Report:

Short Term Scientific Mission at Linnaeus University in Växjö, Sweden, from August 20th to October 12th 2012

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1 Research plan

1.1 Project description

The load carrying capacity of glued laminated timber beams is reduced considerably by notches at the support on the tension side of the beam. Stress concentrations at the notch corner together with low shear and perpendicular to the grain tensile strength lead to brittle failure. That is why notches are to be avoided. If this is not possible they have to be reinforced. For a safe and practical design approach geometrical parameters, material properties, ambient conditions and load characteristics are to be taken into account in a reliable way.

A PhD thesis entitled "Structural behaviour of glulam beams with notches at the support or with holes" currently carried out by the STSM participator at Empa Dübendorf in collaboration with ETH Zürich intends to find reliable approaches for the design of critical regions around notches and holes by means of reinforcement.

1.2 Related work in Switzerland and Sweden

At ETH Zürich, Switzerland, experimental tests have been carried out on glulam beams with unreinforced notches and notches reinforced with self-tapping screws under different angles in respective to the grain direction. These tests help to better understand the structural behaviour of the reinforced notch and give basis for further studies on the influence of varying material properties and changes in moisture content by means of Finite Element (FE) models. The fracture of the notched beam is simulated in FE by a material model accounting for progressive failure of wood. An analytical model for the determination of the load carrying capacity of reinforced notches has been developed.

In Sweden major research on notched beams was done in the past. Researchers from Linnaeus University in Växjö (LnU) and related Universities have knowledge on the structural behaviour of different reinforcement like glued-in steel rods. Furthermore in previous research glulam beams with reinforced and unreinforced holes were studied, both in theoretical and experimental investigations. Recently tests on notched beams reinforced with Glass Fibre Reinforced Plastics (GFRP) and with plywood were carried out at LnU. At Lund University, (LU), a probabilistic model for the analysis of glulam beams with holes was developed.

1.3 Research plan for the STSM

It was intended to benefit both from experience in experimental testing and in theoretical approaches during the STSM. Tests on notched beams reinforced with GFRP and plywood done at Linnaeus University were to be evaluated and then be compared with the results from tests on notches reinforced with screws performed at ETH and Empa. Further tests on notched beams reinforced with GFRP and fully threaded screws were planned for the STSM. The experimental and theoretical knowledge of the load carrying behaviour in shear and tension of these different kinds of reinforcements were intended to be used to validate an analytical model for an optimized design of reinforced notches. The models should take into account further effects like e.g. moisture variation and size.

The network of Linnaeus University with scientists from other Institutes in Sweden (SP Technical Research Institute of Sweden, and Lund University, Structural mechanics) was benefitted from in order to merge available knowledge, methods and approaches about how to reinforce weak points in the design of glulam beams with notches at the support.

Within this report the investigations on notched beams by means of FE-models, experimental tests and analytical models are discussed.

2 Analysis in FEM

The structural behaviour of notched beams can be analysed by means of Finite Element (FE) models. Within the STSM two different models were used. A static model with linear elastic material properties was used to study the stress distribution at the notch corner and the loading of the tip of a predefined crack. The crack growth and fracture energy was studied by means of a model using a non-linear material behaviour implemented in a user defined subroutine.

The commercial software ABAQUS version 6.10/EF-1 by Simulia was used for the simulations.

2.1 Static LEFM analysis

The main intention of the static model was to determine the effect of the reinforcement on the structural behaviour of the notch corner. The reinforcement should reduce the loading of the crack tip and thus help to prevent the crack growing. It could be shown, that the two different types of application of reinforcement reduce the loading of the crack tip in different way and thus lead to different types of failure behaviour. This could be validated in the tests.

2.1.1 Material

The material properties used in the FE-Model are summarized in Table 1. The unisotropy of timber was modelled using orthotropic material. The material properties are based on values specified for GL24h in Standard SIA 265:2012. Carbon fibre reinforcement properties were chosen based on material properties specified for SikaWrap® - 230 C/45 in connection with Sikadur® - 330 two component epoxy resin. In the product data sheet from Sika® the properties for the lamination consisting of CFR and resin of 1.0 mm thickness are given.

Table 1: Material properties used in FE model

Timber, orthotropic								
E1 [N/mm^2]	E2 [N/mm^2]	E3 [N/mm^2]	Nu12	Nu13	Nu23	G12 [N/mm^2]	G13 [N/mm^2]	G23 [N/mm^2]
11'000	300	300	0.4	0.4	0.4	500	500	50
Carbon Fibre Reinforcement (SikaWrap – 230 C/45 with Sikadur – 330 epoxy resin), orthotropic								
E1 [N/mm^2]	E2 [N/mm^2]	E3 [N/mm^2]	Nu12	Nu13	Nu23	G12 [N/mm^2]	G13 [N/mm^2]	G23 [N/mm^2]
25'000	10	10	0.3	0.3	0.3	10	10	10
Steel, isotropic								
E [N/mm^2]	Nu							
210'000	0.3							

2.1.2 Model

The timber beam was modelled in two parts, one with a finer mesh near the notch and a coarser one on the un-notched side: The part with the fine mesh was modelled with second order fully integrated solid elements (C3D20). The coarse part was modelled with first order (linear) solid elements with reduced integration (C3D8R).

The carbon fibre reinforcement used in the tests was orientated unidirectional. The strip together with the epoxy resin has a thickness of about 1mm. Due to its small thickness compared to the other dimensions it was modelled as shell elements. This helps to avoid distortion effects like bending in the reinforcement.

Steel parts were used at the load introduction point and at the support in order to prevent stress singularities due to load application in the timber elements.

Load was applied by a constant pressure on the loading plate of a magnitude of 0.74 N/mm^2 which is equivalent to a load of 9990 N.

The single parts were assembled by tie constraints to avoid excessive run time due to slip at the surface.

A crack of different length was inserted into the model by separating the nodes at the crack. Cracks of length 50, 100 and 250mm were modelled.

2.1.3 Analysis

In the linear elastic analysis with orthotropic material the J-integral can automatically be calculated by the software ABAQUS. However, a separation in fracture modes 1 and 2 is not possible. For the separation of the opening and shearing mode the mean stress method was used. A detailed description of the mean stress method is given in [1].

In this method the stress intensity factors (SIF) K_{I} and K_{II} and the energy release rates G_{I} and G_{II} are calculated from the mean stresses in tension perpendicular to the grain and shear, respectively, along the length x_0 from the crack tip. This length is calculated from the actual stress ratio at the corresponding distance, the elastic properties of the material and the critical energy release rates for mode 1 and 2 (Equation (1)).

$$x_0 = \frac{2}{\pi}\frac{E_I G_{IC}}{f_t^2}\frac{E_x}{E_y}\left(\frac{G_{IIC}}{G_{IC}}\right)^2 \frac{1}{4k^4}\left(\sqrt{1+4k^2\sqrt{\frac{E_y}{E_x}}\frac{G_{IC}}{G_{IIC}}}-1\right)\left(1+\frac{k^2}{\left(f_v/f_t\right)^2}\right) \tag{1}$$

Equation (1) is based on the Norris failure criterion. The elastic constants E_{I} and E_{II} are calculated from the elastic properties of the timber (Equation (2)).

$$\frac{1}{E_I} = \frac{1}{E_x}\sqrt{\frac{E_x}{2E_y}}\sqrt{\sqrt{\frac{E_x}{E_y}}+\frac{E_x}{2G_{xy}}-\nu_{yx}\frac{E_x}{E_y}} \qquad \frac{1}{E_{II}} = \frac{1}{E_x}\sqrt{\frac{1}{2}}\sqrt{\sqrt{\frac{E_x}{E_y}}+\frac{E_x}{2G_{xy}}-\nu_{yx}\frac{E_x}{E_y}} \tag{2}$$

The mixed mode level $k = K_{II}/K_I = \bar{\tau}/\bar{\sigma}$ is determined along the length x_0. Therefore the determination of length x_0 is an iterative procedure, until the result of Equation (1) matches the assumed length x_0. With this length the energy release rate can be calculated using Equations (3).

$$G_I = \frac{\bar{\sigma}_{yy}^2\,\pi\,x_0}{2E_I} \qquad G_{II} = \frac{\bar{\tau}_{xy}^2\,\pi\,x_0}{2E_I} \tag{3}$$

For the evaluation of the loading of the crack tip the resulting energy release rates were normalized by the critical fracture energies G_{c1} = 300 N/mm^2 and G_{c2} = 1000 N/mm^2.

2.1.4 Results and discussion

The load factors of energy release rates of mode 1 and 2 at the tips of cracks of length 50mm, 100mm and 250mm are summarized in Figure 1. The load factors belong to a load of approximately 10kN. The surface of the beam is at a depth of 0mm and the centre of the beam at a depth 45mm. Notched beams without reinforcement and with CFR in 90° and 45° to the grain direction were modelled. Due to distortion between the adhered reinforcement and the timber the values of the load factors at the surface of the beam at 0mm are to be treated with caution.

At the notched beam without reinforcement increasing energy release rates occur with increasing crack lengths. The load factors of mode 1 are significantly higher than the one of mode 2. A failure with crack opening is expected.

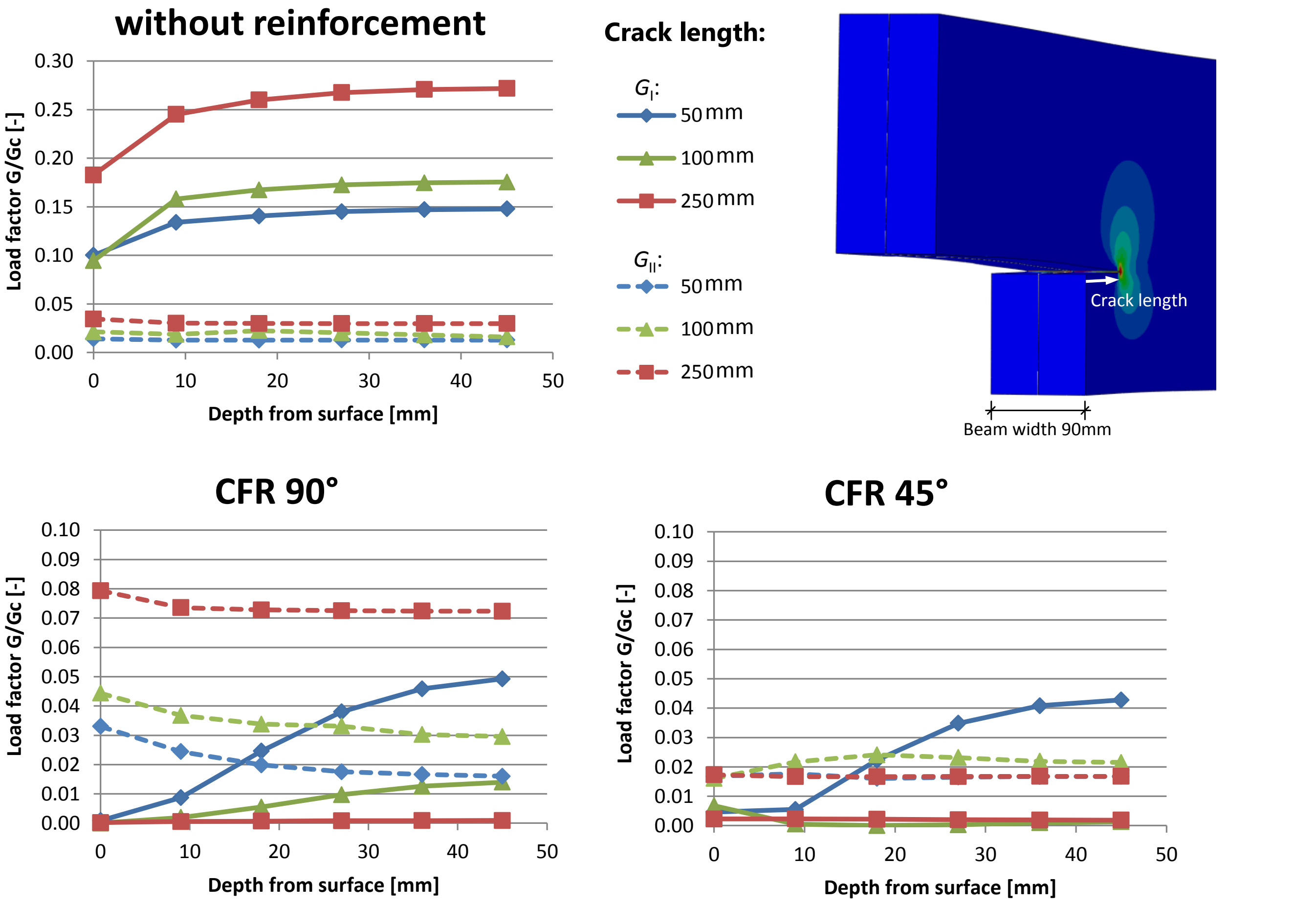


Figure 1: Load factors at the crack tip along the beams width for different crack lengths and applications of reinforcement

With reinforcement in 90° and 45° considerably lower load factors are reached at same loading. Furthermore the load factors of mode 2 fracture are relatively higher in relation to the one of mode 1. Therefore, especially for longer cracks a mode 2 shearing failure is expected.

For both applications of reinforcement the load factor of mode 1 is highest in the centre for small crack length. This coincides with tests, where first cracking is observed in the centre of the beams width at the notch corner at relatively low loads. The load factor in the simulations at a crack length of 50mm is for the reinforced notches about 3 times smaller than for the unreinforced notch. In test first cracking (crack length 0mm) was observed at similar loads both for reinforced and unreinforced notches. From simulations a similar behaviour can be expected for crack length 0mm.

At the notch with inclined reinforcement not only load factors of mode 1 but also of mode 2 are lower compared with the notch with reinforcement perpendicular to the grain. The load factors of mode 2 are not increasing with increasing crack length but are remaining at a constant level. Thus the expected failure will occur with a more constant crack growth compared to the notch reinforced with perpendicular to grain reinforcement. The corresponding R-curves are to be determined.

It can be concluded, that the reinforcement leads to a clear increase in load carrying capacity of the notched beams and the inclined reinforcement reduces the mode 2 shearing load on the crack.

2.2 Non-linear fracture mechanics analysis

The main intention of the model based on non-linear fracture mechanics was to study the fracture initiation and crack growth at the notch corner. Simple tests from material testing were used to validate the material model. The fracture initiation of a notched beam was studied in a later stage.

2.2.1 Material model

The material model based on nonlinear fracture mechanics is based on a linear degradation of stiffness after initiation of fracture. The energy dissipated during degradation is equal to the fracture energy. The model is based on orthotropic material properties with different strength and stiffness properties along longitudinal, tangential and radial direction. This distinction makes fracture along the weakest direction possible.

The same elastic material properties as used in the static LEFM analysis were used. Furthermore fracture energies and tensile and shear strength are required as summarized in Table 2.

Table 2: Material properties used in non-linear FM analysis

Timber, orthotropic								
E1 [N/mm^2]	E2 [N/mm^2]	E3 [N/mm^2]	Nu12	Nu13	Nu23	G12 [N/mm^2]	G13 [N/mm^2]	G23 [N/mm^2]
11’000	300	300	0.4	0.4	0.4	500	500	50

Timber, strength					
$f_{t,l}$ [N/mm^2]	$f_{t,r}$ [N/mm^2]	$f_{t,t}$ [N/mm^2]	$f_{v,lt}$ [N/mm^2]	$f_{v,lr}$ [N/mm^2]	$f_{v,rt}$ [N/mm^2]
40	1.5	1.5	5	5	1.5

Timber, fracture energies					
$G_{c,l}$ [N/mm]	$G_{c,r}$ [N/mm]	$G_{c,t}$ [N/mm]	$G_{c,lt}$ [N/mm]	$G_{c,lr}$ [N/mm]	$G_{c,rt}$ [N/mm]
0.3	0.3	0.3	1.0	1.0	10

2.2.2 SENB model

For the validation of the material model and the calibration of material properties a simple test configuration from material testing was used. The mode 1 fracture energy of timber is determined on single edge notched beam specimens as described by Larsen and Gustafsson [2]. This method is also called Nordtest method according to [3]. The load-deflection behaviour of the FE-model can be compared with results from previous tests. A good agreement is found as shown in Figure 2.

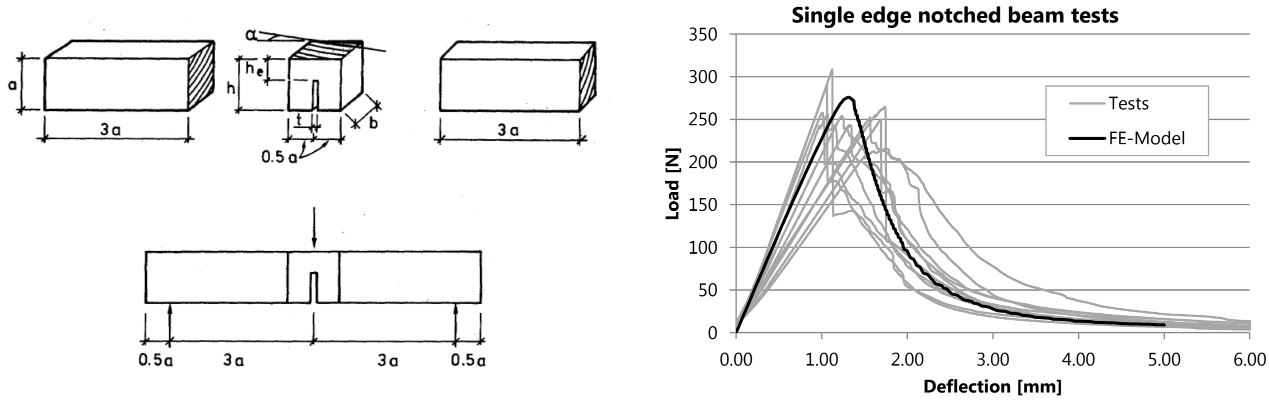


Figure 2: Single edge notched beam specimen [2] and comparison of FE model and tests

2.2.3 Notched beam model

The fracture initiation of the notched beam was studied in a 3D model. It is observed in experimental tests, that fracture initiation occurs in the centre of the beam width. The same was found in the FE-model. A convex shape of the crack front is observed as shown in Figure 3. In further models the influence of the year rings shall be studied.

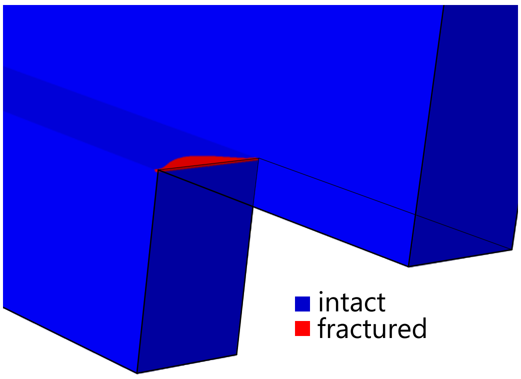


Figure 3: Fracture initiation at the notch corner

3 Tests on notched beams with and without reinforcement

3.1 Problem and aim

Tests have been performed to study the mixed mode state and the influence of different types of reinforcement on that during failure of the notch. Therefor notched beams with out and with two different types of reinforcement applied in two different directions each have been performed.

3.2 Material

3.2.1 Timber

Beams of Scandinavian timber strength grade L40c were used. This grade is comparable to the grade GL30c defined in FprEN14080 in terms of bending strength and stiffness. The most important material property values for the tests of class L40c and GL30c are shown in Table 3.

Table 3: Material properties of L 40c and GL 30c according to Svenkst Trä [4] and FprEN 14080 [5]

			L 40c	GL 30c
Bending strength	$f_{m,g,k}$	[N/mm^2]	30.8	30
Shear strength	$f_{v,g,k}$	[N/mm^2]	3.5	3.5
Compression strength perpendicular to the grain	$f_{c,90,g,k}$	[N/mm^2]	2.7	2.5
MOE parallel to the grain	$E_{0,g,mean}$	[N/mm^2]	13000	13000
Density	$\rho_{g,mean}$	[kg/m^3]	400	430

After testing several parts of the beams were cut out. The glulam was cut into the single lamellas in order to test the existing stiffness properties of these lamellas. These tests will be done at ETH Zurich in Switzerland and not finished for the moment.

At each end of the beams ordered during STSM a slice of approximately 45mm thickness was cut off in order to determine density, moisture content and shape of the growth rings of the lamella in the notch corner. Also densities of the whole slices and beams were determined. The values measured before preparing the reinforcement are given in Table 4.

Table 4: Densities and moisture contents of lamellas and beams

			Lamellas	Slices	Beams
Wet Density	*Mean*	[kg/m^3]	462	478	444
	COV		9.3%	5.2%	3.8%
Moisture Content	*Mean*	[kg/m^3]	11.9%		
	COV		6.7%		

The beams were stored in the lab hall together with the cut-offs of the lamellas and the beams from previous tests for about 3 weeks before testing. After finishing the tests the cut-offs had a moisture content of MC_{Mean} = 8.6% (*CoV* = 2.4%).

3.2.2 Reinforcement

Two types of reinforcement had been used to study the load carrying behaviour of the notched beams: Carbon fibre strips and fully threaded self-tapping screws.

SikaWrap® - 230 C/45 carbon fibre reinforcement was used. The lamella was cut into strips of 50 mm width. These strips were adhered to the timber by use of Sikadur® - 330 two component epoxy resign. The adhesive was applied to the surface with a thickness of about 1 mm. Into this layer the CFR strip was pressed until the resign came through the fibres. Afterwards the remaining resign was equally distributed over the surface of the strips.

Self-tapping fully threaded screws of type SFS WR-T-13 were used. The screws were screwed into predrilled holes in order to guarantee the direction of the screw and to prevent cracking.

3.2.3 Test specimen

For the tests during the period of the STSM 7 beams were ordered at a local timber merchant. In addition 3 beams remaining from former tests were prepared for testing. Preliminary tests were done on 3 beams that were already partly tested in former tests. InTable 5 all tests with respective configuration of reinforcement are given. The reinforcement was applied in two different configurations, perpendicular to the grain and inclined with an angle of 45° to the grain.

Table 5: Test specimen

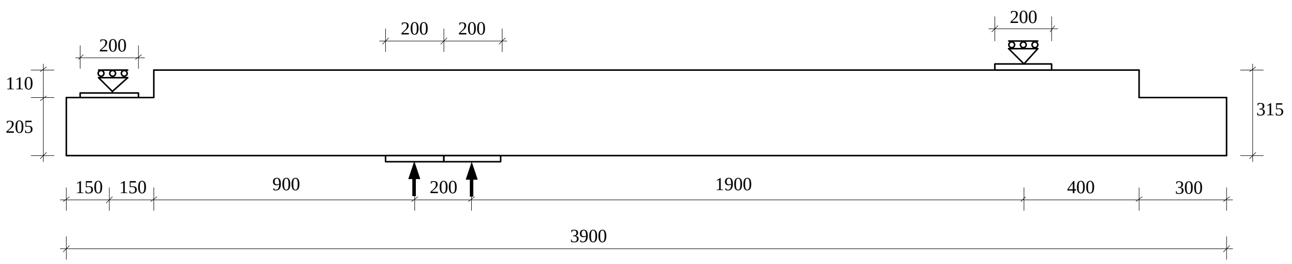
Beam	Notch	Reinforcement	Inclination of RF
3	A	Screw	90°
	B	without	-
4[1)]		Plywood	90°
8[2)]	A	CFR	
	B	CFR	
11	A	CFR	45°
	B	without	-
14	A	without	-
	B	without	-
15	A	CFR	90°
	B	Screw	90°
16	A	CFR	90°
	B	Screw	90°
17	A	CFR	45°
	B	Screw	90°
18	A	CFR	45°
	B	Screw	45°
19	A	CFR	90°
	B	Screw	45°
20	A	CFR	45°
	B	Screw	45°
21	A	CFR	90°
	B	Screw	45°

1) Preliminary test on untested notch from former test series

2) Preliminary tests on notches cracked in unreinforced condition in former test series

3.3 Methods

3.3.1 Procedure and test setup



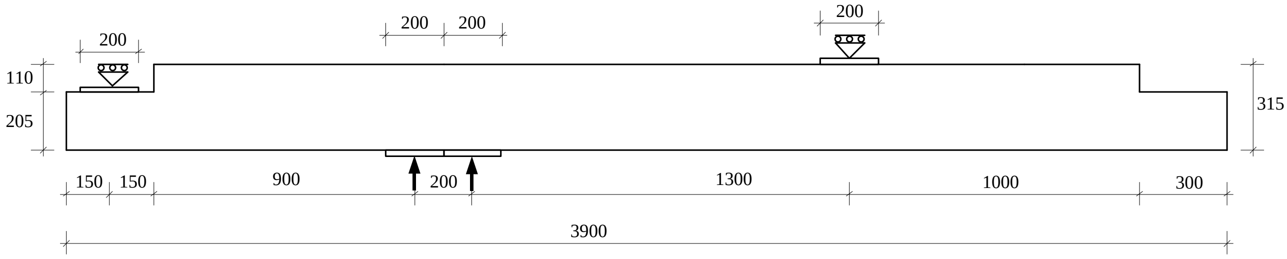


Figure 4: Test setups for initial tests (top) and secondary tests (bottom). The tested notch is on the left side.

Three point bending tests were performed with a span of 3.15 m. The load application was asymmetric leading to higher loading of the notched side of the beam. The load was applied via two loading cylinders with a distance of 200 mm.

Two different configurations were used for the tests. In order to mainly test the notched beam end a smaller distance between load and support was chosen on this side. The support on the other side was placed within the whole cross section and outside the reinforced part of the notch.

When testing the second notch of the beam crack growth from the formerly tested notch occurred in two cases. To avoid the beam to fail due to pure shear cracking growing from the cracked notch, the place of the support was shifted into a region which was mainly uncracked. Additionally the cracked notched was reinforced by means of plywood sheets of 250 length.

3.3.2 LVDT Measurements

Two separate LVDT sensors were used to measure the opening and shearing of the expected crack at the notch. In order to achieve the translation of the same points in the first series run by students in spring 2012 two brackets were used. However due to rotation not the correct horizontal and vertical opening was measured but the brackets started rotating with increasing flexural angle. In the tests run during STSM two separate brackets were used measuring the deformation of two points close to each other's.

Figure 5: Application of LVDT measurement sensors

3.3.3 ARAMIS Measurements

The optical system ARAMIS was used to determine the deformation in the surface of the notched beam. A pattern of small black dots is sprayed on the surface of the beam, which is covered with a white paint. During the measurement images of the surface are taken by two cameras within a predefined time or load step. The incremental displacements of the single dots between two images the total displacements and strains can be calculated by the program.

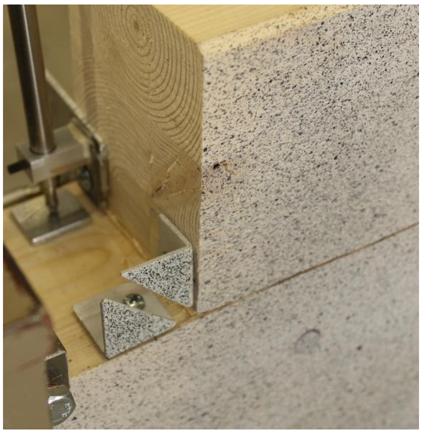


Figure 6: Surface pattern for ARAMIS measurements

3.3.4 Loading

The beams were loaded by two loading jacks controlled by a servo hydraulic system. The servo hydraulic system was pneumatically driven by compressed air. Due to the sensitive actuation of the compressed air it was not always possible to reach a constant loading ramp. It was intended to reach ultimate load within 5 minutes. The difference in load between the two loading jacks was increasing with increasing loading but not exceeding a maximum of around 1 kN.

3.4 Results and discussion

3.4.1 Ultimate loads

The ultimate loads and the type of failure are summarized in Tables 5 and 6. Figure 7 gives a comparison of the ultimate shear stresses in the reduced cross section.

The CF reinforcement with an inclination of 45° failed due to adhesive failure in the part of the reduced cross section at the support.

Table 6: Ultimate loads in in pre-tests

Beam	Notch	Span -ratio	Ultimate load	Shear Force	Comment
4	A	0.635	77.8	49.4	Shear cracking from opposite side
8	A	0.635	39.8	25.2	Shear failure of reinforcement
8	B	0.635	49.0	31.1	Shear failure of reinforcement

Table 7: Ultimate loads in tests on notched beams

Beam	Notch	Span -ratio	Ultimate load	Shear Force	Comment
Without Reinforcement					
3	B	0.635	35.1	22.3	
11	B	0.635	26.5	16.8	
14	A	0.635	30.9	19.6	
14	B	0.635	34.4	21.8	
Screw 90°					
3	A	0.635	31.9	20.3	Bending failure after shear cracking from opposite side
15	B	0.635	45.6	29.0	
16	B	0.635	62.8	39.9	
17	B	0.635	52.7	33.5	
Screw 45°					
18	B	0.635	67.7	43.0	
19	B	0.635	74.4	47.2	
20	B	0.635	62.7	39.8	
21	B	0.635	80.6	51.2	
CFR 90°					
15	A	0.635	62.7	39.8	Bending failure after shear cracking from opposite side
16	A	0.549	79.6	43.7	Notch failure, shear cracking up to load application point from opposite side
19	A	0.635	58.5	37.2	Notch failure, shear cracking up to load application point from opposite side
21	A	0.635	39.1	24.9	Notch failure, shear cracking up to load application point from opposite side
CFR 45°					
11	A	0.549	63.3	34.8	
17	A	0.549	76.4	42.0	Shear cracking from opposite side
18	A	0.635	52.8	33.5	Notch failure, shear cracking up to load application point from opposite side
20	A	0.549	73.1	40.1	Notch failure, shear cracking up to load application point from opposite side

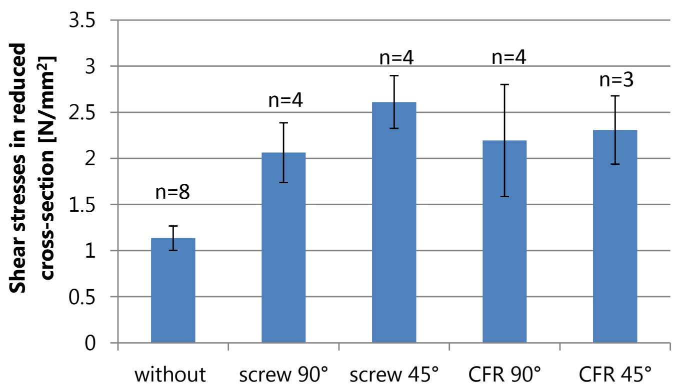


Figure 7: Ultimate shear forces at the notches

3.4.2 Measurements

Screw 90°

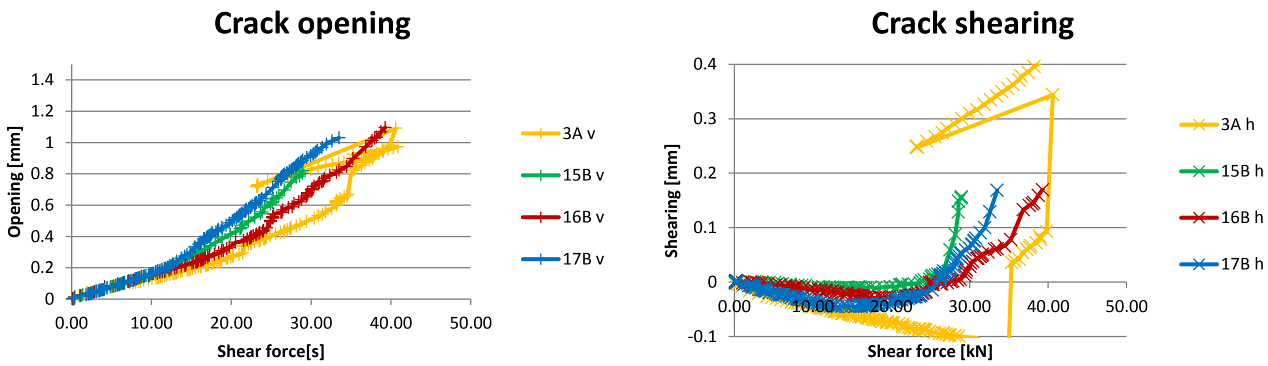
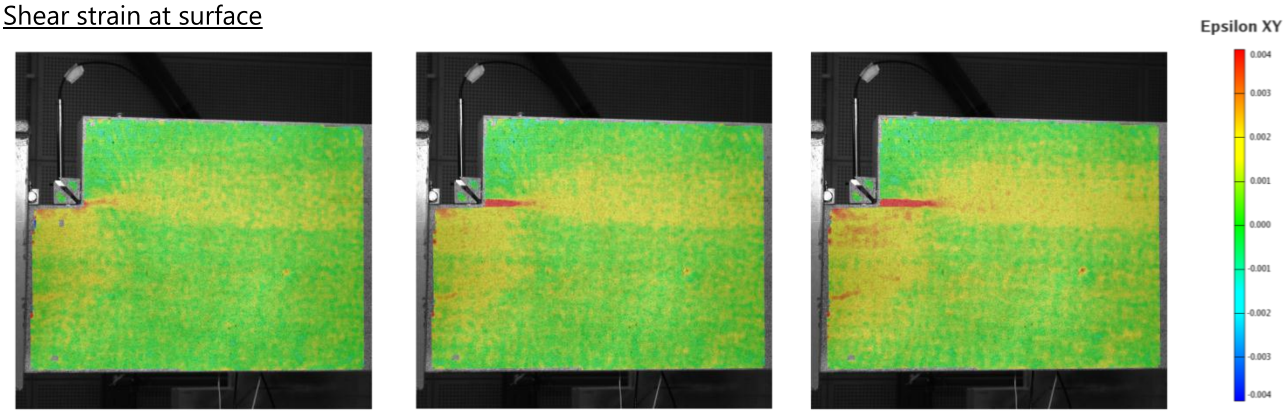


Figure 8: LVDT Measurements of opening and shearing displacement of the notch corner due to cracking

Load steps:

Crack initiation **Fully developed crack** **Before failure**

Shear strain at surface



Perpendicular to grain strain on surface

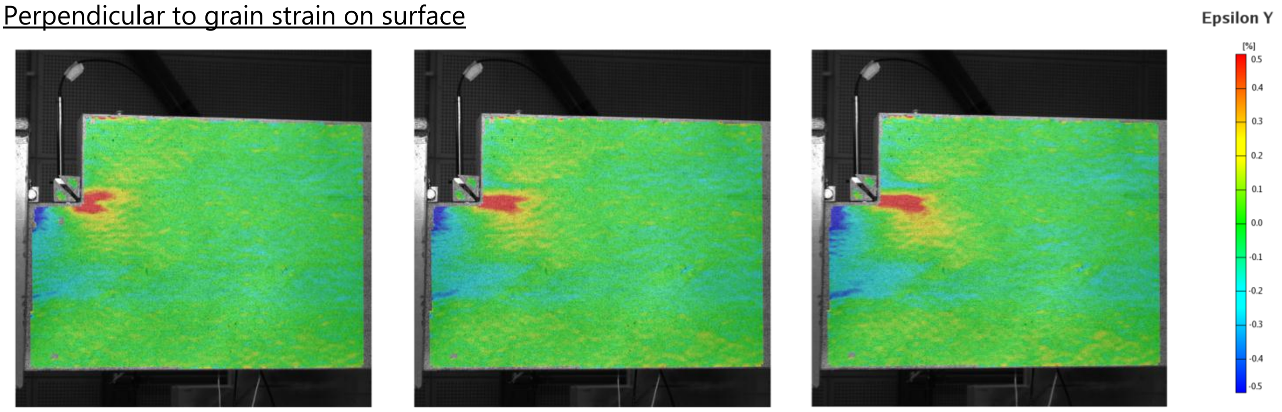


Figure 9: Examples of ARAMIS Measurements of notch 15-B

Screw 45°

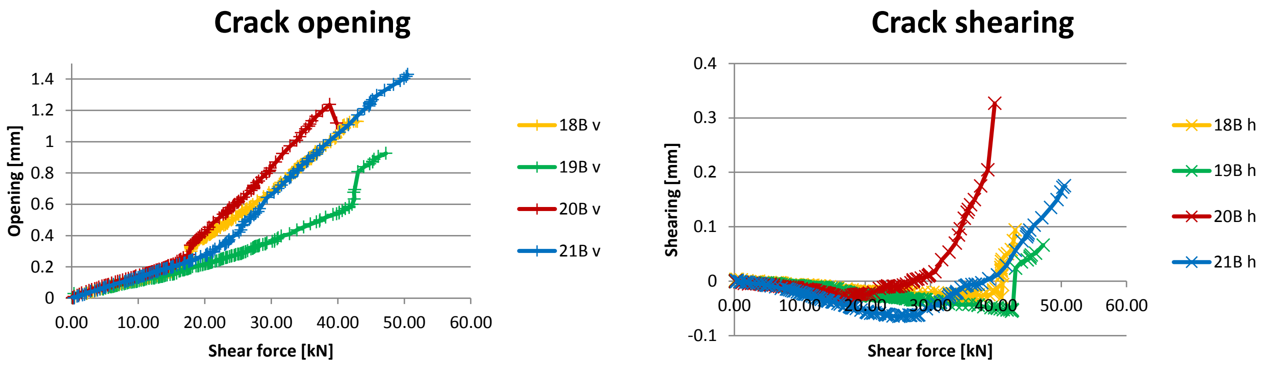
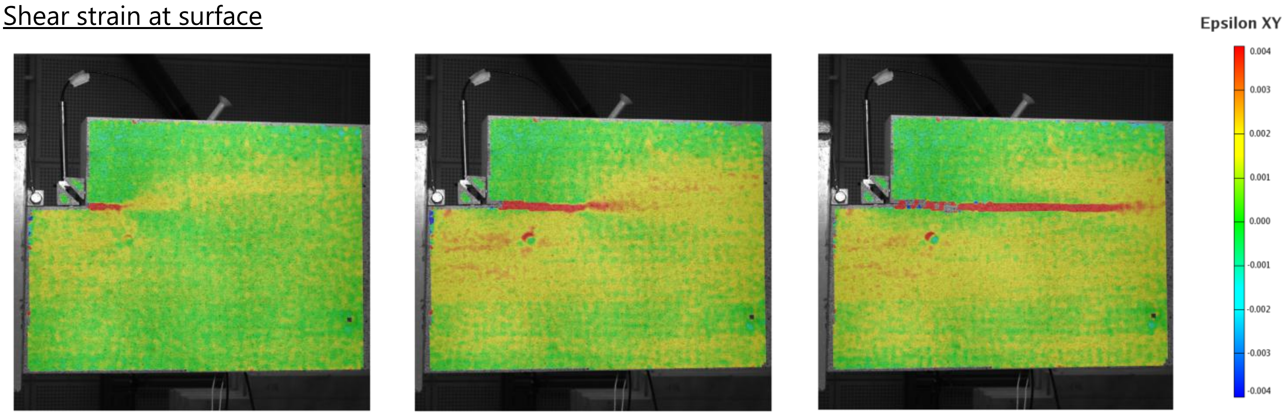


Figure 10: LVDT Measurements of opening and shearing displacement of the notch corner due to cracking

Load steps:

Crack initiation **Fully developed crack** **Before failure**

Shear strain at surface



Perpendicular to grain strain on surface

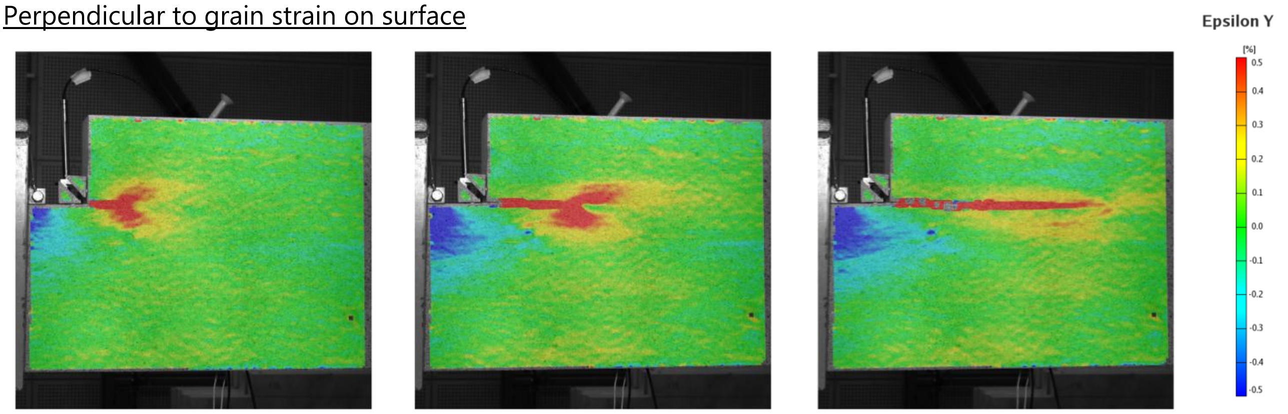


Figure 11: Examples of ARAMIS Measurements of notch 18-B

3.4.3 Discussion

The notches without any reinforcement failed in brittle way at relatively low loads. From the ARAMIS measurements a typical mode 1 fracture can be identified which is resulting in a big crack opening.

The reinforced notches reach higher ultimate loads and crack growth occurred before ultimate failure. The notches reinforced with screws at an angle 45° to the grain reached in medium higher loads compared with the notches reinforced at an angle of 45°. The difference between the notches reinforced with CFR is not significant.

When analysing the results of the CF reinforced notches, it has to be taken into account that two different types of failure occurred. The CFR in 90° to the grain failed by peeling off of the notched part of the cross-section of the beam whereas the CFR in 45° failed by peeling off of the reduced cross section of the beam. The reason for the peeling off of the reduced cross section can be identified in the ARAMIS measurements. In the region of the support, compression strains perpendicular to the grain can be found. The CFR in this region is under high tension leading to high strain differences in the contact zone. The resulting shear strain is leading to failure of the bondline of the CFR and the timber. The minimum of the strength of the adhesive and the rolling shear is decisive for the failure in the bondline.

From the studies on CFR in FE models it can be expected, that the notches reinforced with screw in 45° reach higher load carrying capacities than the one with screws perpendicular to the grain. The measurements with ARAMIS support these findings. In Figure 9 and Figure 11 the strain distributions on the surface of the beam are given. At initial loading both inclined and perpendicular to the grain reinforced notches show a strain distribution typical for mode 1 failure. In both cases a crack is growing up to a length where the reinforcement is in the timber. Just before reaching ultimate load, the strain distribution at the notch with perpendicular to grain reinforcement is still typical for mode 1.

The notch reinforced with inclined screws shows further crack growth. This crack growth is stable with increase in load. The strain distribution just before reaching ultimate load is typical for mode 2 fracture. Though high shear strains exist the timber is not failing in brittle way but is reinforced by the screws.

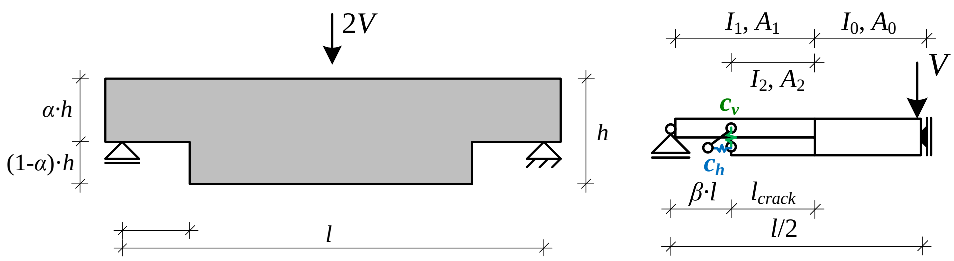
In further studies the detailed portion of load carried by the reinforcement has to be determined.

4 Analytical model

The experimental tests on reinforced notched beams shall be used for the validation and calibration of models based on finite elements and analytical solutions. The FE models intents to simulate the influence of varying material properties and moisture contents and the interaction between timber and reinforcement.

The analytical model describes the structural behaviour of a notched beam with different kinds of reinforcement. It shall help to find a simple equation for the calculation of load carrying capacity of reinforced notched beams. The model was developed at Empa Dübendorf and is based on the fracture mechanical model of a notched beam of Gustafsson [6]. The model consists of different beams of different cross sections connected to each other's by stiff connections in a first step. In a later step the connection can be modelled with a certain elasticity to take the effect of elastic clamping at the change of cross sections into account. By introducing reinforcement in form of springs at the notch corner into the model the effect of the reinforcement is intended be studied. In the model different parameters can be studied: The deflection at the load introduction point and the deformation of the notch corner can be determined in dependency of the beam stiffness and the stiffness of the reinforcements. The deformation of the notch corner and thus the deformation of the reinforcement lead directly to the forces acting in the reinforcement. Since different types of reinforcement (Plywood sheets, screws, Glued in rods etc.) exhibit different stiffness in different directions (axial vs. lateral, in direction vs. perpendicular to the grain orientation of the main veneer) this will influence the deflection of the notch beam in total. From the differential change in deflection during the infinitesimal increase of crack length at the notch the energy release rate can be determined as described by Gustafsson [6]. Since this energy release rate describes the mixed mode fracture state at the notch it cannot directly being used for further analyses. By artificially preventing the crack from opening during crack growth a mode 2 (shearing) state can be generated. The difference to the mixed mode state gives energy release rate of the mode 1 (crack opening). By using these two separated modes a fracture criterion can be used to calculate the load carrying capacity of the notched beam at a certain length of the crack.

In discussion with researchers at the department of structural mechanics at Lund University, especially with Per-Johan Gustafsson who developed the fracture mechanics model for notched beams used in the current EC5, the method of separation of fracture modes could be improved. The crack is not only supported in a discrete point to prevent separation of the crack flanges leading to crack opening but more continuously along its whole path. Thus a better distinction between the two modes is possible. Further studies on how the structural behaviour of notched beams is influenced by different types of outer and inner reinforcement are to be conducted.



$$A_0 = bh$$
$$A_1 = b\alpha h$$
$$A_2 = b(1-\alpha)h$$
$$I_0 = bh^3/12$$
$$I_1 = b(\alpha h)^3/12$$
$$I_2 = b(1-\alpha)^3 h^3/12$$

Figure 12: Notched beam and simplified model with springs as reinforcement

5 Conclusion

During the STSM in Växjö experimental tests and theoretical studies have been carried out to determine the influence of different types and applications of reinforcement on the load carrying capacity of notched beams. In FE Models the influence of CFR applied perpendicular to the grain and inclined with an angle of 45° to the grain on the loading of the crack tip and the resulting ratio of mode 1 and mode 2 energy release rates have been studied. In experimental tests the load carrying capacity and the crack evolution of notched beams has been determined. Conventional measurement devices and optical deformation measurement systems have been used. The results are used for further studies on an analytical model based on an energy description of the beam during crack growth. It is intended to use this model for the development of an approach for the design of optimized reinforcement of notched beams.

6 Outlook

It is intended to further analyse the results from the studies and tests during the STSM and to publish and present them within COST Action FP 1004 and other platforms. It is desired to communicate the results and observations during the next meetings and training schools of COST Action FP 1004 and possibly also in co-operation with COST Action FP 1101. The design approach which is currently developed on basis of the analytical model is intended to be presented on next CIB W18 meeting in summer 2013. The behaviour of self-tapping screws as reinforcement for tension perpendicular to grain and shear shall be presented on RILEM Conference in autumn 2013.

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