Reinforcement of glulam beams
with FRP reinforcement

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1 Introduction

For several years possibilities to reinforce glulam beams parallel to the grain to increase bending and axial stiffness and ultimate load have been investigated. One method is to use Fibre-Reinforced Plastics (FRP) as a tensile reinforcement. Fibres used were glass fibres, aramid fibres and carbon fibres.
At the University of Karlsruhe a research project was carried out where the load-deformation behaviour of reinforced glulam beams was studied. Thin carbon FRP and aramid FRP were used as reinforcements. This paper presents the test results of these beams loaded to failure.
Glulam beams loaded by bending moments fail at the tension side at the position of knots or finger joints. Due to this failure mode glulam beams are mainly reinforced at the tension side to strengthen the weak cross-sections.
The reinforcement for glulam beams should have a high modulus of elasticity (MOE) and a large tensile strain at failure. Materials considered in the past were steel, glass fibre reinforced plastic (GFRP) and since a few years carbon fibre reinforced plastic (CFRP) and aramid fibre reinforced plastic (AFRP). Fibre reinforced plastic (FRP) has the advantage of a high MOE – although generally lower than steel – and a high tensile strength. The disadvantage of steel is the low yield strength leading to plastic deformations before the timber fails. FRP reinforcements do not show this behaviour.
An effective reinforcement leads to a plastic behaviour on the timber compression side. In unreinforced glulam beams this effect hardly occurs.

2 Structure and failure modes of reinforced glulam beams

Figure 1 shows the types of cross section studied. 30 beams of type 1 and 8 beams of type 2 were loaded to failure. In practice, for reasons of fire safety or for esthetical reasons a facing consisting of a load carrying timber lamination is applied below the reinforcement (type 1). Nevertheless 8 beams without a timber facing were tested to study the influence of the timber facing on the load deformation behaviour. The width of the reinforcement always equals the width of the cross section.

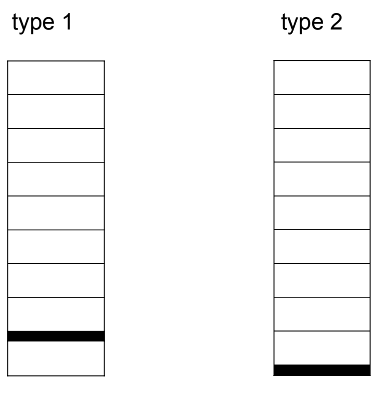

Figure 1: Cross section of the test specimens

For reinforced glulam beams different failure modes are possible. Assuming constant MOE, constant tensile and compressive strength and a linear-elastic-ideal-plastic stress-strain relationship within a cross section the following failure modes are possible.

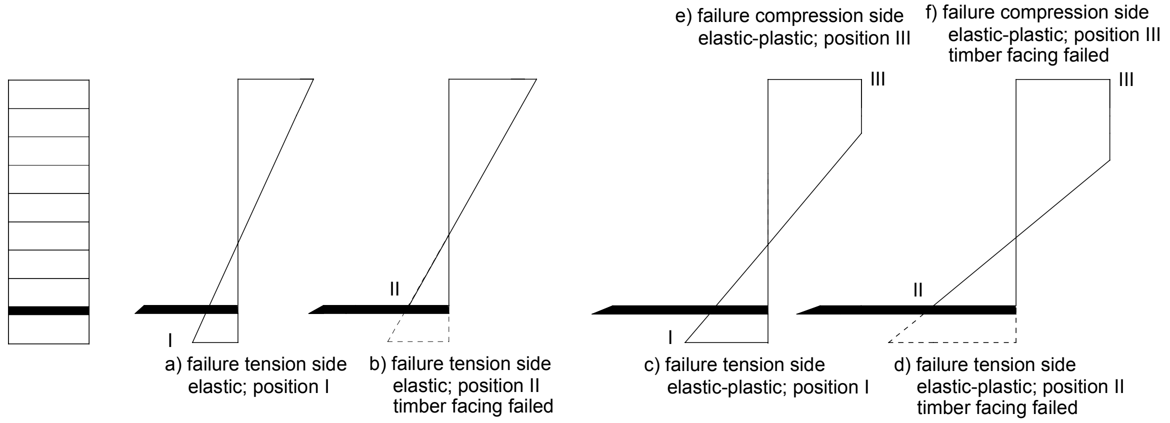

Figure 2: Failure modes

Global failure modes at the tension side:

Mode a: Failure of the timber facing while the cross section is in a linear-elastic state

Mode b: Failure above the reinforcement while the cross section is in a linear-elastic state

Mode c: Failure of the timber facing while the cross section is in a linear-elastic-ideal-plastic state

Mode d: Failure above the reinforcement while the cross section is in a linear-elastic - ideal-plastic state

Failure at the compression side:

Mode e: Compressive failure before the timber facing fails in tension

Mode f: Compressive failure after the timber facing failed in tension with subsequent tensile failure above the reinforcement

Using a tensile reinforcement the compressive stress will exceed the timber tensile stress in beams loaded in bending. Therefore plastic deformations are more probable in beams with tensile reinforcement. Using both, compressive and tensile reinforcement the linear modes will mostly occur due to the reduction of the plastic area in the compressive zone.

3 Experimental study

30 reinforced glulam beams of type 1 and 8 beams of type 2 were tested to failure. Table 1 summarises the FRP properties, table 2 the adhesives being used and table 3 the test program.

Table 1: FRP

Shortcut.	Type of FRP	Tensile MOE [1] mean value [N/mm²]	Tensile strength [1] mean value [N/mm²]	Thickness $h_{R,t}$ [mm]	Width b [mm]
L1	CFRP	173.000	3.050	1,2	100
L2	CFRP	304.000	1.680	1,4	50
L3	AFRP	74.000	995	1,8	132
L4	CFRP	199.000	2.570	1,4	100

[1] from tension specimen of 50 mm width, average of 5 specimens

Table 2: Adhesives

Shortcut	Name of product	Type	Manufacturer / distribution
K1	Sikadur-30	Epoxid	Sika Chemie GmbH
K2	Ispo Concretin SK 41	Epoxid	ispo GmbH
K3	Collano Purbond HB 110	Polyeurethan	Ebnöther AG
K4	Dynosol S-199 with H-629	Resorcin	Dyno Industries A.S.

For the test specimens it was decided to use timber with a low MOE and a low density in order to maximise the reinforcement effect. The MOE and the density of every single board was determined before the glulam production. The boards with the smallest MOE and density values were arranged in the outer areas of the cross-section. The mean dynamic MOE of the boards was 9800 N/mm² for MS 10 (according to German Standard DIN 4074) boards which correspond to strength class C24 according to EN 338.
The tests were performed as four point bending tests with a span of 4,20 m and a distance of 1,35 m from the support to the loading point. The thickness of the timber facing was 34 mm (Tr-5;Tr-6) and 35 mm (Tr-1 to Tr-4).

Table 3: Test programme for bending tests

Test series	Number of specimens	Grade of laminations	Grade of timber facing	Mean height/width h_0/b [mm]	FRP (number of layers)	Ad-hesive	Finger joint
Tr-1	5	MS7 / MS10	MS7 / MS10	308/100	L1 (1)	K2	no
Tr-2	5	MS7 / MS10	MS7 / MS10	312/100	L4 (2)	K2	no
Tr-3	5	MS10	MS10	308/100	L1 (1)	K2	yes
Tr-4	5	MS10	MS10	312/100	L4 (2)	K2	yes
Tr-5	5	MS10 / MS17	MS17	312/100	L3 (4)	K3	yes
Tr-6	5	MS10 / MS17	MS10	312/100	L3 (4)	K3	yes
Tr-7	5	MS10	-	308/100	L1 (1)	K3	yes
Tr-8	3	MS10	-	310/100	L4 (2)	K3	yes

Figure 3 shows different types of cross sections for the test series. The left cross section is without timber facing and with CFRP reinforcement (Tr-7; Tr-8), the cross section in the middle has a timber facing and CFRP reinforcement (Tr-1 to Tr-4) and the right cross section is with timber facing and AFRP reinforcement (Tr-5; Tr-6).

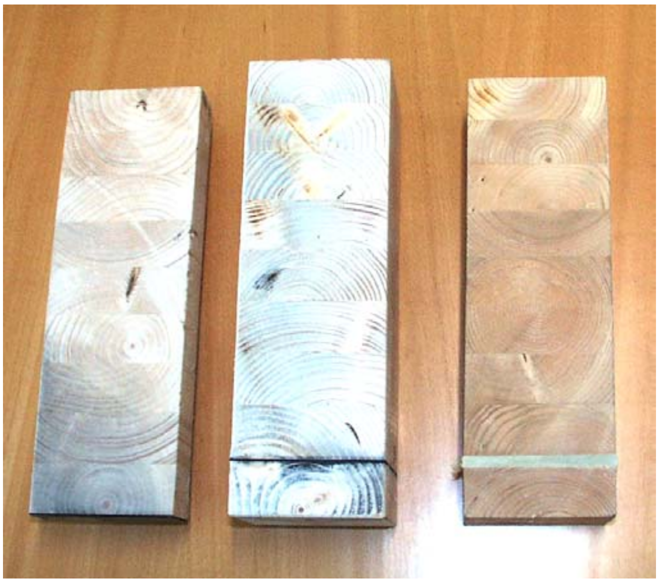

Figure 3: Types of cross section: CFRP without timber facing; CFRP with timber facing; AFRP with timber facing

The specimens of the test series Tr-1 to Tr-6 first failed due to tensile/bending failure of the timber facing. After the first failure, the load generally could be increased. The timber facing of test specimens with CFRP (FRP L1 and L4) delaminated after the global failure. Figure 4 shows a CFRP reinforced glulam beam with a typically delamination of the timber facing shortly before the global failure occurred. The timber facing of beams with AFRP partly failed at two locations and delaminated less than the beams with CFRP.

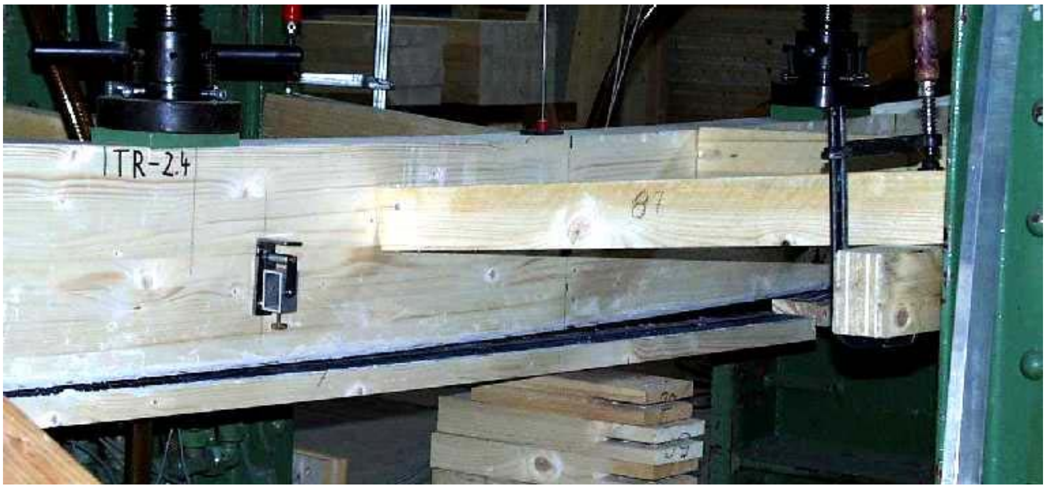

Figure 4: Delamination of the timber facing of specimen Tr-2.4 with CFRP and an Epoxid adhesive

The typical failure for a CFRP reinforced beam shows the left part of Figure 5. The right part of Figure 5 shows the typical high share of remaining carbon fibres on the bond line of the epoxy adhesive joint above the CFRP reinforcement after the global failure. This interlaminate failure effect of the CFRP lamella in connection with epoxy adhesive was observed more frequently and more extensively at the bond line above the reinforcement than below the lamella.

- Failure of the timber facing at a knot (bottom right)
- Failure of a finger joint above the reinforcement (bottom left)
- Compression wrinkle (top middle)

- Failure of a finger joint
- CFRP fibres on the epoxy bond line above the reinforcement

Figure 5: Failed timber beam of test Tr-4.4 and glued joint above the reinforcement after failure of test Tr-3.5

Table 4 shows the test results of the bending tests.

Table 4: Test results

Test series		Tr-1	Tr-2	Tr-3	Tr-4	Tr-5	Tr-6	Tr-7	Tr-8
F_{max}	[kN]	44,1	57,7	43,0	58,1	60,5	59,1	49,8	66,5
$M_{u,mean}$	[kNm]	59,5	77,9	58,1	78,4	81,7	79,8	67,2	89,8
$f_m = M_{u,mean}/W$	[N/mm²]	37,6	48,0	36,7	48,3	50,4	49,2	42,5	56,1
COV	[%]	12,5	4,7	13,0	5,9	6,8	3,5	5,0	6,9
Deflection	[mm]	70,2	86,6	64,0	97,5	88,6	83,2	61,7	74,8
COV	[%]	16,1	6,5	33,4	5,8	12,1	6,6	4,8	12,3
Failure at (number)		K (5)	K (5)	K (3) F (2)	K (1) F (3) T (1)	F (3) A (2)	K (1) F (2) A (2)	K (2) F (3)	K (2) F (1)
Failure mode (number)		c (1) d (4)	d (4) f (1)	c (3) d (2)	d (5)	c (2) d (3)	d (4) f (1)	d (5)	d (3)
ef MOE	[N/mm²]	10.400	11.400	10.300	11.500	12.700	12.200	11.100	13.100
COV	[%]	5,9	4,2	1,7	5,0	4,5	2,3	3,6	0,9

K: knot T: timber
F: finger joint A: abort of test

To compare the test results of the reinforced beams with corresponding unreinforced beams a simulation program was written. For the simulation the dynamic MOE and the density of every single board in the glulam was determined before glulam production. Figure 6 shows the results of the simulation and a comparison of the failure load F for reinforced and unreinforced glulam beams. Further this figure shows a comparison of the loads relating to the

local failure of the timber facing and the global failure. The load causing failure of the timber facing and global failure, respectively for every test series is higher than the failure load for the unreinforced beams. Test series Tr-8 shows the highest reinforcement effect with 33,1 kN for the failure load of the unreinforced beams and 66,5 kN for the CFRP reinforced beams. The large difference is due to the high reinforcement ratio with two CFRP lamellae and the arrangement of the CFRP in the outermost part of the cross section.
The reinforcement effect increases with increasing distance of the reinforcement to the centre of the cross section, with increasing reinforcement ratio and with increasing MOE of the reinforcement.

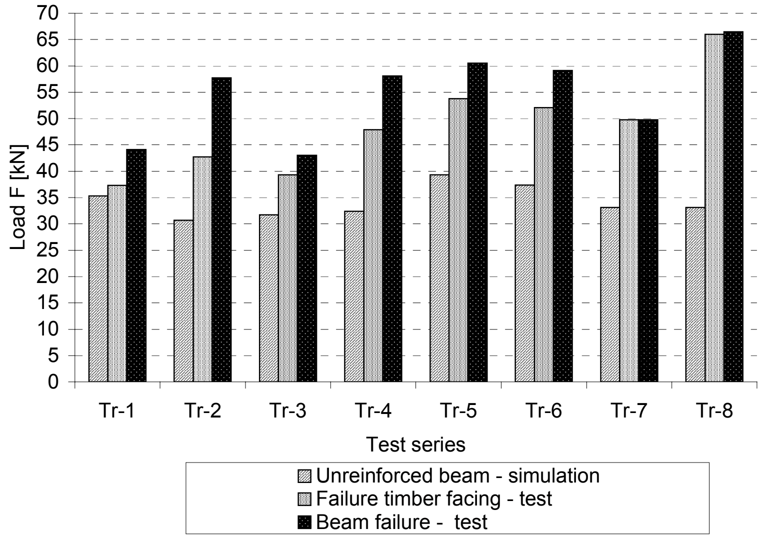

Figure 6: Mean values of the ultimate load for first and global failure

In Figure 7 the load-deflection curve of test specimen Tr-3.4 is presented with a first failure at the timber facing, a consequent global failure starting above the reinforcement after 30 % load increase. This load-deflection curve was typical for most specimens of the bending tests with timber facing. 6 of the 30 beams with timber facing showed no load increase after failure of the timber facing. Two of these beams, reinforced with AFRP, failed at a high load at the timber facing. This was due to the high grade C40 of the timber facing.

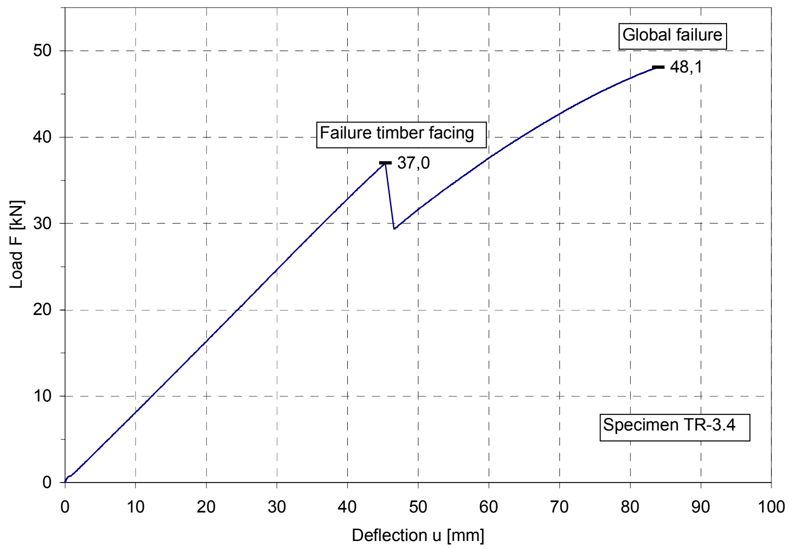

Figure 7: Load deflection curve of test specimen Tr-3.4

4 Summary

The results of the research project shows that by using FRP as tensile reinforcement an increase of the bending and axial stiffness is possible. Most test specimens showed a significant load increase after failure of the timber facing with a non linear load-defection curve. The reinforcement effect increases with increasing distance of the reinforcement to the centre of the cross section, with increasing reinforcement ratio and with increasing MOE of the reinforcement.

Further research will permit a more economic use of FRP reinforced glulam.

The test specimens mainly failed at the tension side at a knot or a finger joint. With a different cross-section set-up reinforced beams are possible which fail in a more ductile way on the compression side and show a reduced delamination effect for the timber facing.

References

Blaß HJ and Romani M (2000) Trag- und Verformungsverhalten von Verbundträgern aus Brettschichtholz und faserverstärkten Kunststoffen. Forschungsbericht der Versuchsanstalt für Stahl, Holz und Steine, Abt. Ingenieurholzbau der Universität Karlsruhe

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