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Shear Reinforcement of Cracked Glulam Beams

Kristine Vik
Structural Engineering and Architecture

Preface

This thesis represents the end of my 5-year degree in Structural Engineering and Architecture. The topic was first presented during a guest lecture by Andreas Stenstad in the course TRE 300, Wood Technology last spring. I saw this as an opportunity to combine my interest for older timber buildings, rehabilitation, and sustainability with a structural design thesis.

I would like to thank my supervisor, Roberto Tomasi and the people at Norsk Treteknisk Institutt, Svein Arne Klinkenberg for help with all the mechanical tests and Andreas Stenstad for all the good advice and support.

Also, I want to thank my roommates for listening to my complaining about having to write a master thesis during a pandemic. And my family and friends for all support and for bearing with during this time. Especially my father for always being just a phone call away and always supporting me and believing in me.

Ås, June 2021

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Abstract

Timber materials for construction have long traditions in Norway, mostly used for smaller and domestic buildings. The expansion of engineered timber such as glulam and CLT has made timber usable also in buildings where steel and concrete have been more prevalent. Such as industrial buildings, office buildings, schools, and sports halls. However, as these buildings age, they are oftentimes demolished when they no longer meet the requirements of modern structural design.

To reinforce structural elements several methods have been established, depending on the properties one wishes to improve. Many involve the use of fibre reinforced polymer (FRP) bonded with wood adhesive, but screws and gap-filling glue are also in use. Although these methods of reinforcement do exist, they are not always used today as they are often extensive and cost of demolition and rebuild is relatively low.

This paper focuses on whether cracks reduce the capacity of glulam beams. And also investigates a means of reinforcement where split glulam is added to the sides of a cracked beam using wood adhesive. First, whole beams and beams with sawn-in cracks were tested for bending with an asymmetrically placed load with the intent of provoking shear fracture. The resulting failure mode was a combination of crushing, bending and shear. Still, the capacity of the cracked and uncracked beams was significantly different. On average, the cracked beams the cracked beams experienced a reduction of capacity of 84 %.

When evaluating the reinforcement method, the focus was on which on-site methods would produce a sufficiently strong glue line. Means of pressurisation, moisture content and surface coating were evaluated when deciding on an ideal gluing method. Painted surfaces or timbe with high moisture content will prevent the glue from bonding with the surface and cause severe delamination.

The strongest glue lines were obtained by following the recommendations of the glue producer. The timber should be dry, 6-25 % MC, with as little difference as possible between the parts that are glued together, and the amount of glue somewhere between 1000 and 2000 g/m^2. Pressure should be applied with either clamps or screws at each 400 mm at the upper and lower side of the beam.

The presence of cracks can reduce the capacity of structural elements. This is mostly accounted for by using the reduction factor k_{cr}, from Eurocode 5, when designing cross sections for shear capacity. But if the cracks are larger, reinforcements are necessary. When using glued-on split glulam for this the surfaces should be dry and not painted.

Sammendrag

Tre som byggemateriale har lange tradisjoner i Norge, for det meste til bruk i boliger og andre småhus. Utbredelsen av bearbeidete treprodukter som limtre og krysslaminert tre har gjort det mulig å bruke tre i bygninger hvor man tidligere ville brukt stål og betong. Som i industri- og kontorbygninger, skoler og idrettshaller. Men etter hvert som disse bygningene blir eldre blir de ofte revet når de ikke lenger lever opp til moderne standarder for prosjektering.

Flere metoder har blitt utviklet for å forsterke konstruksjonselementer avhengig av hvilke egenskaper man ønske å forbedre. Mange involverer bruk av forsterkede polymerer (FRP) og trelim, men skruer og lim til å fylle i spekker er også i bruk. Men selv om disse metodene finnes blir de ikke alltid brukt i dag da de ofte er omfattende, og kostandene ved rivning og gjenoppbygging er relativt lave.

Denne oppgaven fokuserer på hvorvidt sprekker reduserer skjærkapasiteten til limtrebjelker. I tillegg til å undersøke en forsterkningsmetode hvor man limer splittet limtre på siden av oppsprukne limtrebjelker. Først ble hele bjelker og bjelker med innsagde sprekker testet for bøyning med en usymmetrisk last for å framprovosere et skjærbrudd. Det resulterende lastbildet va en kombinasjon as knusing, bøyning og skjær. Allikevel var forskjellen i kapasitet mellom bjelkene med og uten sprekker signifikant. Den gjennomsnittlige reduksjonen i skjærkapasitet var 84%.

Under vurderingen av forsterkningsmetoden var målet å undersøke hvordan forsterkningen kunne foregå på en byggeplass og samtidig oppnå limfuger i henhold til kravene. Pressetrykk, fuktinnhold og overflatebehandling ble vurdert. Malte overflater og tre med høyt fuktinnhold vil forhindre limet fra å feste seg til overflaten og forårsake alvorlig delaminering.

De sterkeste limfugene ble oppnådd ved å følge limprodusentens instruksjoner. Treet bø være tørt, 6-25 % MC, med så liten fuktforskjell som mulig mellom de to tredelene som skal limes sammen, og en limmengde på mellom 1000 og 2000 g/m^2. Trykk bør påføres med tvinger eller skruer for hver 400 mm øverst og nederst på bjelken.

Sprekker kan redusere kapasiteten til bygningsdeler. Dette er vanligvis tatt høyde for ved bruk av reduksjonsfaktoren k_{cr}, fra Eurocode 5, når man dimensjonerer tverrsnitt for skjærkapasitet. Men dersom sprekkene er store, vil forsterkning være nødvendig. Når man bruker splittet limtre til dette bør overflatene være tørre og uten maling.

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1 Introduction

1.1 Background

Timber has been used as a construction material for thousands of years as it is easily available and has a high strength compared to its weight. After the invention of engineered wood material such as glulam and CLT, timber construction has evolved to include larger industrial buildings, sports halls, schools, and some of the most well-known architectural statement-buildings in the country.

One of the factors to be considered when choosing a material is its environmental impact. As more and more people are aware of the importance of sustainability, also in the construction industry, timber has become the preferred material for many. This is because timber has a very low carbon footprint compared to steel and concrete. Wood can be grown sustainably and will store carbon as it grows, and also after being cut down and made into timber.

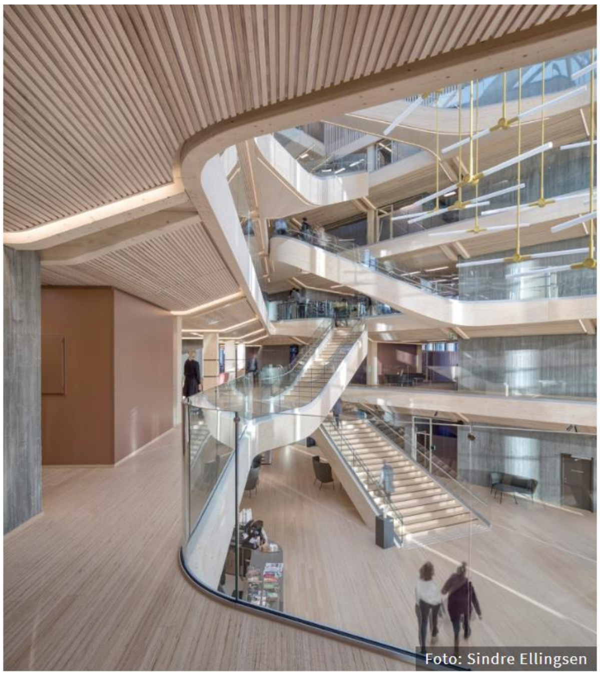


Figure 1: Finansparken i Stavanger, (photo: Sindre Ellingsen– Helen & Hard/SAAHA Arkitekter –Byggherre Finansparken Bjergsted AS)

However, this carbon storage only happens as long as the building still stands. The CO_2 stored in the timber will usually be released after demolition as most of the wood are not recycled but incinerated.

Even though new buildings can be built in a more sustainable manner, the impact of demolition as well as the production and transportation of new materials is so great that it will take decades before the new building is as sustainable as the old one (Fufa et al., 2020). The rehabilitation of older buildings will help keep the materials out of the carbon cycle for a longer time.

Most buildings are designed for a 50 years life span (Standard Norge, 2016a), and as timber is an organic material, and the building will start to deteriorate after that. In addition to this, characteristic loads and rules of design has become stricter and more conservative over the last 50 years leading to many existing buildings being undersized.

To maintain the safety of these buildings, rehabilitation and repair of constructions parts are often necessary. A variety of different repair methods have been developed over the years focusing on different problems. One of the most common failures in older buildings is cracks. These can be caused by varying moisture content and are often the first sign of a capacity problem. The existence of cracks in load bearing elements can significantly decrease their capacity.

Although these methods exist, they are not frequently used and only 1-1.4% percent of buildings are upgraded today (Fufa et al., 2020). Increasing the rehabilitation ratio will not only spare our environment from excessive material use and CO_2 emission, but also preserve buildings of historical value and architectural qualities as

1.2 Aim, scope, and restrictions

This paper will focus on the influence of cracks on the shear capacity of glulam beams. And present a method for repair. Fist, a state-of-the-art summary of the most common reinforcement techniques will be presented. Then experimental methods investigating crack influence on shear capacity, and a method of reinforcement involving gluing on split glulam on the sides of cracked beams for shear reinforcement. The reinforement method is illustrated in figures 2-5, a cracked glulam beam is coated with wood adhesive and an equal-sized piece of split glulam is placed on top.

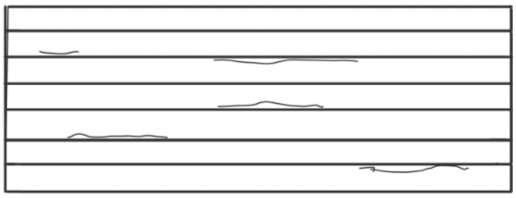


Figure 2: Cracked glulam beam

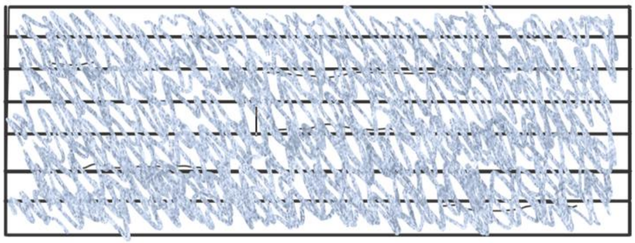


Figure 3: Cracked glulam beam with glue

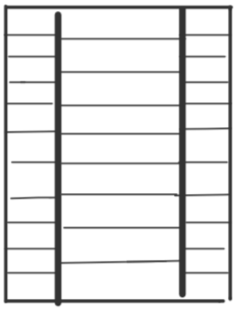


Figure 4: Repaired glulam beam, from the side

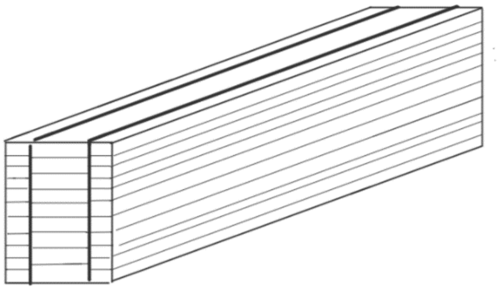


Figure 5: Repaired glulam beam

The research questions to be answered are:

How does the existence of cracks influence the shear resistance of glulam beams?

Which methods of reinforcement and repair are in use today, and what are their characteristics?

When using a repair method involving gluing on split glulam, what should be considered for optimal results?

2 Theory

2.1 Wood as a construction material

As opposed to other construction materials such as steel and concrete wood is a natural and organic material. Its properties vary according to the orientation of the wood, meaning that the strength of the wood is different along the growth length, tangentially to the annual rings and radially to the annual rings. When a material's properties differ in three directions that material is called orthotropic (Dahl, 2009). Dahl (2009) lists of previously measured strengths of spruce shows that its elastic modulus varies on average from 10991 N/mm^2 in longitudinal direction to 716 N/mm^2 in radial and 435 N/mm^2 in tangential directions. As the elastic modulus in the longitudinal direction is significantly higher than in both the radial and the tangential directions, in many cases the strength properties of wood would only be divided into parallel and orthogonal to the grain/direction of growth.

Even though small samples of clear wood can be measured to high strengths the same values will not apply to construction wood used as beams and columns in buildings. This is because these measurements do not account for impurities, such as knots, in the wood. The area around the knots will have an irregular fibre structure and the wood will be weaker. When sorting timber, one would therefore assign a lower strength class to knotted timber (Standard Norge, 2009)

2.2 A brief history of glulam

In 1906 the German engineer Otto Hetzer patented a method of creating curved beams by gluing together thin lamellae of wood. These beams, called «Hetzer binder» were used in constructing the "Reichseisenbahnhalle» for the World Industrial Exposition in Brussel *(Exposition Universelle et Industrielle des Bruxelles)*. Glulam production in Norway and Sweden was started in 1918-1919 by Guttom Brekke. Some of the earliest glulam constructions in Scandinavia are the railway station-halls in Stockholm, Malmö, and Goteborg (Norske Limtreprodusenters Forening, 2016). Aside from these examples widespread use of glulam was not common until the 1960s. Today, glulam products are used in a variety of buildings, the opportunity of long spans makes them particularly common in industrial buildings, schools, and sports halls.

2.3 Production of glulam

Glulam is made by gluing together thin lamellae of between 6- and 45-mm thickness where the longitudinal direction of the fibres is parallel to the length of the lamellae (Standard Norge, 2016b). Fist, the lamellae are cut from raw timber, then dried, strength-graded, finger jointed along the length, and glued together (Norske Limtreprodusenters Forening, 2016). The moisture content of the lamellae should be about 6-15 % to optimize the strength of the glue line.

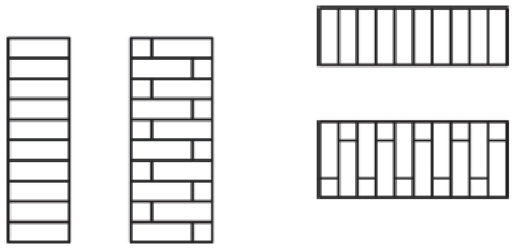


Figure 6: Glued laminated timber, figure 4 from NS-EN 14080

Only one species of wood can be used for the same glulam member. In Norway spruce (*Pica Abies*) is most used, but the glulam standard, NS-EN 14080 also includes other species of softwood. Using only laminations of the same strength result in a homogenous glulam element, e.g. GL30h if its bending strength is 30 MPa. To better make use of the raw material it is common to use the best timber qualities in the outer lamellae and a lower quality in the middle. This is called combined glulam and will be assigned the strength class GL30c. Table 1 shows how the assembly of combined glulam elements from different grades of structural timber.

Table 1: Strength sorting of glulam depending on the strength class of the laminations, Table 2 from NS-EN14080

Glued laminated timber	Outer zones of laminations			Intermediate zones of laminations			Inner zone of laminations		
Strength class	Strength class	Propor-tion [%]	$f_{m,j,k}$ [N/mm^2]	Strength class	Propor-tion [%]	$f_{m,j,k}$ [N/mm^2]	Strength class[a]	Propor-tion [%]	$f_{m,j,k}$ [N/mm^2]
GL 20c	T13	2x33	21	-	-	-	T8	34	18
GL 22c	T13	2x33	26	-	-	-	T8	34	18
GL 24c	T14	2x33	31	-	-	-	T9	34	19
GL 26c	T16	2x33	34	-	-	-	T11	34	22
GL 28c	T18	2x25	37	-	-	-	T14	50	28
GL 28c	T21	2x17	36	-	-	-	T14	66	26
GL 28c	T21	2x17	38	-	-	-	T13	66	25
GL 28c	T21	2x25	35	-	-	-	T11	50	22
GL 28c	T21	2x20	35	T14	2x20	28	T11	20	22
GL 28c	T22	2x20	35	-	-	-	T13	60	25
GL 30c	T22	2x17	40	-	-	-	T15	66	27
GL 30c	T22	2x17	41	-	-	-	T14	66	28
GL 30c	T22	2x20	40	T14	2x20	30	T11	20	22
GL 30c	T22	2x17	42	T14	2x23	31	T11	20	22
GL 32c	T24	2x17	44	-	-	-	T18	66	31
GL 32c	T26	2x17	45	-	-	-	T14	66	26
GL 32c	T26	2x10	48	T18	2x20	32	T11	40	22

The strength of the glulam is determined from the strength of its components and their material properties. This includes the strength of the laminations as well as the strength of the glue lines and finger joints. Bonding strength is the strength of the glue lines between laminations and the strength of finger joints. NS-EN 14080 states the shear strength of each glue line to be minimum 6 N/mm^2, although if there is no delamination this can be reduced to 4 N/mm^2.

The glues qualified for glulam production according to NS-EN 14080 are phenolic and amino plastic (MF, MUF, PRF, UF), moisture curing one-component polyurethane (PUR) or emulsion polymer isocyanate (EPI) adhesives. EPI can only be used in service class 1 and 2.

In current glulam production the most common type of glue is MUF (melamine-resorcinol-formaldehyde). Two-component PRF-glue (phenol-resorcinol-formaldehyde) can mostly be found in older glulam members as it used to be more common in manufacturing.

PRF is mostly used for large finger joint and for instances where normal pressure requirements are difficult to achieve (Dynea, 2017). For connections and on-site repairs polyurethane and epoxy is commonly used (Norske Limtreprodusenters Forening, 2016).

2.4 Crack influence on timber

2.4.1 Causes of cracks

As an organic material, wood contains water. Directly from the factory, glulam will have a moisture content (MC) of about 12%. As the material is in use it will adjust its moisture content to the environment around it. The humidity of the air changes with the seasons, and so does the moisture content of the timber. Indoor timber usually has a higher moisture content in the summer, while outdoor timber har a higher moisture content in the winter.

Timber materials swell with high MC and shrink with low MC. This change is greater perpendicularly to the grain (0,2% per percentage increase in MC) than parallel to the grain (0.01% per percentage increase in MC) (Norske Limtreprodusenters Forening, 2016). If this motion is hindered in some way, it will result in internal stresses in the wood that may exceed its radial or tangential strength (Franke et al., 2015). These stresses are what causes cracks.

The different laminations constituting the glulam element may have differences in strength, moisture content and other qualities. When the swelling-shrinking motion approaches the glue line, it will be stopped by the rigidity of the glue. As a result, many cracks in glulam appear near the glue line, although not in the glue line itself (Sandberg et al., 2013).

Errors during the gluing process, such as poor conditions during cuing, or surface preparation can make the bonding unsuccessful and lead to delamination (Gomes Ferreira et al., 2017). A delamination is essentially a “crack” in the glue line and may negatively impact the strength of the glulam similarly to cracks in the timber.

2.4.2 Research on crack influence

To evaluate the crack influence in shear capacity Berg et al. (2015) conducted a three-point bending test of beams with pre-manufactured cracks to determine the failure load due to cracks. The results where later verified with numerical simulation. All the beams they tested had their capacity reduced due to cracks. Tis reduction varied according to crack placement and the number of cracks, between 90 and 70% of full capacity.

Gomes Ferreira et al (2017) investigated the effect of delamination on the strength and stiffness of glulam beams. In their results the beams with end delamination showed a decrease in strength and stiffness. This reduction was more severe in beams with longer delamination lengths. When the delamination did not involve the whole width of the cross-section, the strength reduction was not deemed significant.

2.4.3 In EC5

Cracks in the timber will essentially create a gap in the material, reducing the original width of the beam or column. In Eurocode 5 (Standard Norge, 2010), the crack influence on shear capacity is considered with the use of the constant k_{cr}. For glulam and structural wood this reduction factor is 0,67. Thus, the effective width of a cross-section is given as:

$$b_{ef} = k_{cr} \times b \qquad (1.1)$$

where b is the width of the cross section

Eurocode 5 states the following conditions for shear:

$$\tau_d \leq f_{v,d} \qquad (2.2)$$

Where: τ_d is the dimensioning shear stress

And $f_{v,d}$ is the dimensioning shear strength under real conditions

2.2 Shear testing

2.2.1 Shear test of beams

The standard for determining mechanical properties of timber, NS-EN 408, describes two methods for determining the shear modulus of glulam or structural timber. The torsion method uses a test piece with a rectangular cross section that is at least 19 times the largest of the cross-sectional dimensions. The pieces are clamped at the support spaced at least 16 times the largest cross-sectional dimension. Then it is subjected to torsion. The relative rotation of two cross sections on the free testing length is measured as well as the torque. The shear modulus is derived from the relationship between the applied torque and the relative rotation.

The shear field test method uses a test piece with a length that is 19 times the depth. It is loaded symmetrically in bending at two points over a span 18 the depth of the specimen (Show figure). In the middle of the area under constant shear stress, between loading point and support, a square is marked on both sides. A device that measures the diagonals of the square is fixed to its surface. When load is applied this device measures the deformation of the squares, and the shear modulus is derived from this.

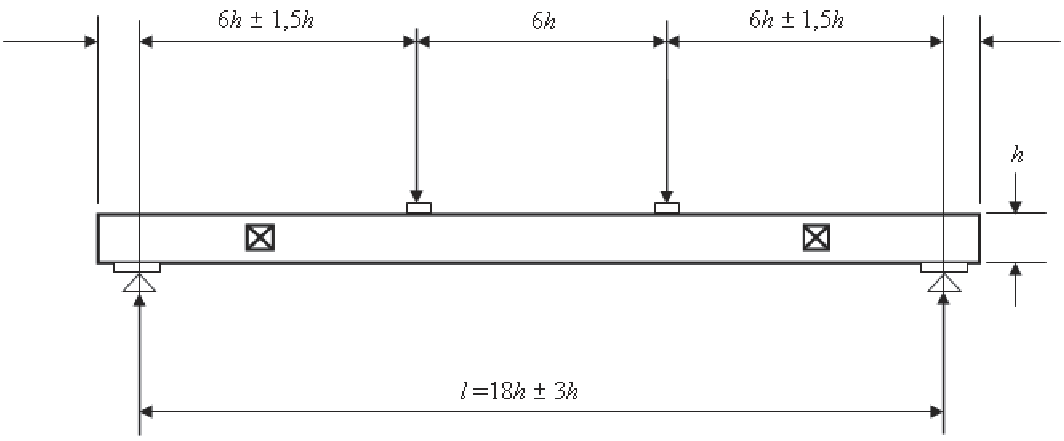
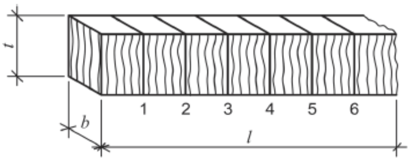


Figure 7: Test arrangement for shear field test, figure 7 from NS-EN 408

2.2.2 Shear test of glue lines

The shear strength of glue lines can be determined using a method given in Annex D of the glulam standard, NS-EN 14080.



Key

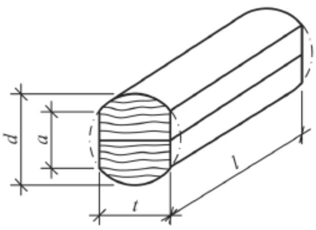
b width, dimensions 40 mm to 50 mm

l length

t thickness, dimensions 40 mm to 50 mm

1 to 6 number of glue line within the specimen

Figure 8: Test bar and numbering of the glue lines, figure D.2 from NS-EN 14080



Key

a straight edges, (23 ± 5) mm

d diameter, (35 ± 5) mm

l length, 50 mm to 120 mm

t thickness, (26 ± 3) mm

Figure 9: Drill core with machine parallel plane surfaces, figure D.3 from NS-EN 14080

The test pieces can be prepared in two ways, as test bars or drill cores. The test bars are cut from the whole cross-sectional specimens and can be used to test all glue lines in the specimen. At least three glue lines each in the lower, middle, and upper part of the beam must be tested. If the beam consists of less than 10 laminations, the whole cross-section must be tested.

It is recommended that the full cross-sectional specimens are taken within areas of the glued laminated timber or glued solid timber where sufficient clamping pressure has been established.

A single glue line can be tested using core samples. A core can be drilled out of the beam without destroying the element, making this method particularly useful in evaluating the bond strength of glulam elements in use (Tannert 2012). The core samples are drilled in such a way that the glue line is in the middle of the sample, and then planed at the sides so that the shearing area is rectangular.

The samples should be conditioned to a standard climate of 20°C ± 2°C and 65% ± 5% RH and measured to determine the sheared area. Then the test piece is placed in the shearing tool so that the load will go along the direction of the grain. The glue lien is positioned so that the distance between the shearing tool and the sheared plane is no more than 1 mm. For testing glue lines with gap-filling adhesives, the shear plane should be in the timber-adhesive interface. The testing machine will then apply a compressive force to the shearing tool at a constant rate.

The machine measures the maximum load and the shear strength of the glue line in calculated from:

$$f_v = k_v \frac{F_u}{A} \tag{2.3}$$

Where: F_u is the ultimate load, A is the sheared area and k_v = 0,78 + 0,0044*thickness

Wood failure is rupture in or between the wood fibres. When there is more than one cell layer left on the glue side, one would consider this wood failure. This is the opposite of delamination indicating that the bond between wood and glue is strong. When evaluating glue lines the percentage of the wood failure area in relation to the whole shear area is determined by visual inspection. The percentage of wood failure is then rounded off to the nearest 5%

Table 2: Minimum wood failure percentage relating to the shear strength f_v^a, table 10 from NS-EN14080

	Average			Individual values		
Shear strength f_v, in N/mm²	6	8	$f_v \geq 11$	$4 \leq f_v < 6$	6	$f_v \geq 10$
Minimum wood failure percentage, in %[b]	90	72	45	100	74	20

[a] For values in between linear interpolation shall be used.

[b] For average values the minimum wood failure percentage shall be: 144 – (9 f_v). For the individual values the minimum wood failure percentage for the shear strength $f_v \geq 6{,}0$ N/mm² shall be: 153,3 – (13,3 f_v).

2.3 Existing methods of reinforcement – State-of-the-art

2.3.1 Repairing cracks with glue

Small cracks, less than 10 mm wide, can be repaired with glue (Franke et al., 2015). The cracks should first be sawn out and cleaned to get rid of any impurities and jagged edges. Then an adhesive can be injected. However, this method does not seem to have much effect on structural strength (Hubble, 2017). And these repairs are often done for aesthetic reasons, as the gap-filling material can be coloured to look like wood or painted over. Adhesives commonly used for on-site repairs are two-component polyurethanes and epoxies (Pizzo & Smedley, 2015).

2.3.2 Repairing cracks with screws

When using screws or other mechanical fasteners in repair work it is important that the shear stress can be redistributed between the timber beam and the reinforcement (Dietsch & Brandner, 2015). in the uncracked state, the estimated increase in capacity is up to 20%. As shear fractures are brittle, the reinforcements should be designed in such a way that they can carry all the stresses in in a fractured state, this will produce a safer construction element.

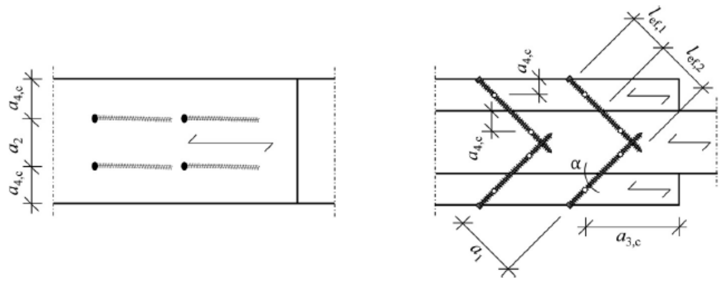


Fig. 4. Definition of spacings, end and edge distances for axially loaded screws.

Figure 10: Dietsch & Brandner. (2015). Definition of spacings, end and edge distances for axially loaded screws. In: Dietsch & Brandner (red.) Self-tapping screws and threaded rods as reinforcement for structural timber elements – A state-of-the-art report. Construction & Building Materials*, 97: 78–89. doi: https://doi.org/10.1016/j.conbuildmat.2015.04.028.*

Gomes Ferreira et.al. (2017) investigated methods for the repair and reinforcement of delaminated glulam beams. Delaminated beams were reinforced with self-tapping screws. This method was considered effective for increasing strength, though they are not as strong as beams without any delamination. A repair method using plywood and self-tapping screws was also considered. Using screws through the delaminated area allows for transmission of stresses and makes the beam behave more like a monolithic beam. The method is considered more effective for shear than axial stresses.

2.3.3 Reinforcement methods using fibre reinforce polymer (FRP)

The most commonly researched methods of reinforcement are based on fibre reinforced polymer (FRP), in the form of rods or sheets(lamellae) bonded with adhesives. These methods have a great variety of uses according to which part of the construction they are meant to reinforce. To improve the bending strength of old timber floors (Shober & Rautenstrauch, 2006) used a method of embedding CFRP lamellae into the existing floor beams, significantly improving their stiffness.

(Raftery & Harte, 2009) investigated the use of Glass Fibre Reinforced Polymer rods in retrofitting low-grade glulam beams. Grooves were cut on the underside of the beams and GFRP rod were added with epoxy adhesive, improving the mechanical strength and the stiffness of the beam.

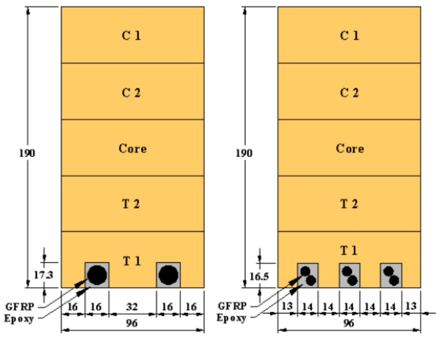


Figure 1: Reinforcement arrangement for repaired 190mm deep beams.

Figure 11: Raftery & Harte (2009). Reinforcement arrangement for repaired 190mm deep beams. In: Raftery, G. M. & Harte, A. M. (2009). Repair of glulam beams using GFRP rods. WIT Transactions on The Built Environment

To repair beams of pine wood damaged by shear, (Barreto et al., 2010) used adhesively bonded carbon-epoxy patches. As shear damage is characterized by horizontal cracking near the neutral axis, the patches were placed on top of this to prevent sliding between the beam arms. (Morales-Conde et al., 2015) give a method using fibreglass and cork plates bonded with epoxy resin. This method was used to repair beam ends that had rotted, and repair and reinforce the centre of beams to increase capacity. Both reinforcement methods were effective and increased load carrying capacity up to 50%

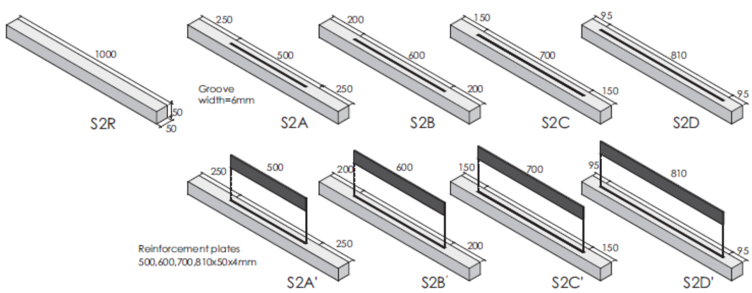


Fig. 4. Samples to test the *Reinforcement system 2* (*S2*).

Figure 12: Morales-Conde (2015). Samples to test the Reinforcement system 2 (S2). In: Morales-Conde, M. J., Rodríguez-Liñán, C. & Rubio-de Hita, P. (2015). Bending and shear reinforcements for timber beams using GFRP plates. Construction & building materials, 96: 461-472. doi: 10.1016/j.conbuildmat.2015.07.079.

Experiments done by (Raftery & Rodd, 2015) show that PRF-glue (phenol-resorcinol-formaldehyde) as used in glulam production is sufficient for these kinds of repairs, and more expensive epoxy adhesives can be avoided. Glass fibre reinforced plate (GPRF) was glued to the wood using PRF adhesive, improving the strain performance of the beams. This bonding method is considered to work well, having low slip at the FRP-wood interface, and improving strain performance of the beams.

(Borri et al., 2015) studied the bond strength of CPRF bars used to reinforce timber. The pull-out capacity was higher for longer bars. (Nadir et al., 2016) reported an increase in flexural stiffness when strengthening glulam with CPRF and GPRF composite sheets.

FRP reinforcement can be used to enhance properties of weaker timber that would otherwise not be used. (Basterra et al., 2017) studied the behaviour of low-grade glulam reinforced with Glass Fibre Reinforce Polymer. Tested 30 unreinforced beams, 60 reinforce with 2 different methods. Results show improvement in flexural behaviour, increase in stiffness and ultimate moment capacity. Using low reinforcement (1,.07%, 1.6%) in the tension zone results in an average of 12.1% and 14.7% increase in stiffness, and an increase up to 23% in moment capacity. The reinforcement also seems to reduce the influence of knots and cracks in the timber.

GFRP bars glued in perpendicularly to the grain can be used reinforce end-notched beams for shear and tensile stress (Todorvic et al., 2019). Before repair, beams failed due to crack openings because of tensile stresses perpendicular to grain and shear stresses. Repairing after failure restored and improved load carrying capacity to average 194%. Failure mode changed from ductile to brittle.

(Wdowiak-Postulak & Brol, 2020) tested the ductility of beams reinforced with CFRP. The increase in load-bearing capacity was increased by 23% for glulam and 28% for solid timber compared to the control beams. Due to the high tensile stiffness of CFRP the reinforcement helps reduce the impact of knots and other weaknesses, as also stated by Basterra et al. (2017), resulting in less brittle fracture and safer structures.

3 Method

When deciding on a reinforcement method, many factors must be considered. Including the properties which one wishes to enhance, the materials available, and the appearance of the finished product. Most of the repair methods discussed will result in a very different-looking beam than the original. The repair method suggested in this thesis, consists of gluing on split glulam using wood adhesive. This means that the repaired glulam beam will look less “repaired” than the repaired beams discussed in the theory chapter.

To investigate the influence of crack on the shear capacity of the glulam beams, 10 uncracked beams were tested with the intention of provoking shear failure. Then 10 beams with sawn-in cracks were tested in the same manner.

3.1 Test preparation, selection of materials and dimensions

The test rig that was used had two load cylinders with a capacity of 100 kN each. To be certain the beams will break during testing they will need to have a lower capacity than what the test rig can handle. As the beam in meant to break due to shear stresses, the dimensions should be such that it reaches its maximum shear capacity before its maximum bending capacity.

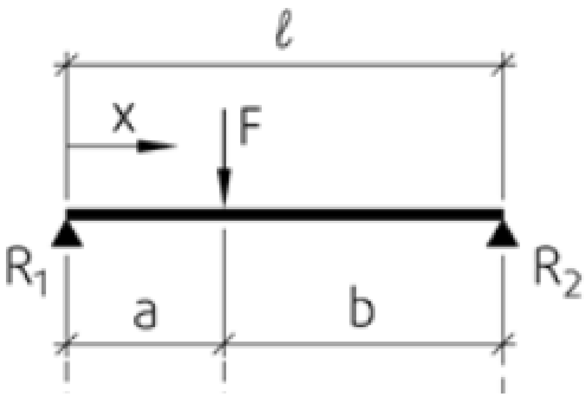


Figure 13: Asymmetrically placed load, SINTEF Byggforsk 421.051

When testing a beam with asymmetrically placed load:

Shear stress:

$$\tau_d = \frac{b \times F}{l \times A} \tag{3.1}$$

Where: τ_d is the design shear stress

F is the applied force

b is the distance b form figure 13

l is the distance l from figure 13

A is the cross-sectional area

Bending stress:

$$\sigma = \frac{F \times a \times b}{l \times W_y} \tag{3.2}$$

Where:

σ is the bending stress

a is the distance a from figure 13

b is the distance b form figure 13

l is the distance l from figure 13

and:

$$W_y = \frac{w \times h^2}{6} \tag{3.3}$$

Where:

w is the width of the cross section

h is the height of the cross section

The beams chosen were 2m long GL28c with a cross-section of 48x250 mm and split glulam with a cross-section of 36x250 mm.

3.2 Glue

The glue used is a PRF adhesive Prefere 4094 form Dynea with the hardener Prefere 5827. This glue is especially suitable for on-site bonding as it is effective for glue lines up to 1.5 mm (Dynea, 2017). The data sheet following the adhesive gives instructions for achieving a successful bonding. The wood used should be dry, between 6 and 15 % moisture content, and the difference in moisture content between the lamellae should not be more than 5%. When the glue and the hardener are mixed the glue will star to cure. The time this takes will depend on the amount of hardener, Dynea recommends 100 parts glue to 20 parts hardener measured by weight. Curing time will also depend on the temperature, high temperature will make the glue cure faster.

The amount of glue required will vary according to the surfaces to be bonded and the pressure that can be applied. (200 - 2000g/m^2 for smooth-rough) Assembly time, time form when glue is applied to pressure is applied, should be as short as possible. When manufacturing glulam this pressure would be between 0.6 and 1.0 N/mm^2, but with larger amount of glue pressures down to 0.01 N/m^2 may be sufficient.

3.3 Testing

3.3.1 Shear test of glulam beams

First, the 10 glulam beams without cracks were tested. The beam was placed in the test rig with the supports 100 mm form each end. The test cylinder bore down on the beam with a constant speed 400 mm from one edge. The amount of force necessary to break the beam was registered.
Artificial cracks were cut into 10 new glulam beams at the glue lines between the 2nd, 4th, 6th, and 9th laminations. The cracks were cut 8 mm deep on both sides for the first four beams and 12 mm deep on both sides for the next six beams. All the cracks were 500 mm long from the end point.
The cracked beams were then tested in the same way as the uncracked ones. The maximum load of each beam is measured, and the shear load is calculated form this using formula 3.1.

Figure 14: Sawn-in cracks

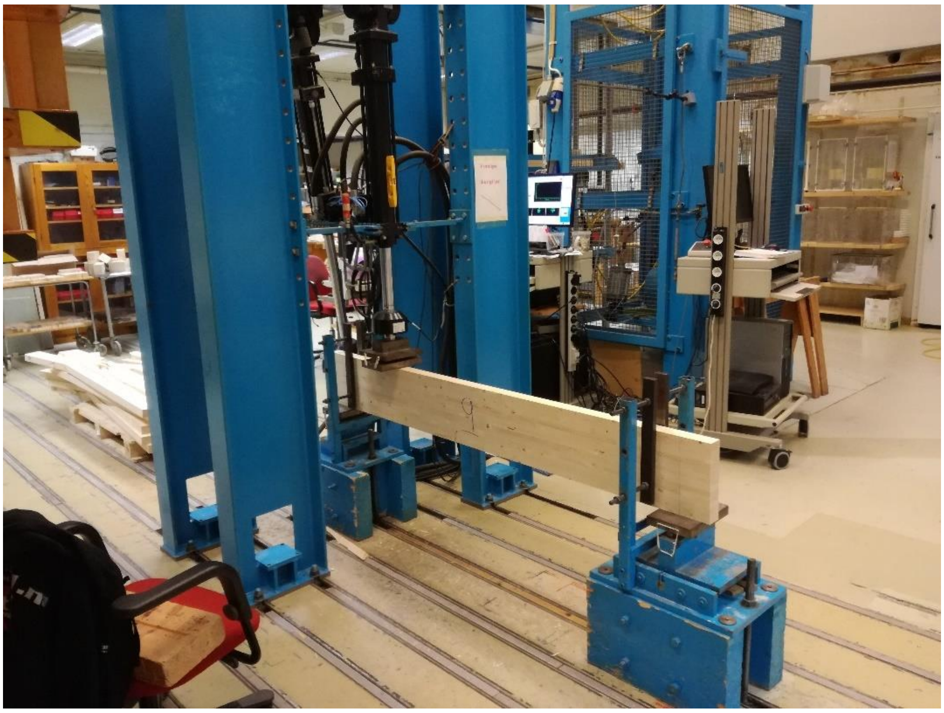


Figure 15: Test setup for beams

3.3.2 Shear test of glue lines

3.3.2.1 Preparation of samples

To investigate the conditions of a successful bonding between a cracked glulam beam and split glulam used for repair 10 400 mm long test pieces (called part A) were cut from the 250x48 mm beams along with 10 400 mm test pieces (called part B) from the 250x36 mm split glulam. The different treatments, amount of glue and methods of pressurisation are given in table 1.

Table 2: Configuration of type A samples

Preparation	Moisture content	Amount of glue	Pressure
None	13-14%	50 g	Screws
None	13-14%	100 g	Screws
None	13-14%	50 g	Clamps
None	13-14%	100 g	Clamps
Dried	9-10%	100 g	Self-weight
Dried	9-10%	200 g	Self-weight
Wet	23 %	100 g	Self-weight
Wet	23 %	200 g	Self-weight
Painted	12-13%	100 g	Self-weight
Panted and sanded	12-13%	100 g	Self-weight

To establish a method for reinforcement that can be used on-site, the test pieces were prepared using different methods emulating conditions and existing beam could be subjected to. Four of the part A test pieces were kept under normal indoor conditions to investigate different methods of pressurisation and amount of glue.

Figure 16: Preparation of wet samples

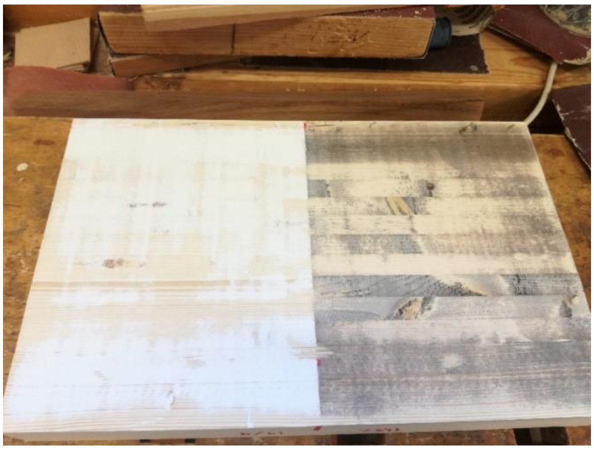


Figure 17: Painted and sanded down surface

Two part-A test pieces were put in a drier for about one hour, and then placed in a room with low relative humidity, resulting in a MC of 9-10 % Another two samples were placed under running water until they had a moisture content of 23% in the surface area. The last two samples had one side painted with wood stain and one side painted with wall paint. One of these was later sanded down so about half the paint was gone.

3.3.2.2 Gluing process

The glue was mixed with a glue-to-hardener ratio of 100 to 20 parts by weight. First, the liquid glue was poured into a bucket and weighed, and then hardener 20% the weight of the glue was mixed in. The amount of glue is measures onto each type-A test piece according to table 2 and distributed with a roller. A type-B test piece was placed on top of the glue and for the first four pieces pressure was then applied. The samples pressurised with screws had one screw drilled into each corner, and the samples pressurised with clamps had one clamp fastened on each corner. The next six samples were left as they were, pressurised by the self-weight of the split glulam. All the samples were then left to cure for at least 48 hours.

Figure 18: Glue line sample with screws

Figure 19: Glue line sample with clamps

3.3.2.3 Testing of glue lines

After curing, the samples were cut into test bars as shown in figure 17 with type-A a cuboid of 50x50x48 mm and type-B a cuboid of 50x50x36 mm. the two cubes connected by a glue line were slightly skewed so that the shearing area was 45x50 mm. This was done so that the shearing tool would get a better grip on the test bar.

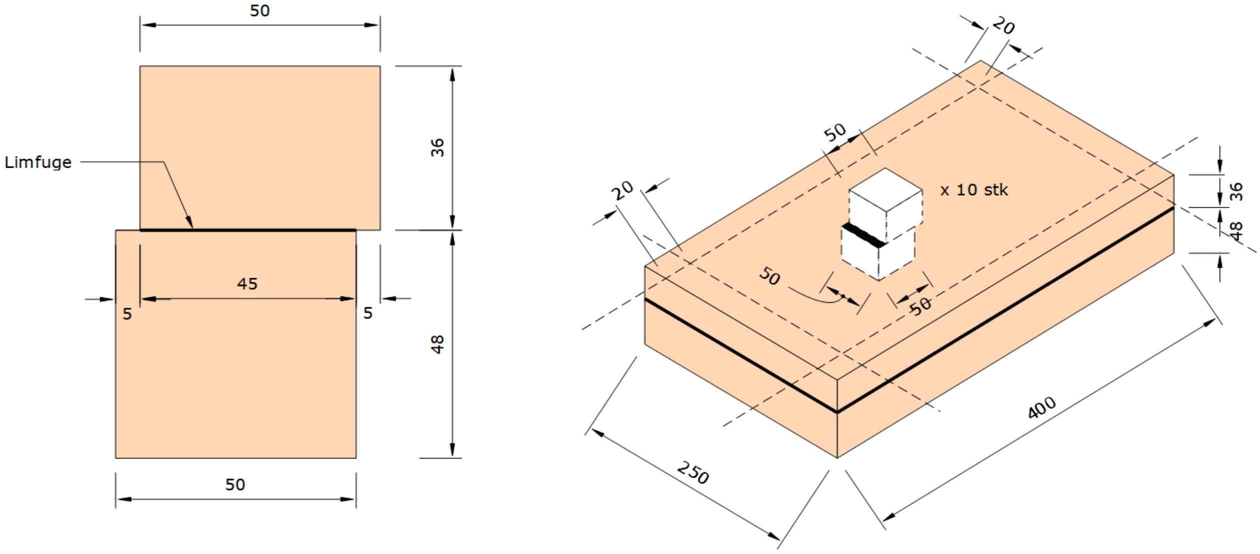


Figure 20: Preparation of glue line test bars, Illustration: Andreas Stenstad, NTI

Figure: Preparation of glue line samples, Andreas Stenstad, NTI

The test bars were then placed in the shearing tool and subjected to a shear load until failure. The maximum load was measured, and shear strength calculated as given in formula 2.3. The percentage of wood failure was determined by visual inspection. And the results validated via table 2.

3.4 Statistical analysis

Statistical analyses of the results were performed using JMP (SAS Institute Inc, 2021). Results were deemed significant when the p-value was lower than 0.5%.

4 Results

4.1 Bending test of beams

The results from the bending test is given in table 3.

Table 3: Results from bending test

Type	Specimen	Width measured	Height measured	Max. load	Shear load	Shear stress
	No.	mm	mm	kN	kN	MPa
Uncracked	1	48.1	250.1	51.1	42.6	3.5
Uncracked	2	48	250	54.7	45.5	3.8
Uncracked	3	48	250	58.6	48.9	4.1
Uncracked	4	48	250	59.4	49.5	4.1
Uncracked	5	48	250	59.8	49.8	4.1
Uncracked	6	48	250	56.5	47.1	3.9
Uncracked	7	48	250	52.4	43.6	3.6
Uncracked	8	48	250	50.7	42.3	3.5
Uncracked	9	48	250	53.4	44.5	3.7
Uncracked	10	48	250	53.3	44.4	3.7
Cracked	11	48	250	56444	47036.7	3.9
Cracked	12	48	250	47656	39713.3	3.3
Cracked	13	48	250	50130	41775.0	3.5
Cracked	14	48	250	49879	41565.8	3.5
Cracked	15	48	250	43533	36277.5	3.0
Cracked	16	48	250	43049	35874.2	3.0
Cracked	17	48	250	43381	36150.8	3.0
Cracked	18	48	250	42048	35040.0	2.9
Cracked	19	48	250	42852	35710.0	3.0
Cracked	20	48	250	49004	40836.7	3.4

The beams without cracks were tested to an average capacity of 3.8 N/mm^2. The 10 beams with cracks where tested the same way, and had a slightly lower capacity, on average 3,2 N/mm^2. On the exception of the first beam, they all measured lower than the lowest beam without cracks.

Figure 21: Shear fracture on one side of the beam

Figure 22: Bending fracture of beam

Figure 23: Combination of shear and bending fracture

Analysis of variance between cracked and uncracked beams give a P-value of 0.0003, a significant difference of mean stress.

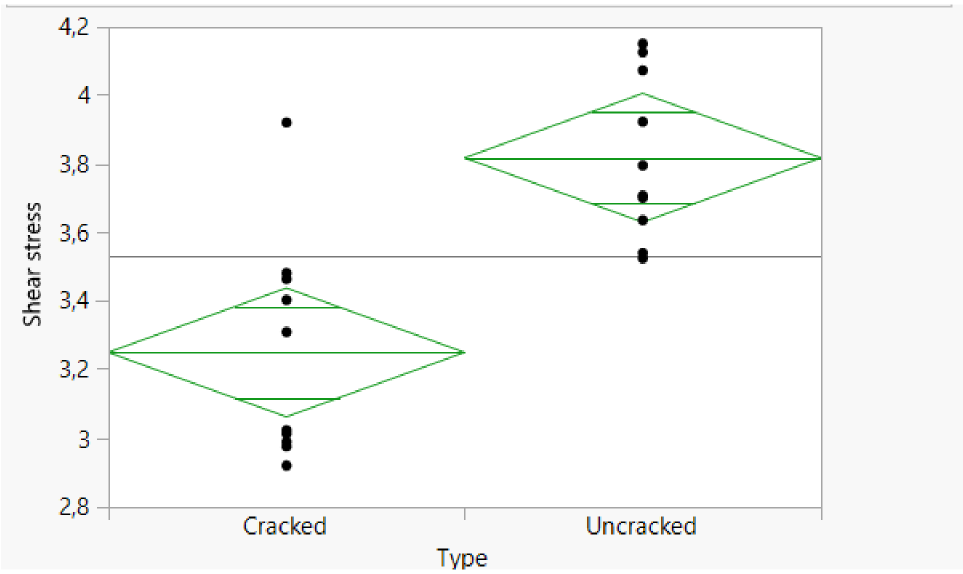


Figure 24: Analysis of variance, cracked and uncracked beams

4.2 Shear test of glue lines

The results from the glue line tests are given in table 4.

Table 4: Results for glue line tests

Gluing method	**Average shear resistance** [N/mm^2]	**Average wood failure** [%]	**Average delamination** [%]	**Invalid samples**
Screws 50 g glue	7.89	73.5	26.5	0/10
Screws 100g glue	7.47	77	23	2/10
Clamps 50g glue	7.35	64	36	3/10
Clamps 100g glue	7.4	78	22	0/10
Dry 100 g glue	6.42	68.5	31.5	6/10
Dry 200 g glue	5.73	29.5	70.5	9/10
Wet 100 g glue	4.33	17	83	10/10
Wet 200 glue	6.18	33.5	66.5	9/10
Painted 100 g glue	4.32	2.5	97.5	10/10
Painted and sanded down 100 g glue	4.61	12	88	10/10

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Figure 25: Glue line fractures, Screws-50g-glue

Figure 26: Glue line fractures, Painted-100g-glue

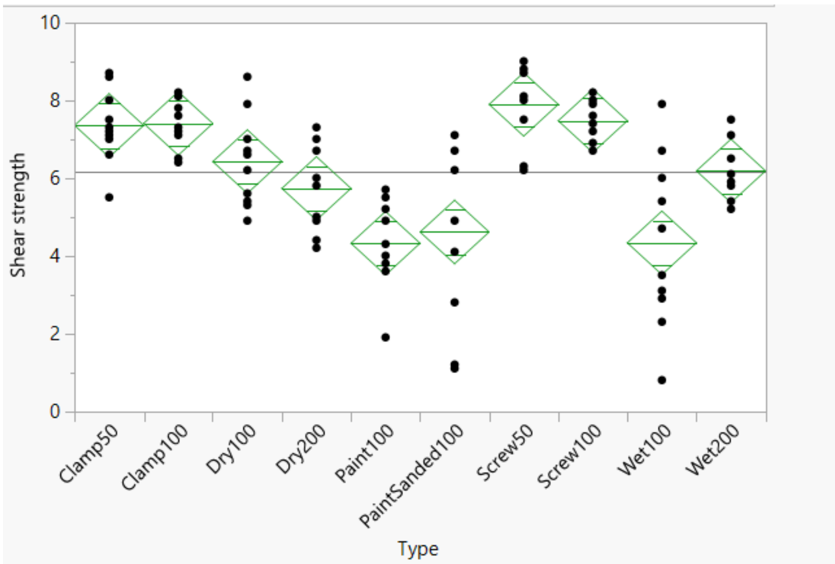

Figure 27: Analysis of variance, Shear strength by type

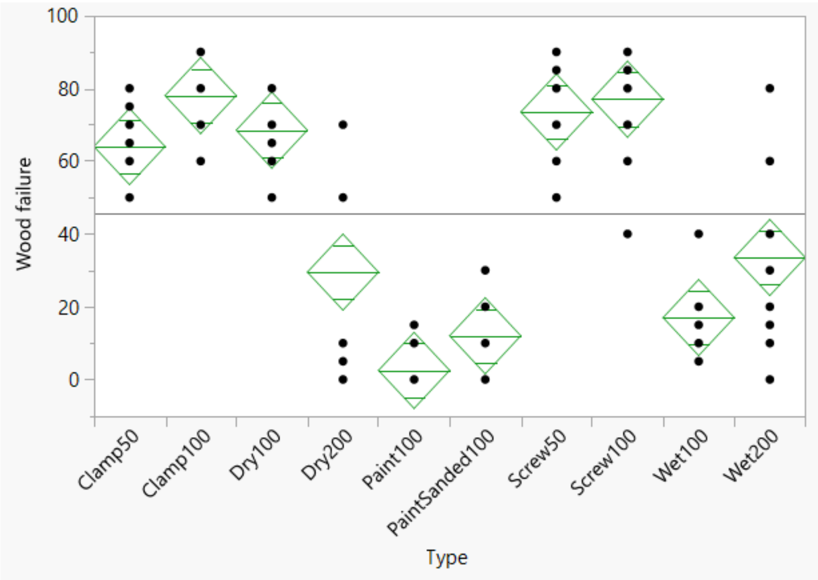

Figure 28: Analysis of variance, Wood failure by type

The analysis of variance between the samples give that there is significant difference in both the glue lines' shear strength and the percentage of wood failure between the samples. A Tukey-Kramer HDS comparison of the mean shear strength values show the samples that are not significantly different as connected by the same letter as given in table 5. The average wood failures of the glue lines have more significant differences between the sample types, as shown in table 6. The levels not connected by the same letter are significantly different.

Table 5: Tukey-Kramer shear strength

Type					
Screw 50	A				
Screw 100	A	B			
Clamp 50	A	B			
Clamp 100	A	B	C		
Dry 100	A	B	C		
Wet 200	A	B	C	D	
Dry 200		B	C	D	
Painted-sanded 100			C	D	
Wet 100				D	
Painted 100				D	

Table 6: Tukey-Kramer wood failure

Type	A			
Clamp 100	A			
Screw 100	A			
Screw 50	A			
Dry 100	A			
Clamp 50	A			
Wet 200		B		
Dry 200		B		
Wet 100		B	C	
Painted-sanded 100		B	C	
Painted 100			C	

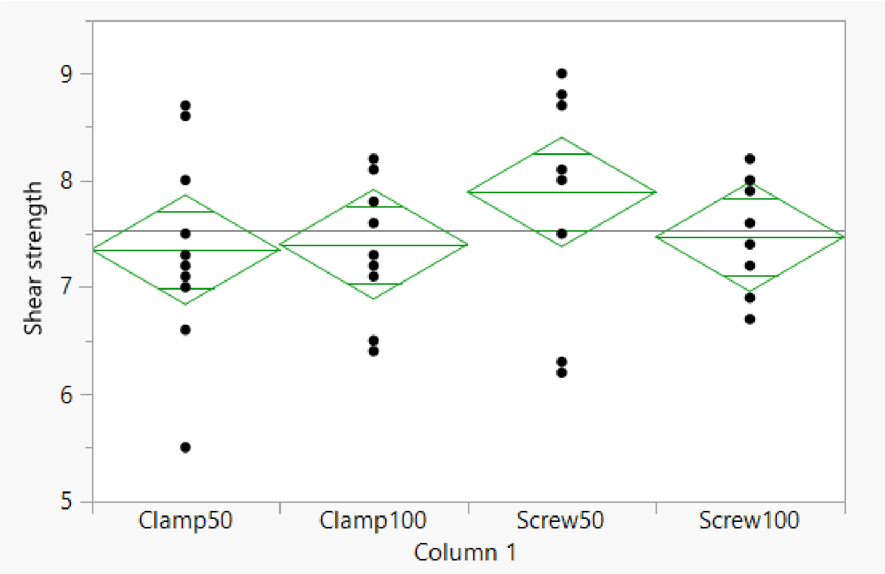

Figure 29: Analysis of variance, Shear strength by type, clamp- and screw-samples

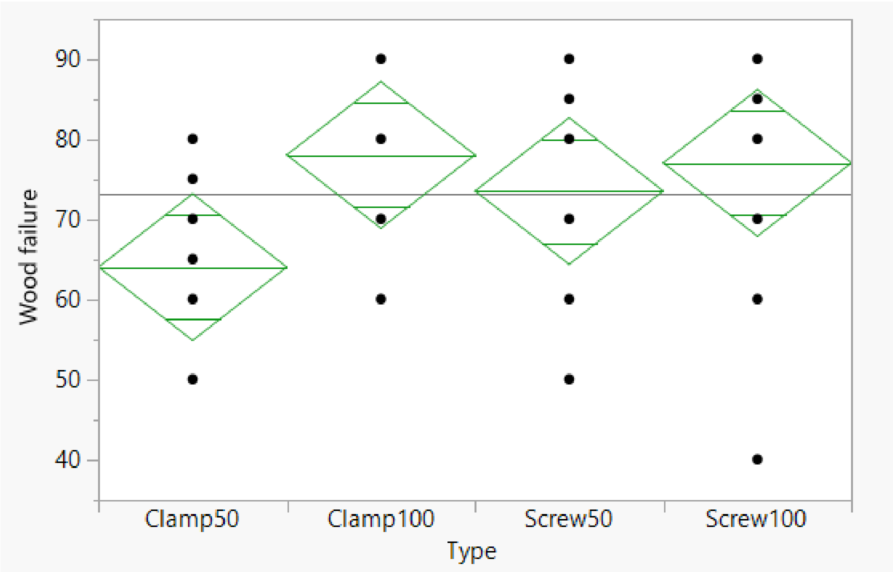

Figure 30:Analysis of variance, Wood failure by type, clamp- and screw-samples

When comparing only the samples pressurised with clamps or screws, there is no significant differences between neither the shear strength nor the wood failure of the glue lines.

Comparing the glue lines of the six samples pressurised by self-weight, they have significant differences in shear strength and wood failure between them. The dry sample with 100 g glue is not significantly different from the samples with clamps or screws.

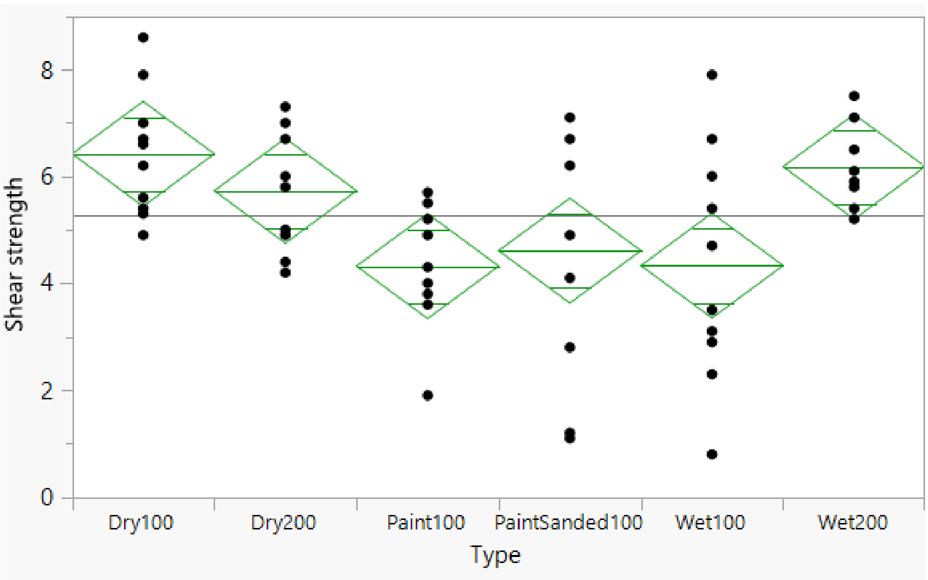

Figure 31: Analysis of variance, Shear strength, Self-weight samples

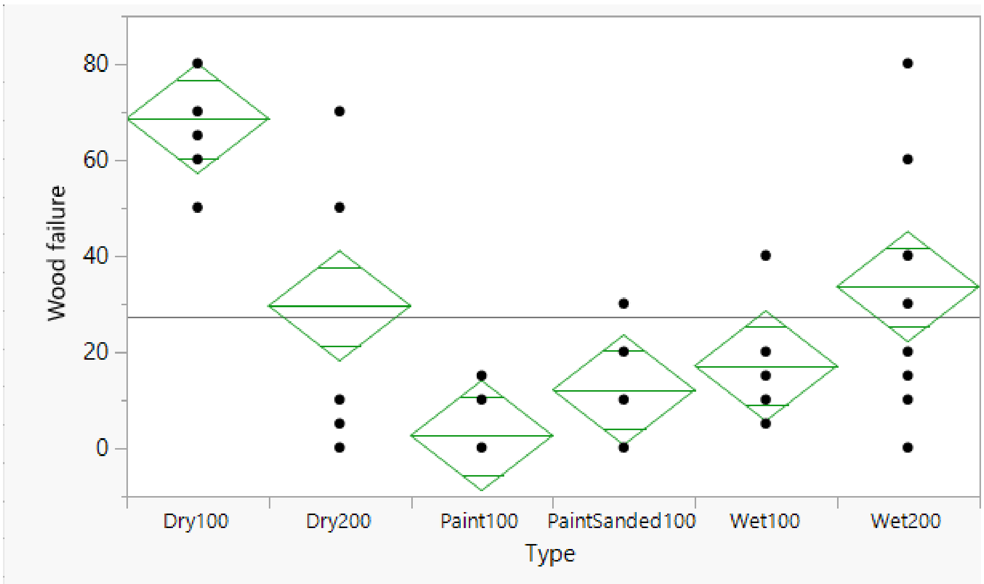

Figure 32: Analysis of variance, Wood failure, Self-weight samples

5 Discussion

5.1 State-of-the-art

When deciding on a means of reinforcement there are certain considerations that must be taken. Firstly, the purpose of the reinforcement and which properties one wishes to enhance. Many will work for multiple failure modes, but it essentially comes down to reinforcement in the direction of the grain, which will improve bending strength and flexural stiffness. Or reinforcement perpendicularly to the grain, which will improve shear strength and tensile strength perpendicularly to the grain.

Different structural elements will also be in need of different kinds of repairs. Columns are mostly subjected to compressive load in the grain direction. This is the direction where the wood is strongest and is usually not the first part needing reinforcement. That is probably the reason why there is little research concerning reinforcement of column. Most composite materials used for reinforcement are quite thin and would therefore not be suitable for compressive reinforcement. The easiest way to reinforce a column would probably be to put up another column beside it, sharing the load.

Beams are subjected to both bending and shear, which of these is decisive depends on the dimensions of the beam and on the load distribution. During bending failure, the break often starts on the tension side. Placing flexural reinforcement there will push the neutral axis down and place a larger part of the beam in compression. This will essentially make for a safer fracture when the compressive fracture at the top will occur first. Reinforcement for shear will reinforce perpendicularly to the grain, either by glued in rods, screws, or patched at the side.

Older floor beams may be in need of flexural reinforcement. Many floors are designed for service limits that accounts for more deflection than what modern people are comfortable with. CFRP lamellae can improve their stiffness, and also increase their strength.

Filling cacks with adhesive is an easy repair method when the cracks are small. However, this method will not work that well on larger cracks, and delamination may still occur in the adhesive-wood interface. Also, as the glue-filled cracks are still visible, this method makes the timber look very “repaired”.

Another factor that should be considered is the appearance of the repair. Secondary to mechanical properties it is still an important concern, especially in the cases were structural elements are visible. Most kinds of patches, fastened with screws or with adhesives, are noticeable and may ruin the appearance of the original structure. There are methods, especially by using fibre reinforced polymers and adhesives, where the repairs can be invisible, but these are also the most extensive and thus expensive.

Additionally, older buildings may be guarded against extensive procedures and under strict rules regarding the use of certain materials. For the most valued historical buildings, only materials that were in use in the time when it was first built can be used. This generally excludes most modern methods of reinforcement, leaving repairs mostly to traditional carpentry.

5.2 Shear test of beams

Evaluating the fractures form these tests they were often a combination of bending, shear, and crushing of the fibres. It is therefore difficult to say if the shear capacity was the deciding factor leading to the breaking of the beam. When the test cylinder bore down on the beams most would first experience crushing perpendicularly to the fibres, then go to bending fracture.

The beams are probably more prone to bending failure than what one would wish. Short beams are often more prone to shear failure in building elements, but the use of a short beam in the test rig will cause problems with pressure perpendicular to the grain direction and crush the beam without provoking shear failure.

From the analysis of variation, it is clearly seen that the presence of cracks significantly influences the capacity of the beams. On average, the shear capacity was reduced by a factor of 0.84. This is comparable to Berg et.al (2015)'s results showing a decrease in capacity between 70 and 90 %.

In the sawn-in cracks the width of the cross-section is reduced to 67 % of the width for the first four cracked beams, 50% of the width for the next six. This means that the b_{ef} in these points is equal to or lower than what the b_{ef} would have been using the reduction factor k_{cr}.

Design standards are intentionally conservative as it is impossible to consider every single variation in every structural element. Reduction factors are safety factors are put in place as a precaution because the consequences of a collapse can be very serious.

5.3 Discussion of glue line results

The results from the shear testing of glue lines show that it is possible to achieve sufficiently strong glue lines between two glulam elements using on-site methods. Both clamps and screws are easily available, and as the dry samples achieved relatively high strengths with the pressure of self-weight, they may not even need to be very tight.

The samples pressurised with clamps or screws were not significantly different in terms of shear strength and wood failure. This could indicate that the pressuring method is not that important as long as it is possible to achieve sufficient pressure equal. Upon visual inspection the glue lines of both side A and side B have a high percentage of wood fibres in the glue, which means that the wood around the glue failed before the glue line itself.

Figure 33: Glue line fractures, Clamps-50g-glue

Of the samples pressurised with self-weight the dry were clearly the best. The dry samples with 100 g glue were not significantly different from the clamp- and screw- samples, either for shear or wood failure. Though they had a higher amount of invalid shear lines.

These samples were still within the range of recommended moisture content, and although the type A samples had a lower MC than type B that difference was not enough to impede the bonding.

The dry sample with 200 g of glue had significantly lower wood failure as stated by the Tukey-Kramer HDS. The shear strength, however, was not significantly different from either of the above except the screw-50g-glue, and all except one glue line was invalid. A larger amount of glue, and therefore a longer curing time may have made the surface of the wood wet, and the bonding weaker.

Figure 35: Glue line fracture, dry-200g-glue

Figure 34: Glue line fracture, dry-100g-glue

In the case of the wet samples it is the opposite from the dry. The glue lines with the most glue were stronger and had more wood failure, although neither glue amount resulted in glue lines meeting the requirement stated in NS-EN 14080. When comparing these results with the results from the dry samples, as a dry surface is important, too much glue will weaken the glue line. However, if the surface is already humid, more glue will not impede the bonding, but make it stronger.

Although the shear strengths of the wet-200g-glue-lines are not significantly different from the dry glue lines, the percentage of wood failure is significantly less than the dry-100g-glue-lines. As can be seen in the figure *csc* most failed in the wood-glue interface. The high shear resistance may be attributed to the strength of the glue itself as there is more glue in the wet-200g-glue-lines than in the wet-100g-glue-lines.

Figure 37: Glue line fracture, Wet-200g-glue

Figure 36: Glue line fracture, Wet-100g-glue

The results from the samples with paint again highlight the importance of a surface with good adhesion qualities. Paint seals the pores of the wood, and so the glue does not work properly. When subjected a shear force, the glue simply comes loose from the painted surface. This effect is seen in both the stained and painted samples. The samples with half-sanded down paint, measure better shear resistance and most have a little wood failure, about the same as wet 100g samples. When glue is used on a half-sanded down surface, it will have a slightly better grip than a fully painted surface, but for a valid bonding resistance the surface should be sanded down completely.

This gluing method could work for both shear and bending. As discussed, adding strengthening material to the sides of the beam would improve its shear strength, while adding strengthening material to the bottom would improve bending strength. This method also has disadvantages in some cases. As all wood-based materials split glulam is also able to crack, although not as much as wider cross -sections. Split glulam is also generally heavier than FRP-materials and would not be best suited when weight is an issue.

When using this method for reinforcing the shear capacity of beams, the beam should be cleaned and sanded down if it is painted. The moisture content should be measured, if the MC is too high, i.e. more than 25% the beam would need to be dried or the glue will not be able to bond with the wood. The amount of glue should probably be up to as much as is recommended from the producer. The glue lines with the most glue, 2000 g/m^2 had slightly less wood failure, but 1000 g/m^2 is sufficient. Applying glue to a vertical side, too much glue would only drip. After applying the glue, the split glulam, with the same moisture content as the beam, would be placed on top and secured in place and pressurised. Using screws would secure the split glulam in place as well as applying pressure. Clamps would probably do the same, but if the interface is very slippery, the reinforcement may need additional support when curing. Both these pressurisations would be placed at a 400 mm interval at the upper and lower side.

Figure 38: Glue line fracture, painted ad sanded down

6 Conclusion

How does the existence of cracks influence the shear resistance of glulam beams?

The influence of cracks significantly decreases the capacity of glulam beams. This is usually taken into account by the reduction factor, k_{rc}, from Eurocode 5. But cracks that reduce the cross-sectional area more than 0,67 may need structural reinforcement. Whether the reinforcement should be designed for shear or for bending should be considered for each separate case, as the failure modes for beams varies according to its dimensions and load distribution.

Which methods of reinforcement and repair are in use today, and what are their characteristics?

Today, screws can be used to reinforce cracked beams, mostly as a first response measure. Crack filling adhesives such as epoxy ae used to repair smaller cracks. Fibre reinforced polymers are very versatile and can be used for a variety of reinforcements and repairs, but these methods are often extensive and often involve sawing grooves or holes to be filled with FRP-material and adhesives essentially making a composite material, which is not always desirable.

When using a repair method involving gluing on split glulam, what should be considered for optimal results?

The most important aspect to consider when choosing this reinforcement method is to comply with the specifications of the glue. Painted surfaces should be sanded down completely, the timber should be dry within the specified MC range stated by the glues data sheet. Pressure should be applied at regular intervals, 400 mm. Not all conditions would work for this kind of repair, especially elements subjected to high moisture content should be evaluated carefully before rehabilitation.

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Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway