was investigated through a parametric study encompassing more than 120,000 simulations.



Eigenschaft	Wert	Einheit
Trägerbreite, b	120	[mm]
Trägerhöhe, h	360	[mm]
Gesamtfläche, A,H	43.200	[mm²]
Schichtanzahl	9	[St.]
Brettstärke, a	40,0	[mm]
KZV-Verbindungen	21	[St.]
Holzlamellen	30	[St.]
M(x)-Regionen	30	[St.]
untere Lastgrenze, F,min	0,000	[kN]
obere Lastgrenze, F,max	100,000	[kN]
Lastinkrement, ΔF	10,000	[kN]
Eigengewicht, q	nicht ansetzen	[-]
maximale Krümmung, κ,max	0,0500	[1/m]
Krümmunginkrement, Δκ	0,0005	[1/m]
CFK-Lamellen	3	[St.]
Lamellenfläche, A,L	150	[mm²]
Verstärkungsgrad, ρ	0,35	[%]

Figure 4: *Computer program for stochastic simulation of CFRP-strengthened glulam beams*

Experimental investigation of roof bracing

Through an additional study, the feasibility of CFRP-laminates for manufacturing stiff and lightweight bracing systems for glulam roof structures was tested using a scaled model. The general test setup was based on the results from an economic analysis previously conducted at the Technische Universität Berlin [Hil07]. Following the principle of dimensional analysis, the load-bearing components of the original roof structure were scaled using a ratio of 1:6. To assess the load-deflection behavior of the entire roof frame during testing, the experimental results were compared to a comprehensive analytical analysis.

To limit the complexity and manufacturing processes involved in the experimental design while allowing for a suitable model scale, the original bracing system consisting of 11 fields was reduced to a 4-field array. All materials were selected according to those of the original structure. Hereby, stress levels comparable to those in the original structure could be obtained in the model. Figure 5 shows the general experimental setup including the application scheme for the simulated wind force.

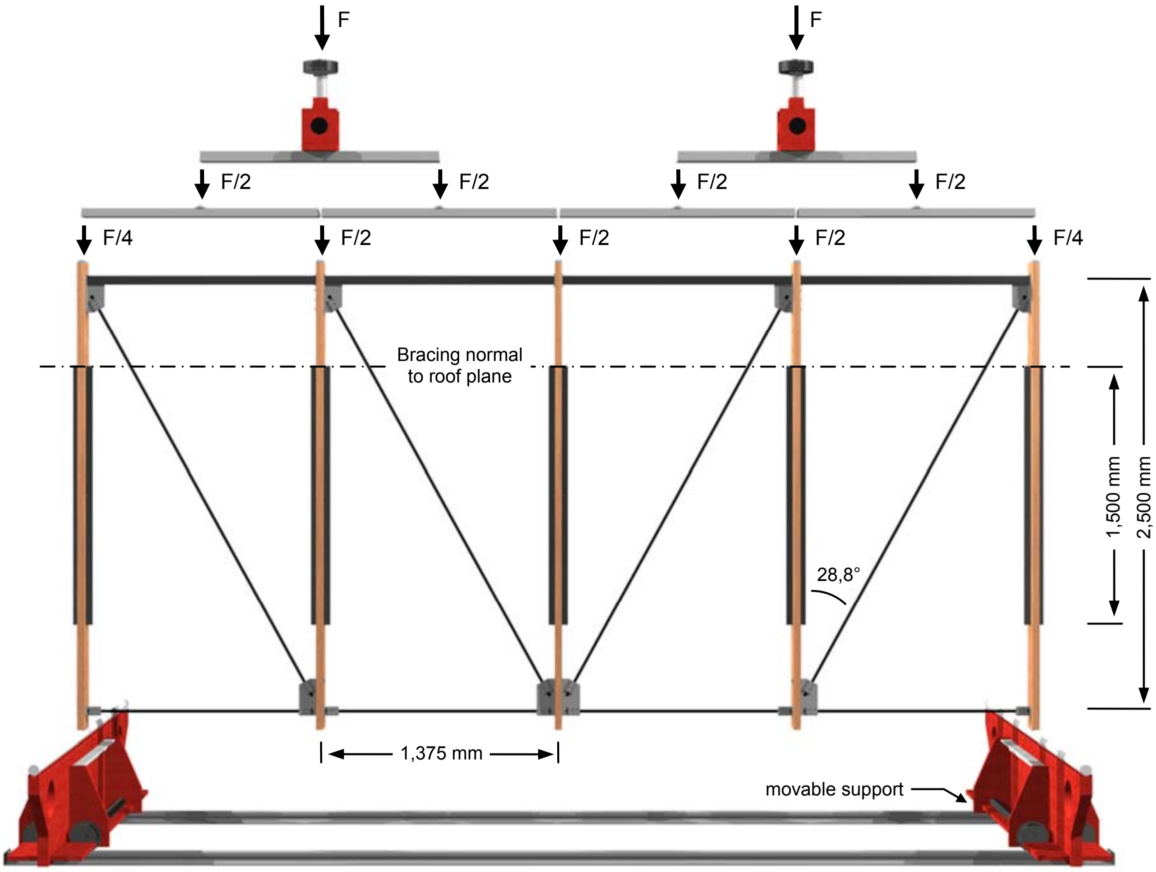


Figure 5: *Model test of roof bracing system*

3. Summary and results

Derivation of a bond model

Based on the evaluation of laminate force distibution obtained from the pull-out tests, it was shown that a sufficient numerical representation of the bond-slip behavior cannot be obtained using a constant bond-slip model. Instead, the bond-slip model must vary throughout the effective bond length. Also, shear deformation between the joined materials must not be assigned to the adhesive bondline exclusively. Due to the low shear stiffness of glulam parallel to the fiber direction, such simplification, yielding acceptable results for NSM reinforcement in reinforced concrete structures, would lead to erroneous results in timber. Given the effective bond length l_v, the following maximum pull-out strength was established for a single unidirectional laminate:

$$F_{v,k} = U_{ad} \cdot t_L^{0,325} \cdot \left[0{,}110 \cdot \ln(l_v) - 0{,}143\right] \qquad \text{for } l_v \geq 50 \text{ mm}$$

with:

$$U_{ad} = t_L + 2 \cdot b_L + 4 \cdot t_{ad}$$

Figure 6 shows various distributions of the characteristic pull-out strength $F_{v,k}$ as a function of bond length l_v and laminate width b_L assuming a laminate thickness of t_L = 2,5 mm as well as a proposed adhesive bondline thickness of t_{ad} = 1,0 mm.

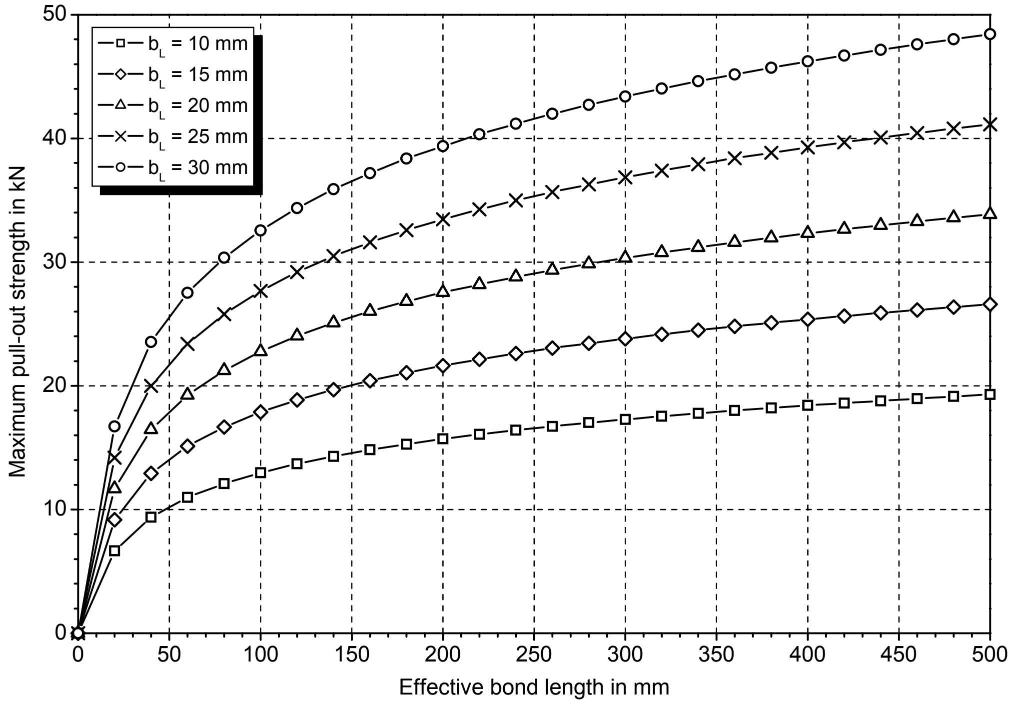


Abbildung 6: *Characteristic pull-out force for different laminate widths* (t_L *= 2.5 mm)*

Analysis of flexural behavior

Results from the 4-point bending tests indicated that the load-bearing capacity of glulam beams may be significantly enhanced by applying reinforcement ratios as low as 0.35%. Furthermore, the bending stiffness and utilization of the compression zone were superior compared to unreinforced specimens. Unlike surface mounted reinforcement, specimens with NSM reinforcement generally experienced a more preferable failure mechanism as well as higher post-failure bending capacities. However, eventual failure of most reinforced and unreinforced specimens was initiated by a tension failure of the finger joints and/or local defects located within the lower regions of the glulam cross-section.

Recalculation of the experimental tests was performed using the stochastic simulation software presented in Figure 4. It was shown that the analytical results are in good agreement with the experiments. The subsequent parametric study confirmed a strong dependency of the load-bearing behavior on the reinforcement ratio, the laminate length, as well as the laminate stiffness. For glulam of grade GL24h, an upper limit for the reinforcement ratio of about 1.5% was established. It was further shown that local strengthening schemes tend to result in exceedingly high bond stresses and/or failure of the glulam boards just outside the reinforced cross section. Also, early collapse may occur when using CFRP laminates with an elastic modulus above 250,000 N/mm², as the increase in material stiffness typically results in a significant reduction of the ultimate failure strain.

In contrast, the spacing of finger joints and the slope of the falling branch of the stress-strain relationship for timber had only a limited effect on the overall bending behavior. Hence, a bilinear model with a constant yield stress was used in performing the stochastic calculations. Based on the experimental results as well as the findings from the subsequent parametric analysis, the relevant design calculations for CFRP-reinforced glulam beams were established. These encompass:

- Calculation of the effective reinforcement ratio ρ_{eff} given a maximum allowable tensile strain at the lower beam fiber and a corresponding stress distribution (elastic or inelastic)
- Calculation of the ultimate bending capacity under elastic or inelastic bending
- Calculation of the bending stiffness according to elastic composite theory
- Evaluation of shear stresses in the adhesive bondline (laminate end regions)
- Evaluation of timber shear stresses just outside the reinforced beam span

Wind bracing of roof area

Experimental results from the scaled model of Figure 5 have confirmed that the proposed roof bracing system can efficiently withstand additional horizontal wind loads originating from the inclined installation of solar panels. However, particular attention must be given to the laminate anchorage mechanism as well as the force transfer between the anchorage assembly and the glulam beam. Due to the orthotropic material behavior of CFRP, the clamping forces must not exceed the maximum compressive strength perpendicular to the fiber direction. It was shown that the use of specially profiled anchorage plates may limit the maximum compressive stress acting on the CFRP. Also, protruding shear plates can be used to allow for higher shear stresses at the interface between the front plate of the anchorage assembly and the glulam beam and thus ensure an adequate force transfer between the structural components.

Outlook and future perspectives

The results of this research study outline the high potential of carbon fiber reinforced materials for retrofitting of existing timber structures. Apart from excellent mechanical properties, the material shows good chemical resistance while being extraordinarily lightweight. Given the extensive research on CFRP and a wide range of practical applications in the civil engineering field, necessary prerequisites for prospective applications in timber structures are met.

However, to complement the short-term behavior investigated in this study, the authors suggest that further experimental work be conducted. For the special case of NSM reinforcement in timber structures, only a limited series of experiments have been published regarding durability under quasi-static and dynamic loading as well as moisture. Through additional research, the safety and reliability of the proposed strengthening method would be strongly promoted.

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