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ORIGINAL

Use of a resilient bond line to increase strength of long adhesive lap joints

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Abstract
The load capacity of long adhesive lap joints is often governed by stress concentrations at the lap ends. This paper investigates a method to minimize these stress concentrations by using a bond line with low shear stiffness and sufficient strength, here denoted as a resilient bond line. The resilient bond line is intended to increase the load carrying capacity of long lap joints by achieving a more uniform shear stress distribution while maintaining an elastic joint behaviour without damage or plastic deformation. The study comprises analytical, numerical and full-sized experimental work on double lap joints with lengths 200–700 mm comparing conventional stiff bond lines to resilient bond lines. Different resilient bonds lines were obtained by using rubber-like adhesives and by having a rubber mat within the bond line. An analytical definition of a 'long' lap joint is suggested and a study of adhesive-rubber bonding is also presented. The numerical analysis clearly indicates that an increase in load carrying capacity is made possible using resilient bond lines. A good agreement is also found between the numerical results and the analytical Volkersen theory, indicating that reasonable strength predictions can be obtained by hand calculations if the joint is designed in order to minimize the influence of peel stress. The experimental results of the resilient bond line verify the numerical findings, although production difficulties decrease the statistical significance of the result. On the contrary, the experimental results of the conventional bond lines significantly exceeded the numerical predictions, showing similar load carrying capacities to the resilient bond line. This is probably due to the specific boundary conditions used in the test setup. Despite some contradictory experimental results, the conclusion of this study is that the efficiency of long lap joints can be increased by the use of a bond line with low shear stiffness and sufficient strength.

1 Introduction

Lap joints have historically been used in engineering as a simple means of assembling structural members. Lap joints are today still used on a variety of materials, but the early examples are mainly for wood. Standing for well over a millennium, high-rise Japanese pagodas as well as the slightly younger Nordic stave churches are good examples of how timber can be assembled for durability, in which some joints are based upon a lap joint design (Sumiyoshi and Matsui 1991; Zwerger 2000). Today's efficient production and optimized material usage often rule out the old production methods and lap joints are hence rarely seen in modern timber structures. However, the resilient adhesive lap joints studied herein might prove to again increase the competitiveness of lap joints in heavy timber structures.

The use of long adhesive lap joints with conventional stiff bond lines is limited in terms of load carrying capacity. The utilization rate of the bond line is kept low due to high stress concentrations at lap ends. With the aim of increasing the load carrying capacity, it was realized that the stress concentrations in lap joints can be minimized if an elastic bond line with low shear stiffness and high strength is used. This combination of a bond line with low stiffness and high strength is henceforth denoted as a resilient bond line, which also relates to the elastic response to high strains common for the elastomers used. A test series based upon the idea of using an intermediate rubber foil was conducted without any comparisons to conventional stiff bond lines (Gustafsson 2007). As damage typically occurs at low load levels for this type of adhesives, the behaviour is typically non-resilient. Further work has since been conducted on resilient bond lines using different types of rubbers (Danielsson and

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Björnsson 2005), other full scale tests of innovative timber joints using the technique (Yang et al. 2015) and a numerical bond line model has been presented (Larsson et al. 2016).

Previous studies indicate that the length of the adhesive lap joint is a key factor in the comparison between conventional bond lines and bond lines with lower shear stiffness, in which the latter is more effective for longer joints. An analytical approach is here proposed in order to define an upper length limit for the lap joint length after which a resilient bond line is favourable. One type of resilient bond lines studied herein is achieved by using an intermediate rubber layer between the timber adherends. However, previous studies indicate difficulties in achieving a strong bond between the adhesive and rubber. Thus, parameter study regarding the rubber treatment is also added to this study.

The present paper aims to determine the possible effect of using a resilient bond line in full scale wooden lap joints by a comparative study. The study comprises:

- An analytical definition of a 'long' lap joint.
- Experimental study of rubber-adhesive bonds for different rubber treatments.
- A full scale experimental test series of double lap joints with lap lengths from 200 to 700 mm. Conventional stiff bond lines are compared to low stiffness resilient bond lines, but also different techniques to achieve a resilient bond line are tested.
- Numerical and analytical analyses of an ideal lap joint comparing geometrically similar resilient and non-resilient bond lines. Sensitivity analysis according to the method of factorial design is also conducted.

2 Methods

Double adhesive lap joints were tested experimentally in full scale quasi-static shear tests, accompanied by numerical analyses. Rational design equations can possibly be derived from analytical expressions based upon Volkersen theory (Volkersen 1938). The study aims at investigating possible benefits of using a resilient bond line for large lap joints, in which a conventional stiff adhesive bond line is used as reference.

2.1 Tests

2.1.1 Test series

Double adhesive lap joints with increasing lap lengths according to Fig. 1 were used in the test series, in which the bond line material varied according to Table 1. The height of the test specimens was 225 mm, and the width was

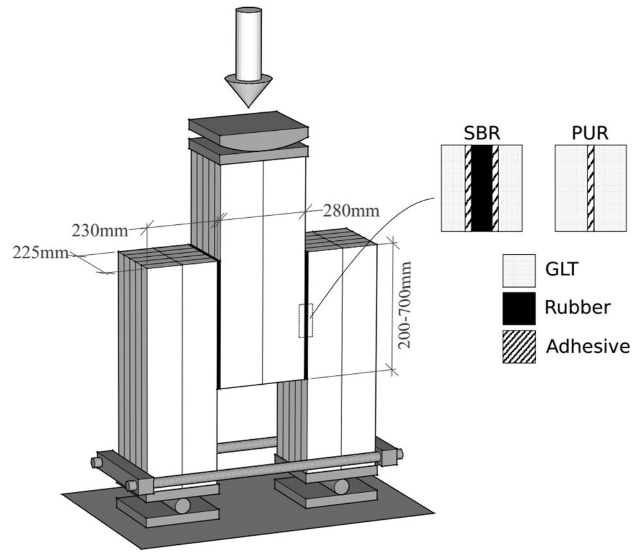

Fig. 1 Double lap joint test setup

230 and 280 mm for the side members and centre member respectively.

To achieve a resilient bond line, a sheeting made from a mix of natural rubber (NR) and styrene-butadiene rubber (SBR) was primarily used, denoted as the SBR specimens in Table 1. The conventional stiff bond line was the PUR-series which consisted of a 2-component polyurethane (PUR), the same as used for the rubber specimens, see Fig. 1. These two types of specimens were used for the lap length investigation ranging from 200 to 700 mm. One additional specimen of each type with 700 mm lap length was included to investigate the effects of boundary conditions, denoted SBR/PUR-700 s and further discussed in Sect. 2.1.4.

In order to possibly simplify the manufacturing process of resilient bond lines, three additional types were added to the test series. The use of chloroprene rubber sheeting (CR) was intended to possibly decrease preparation work while rubber can be replaced entirely by using resilient adhesives such as SikaTack Move IT (IT) and Collano RESA HLP-H (CO).

The SBR/NR used was 3.5 mm thick with a hardness of 60 shore A (1.2 MPa), tensile strength $f_t \geqslant 17.5$ MPa and an elongation at failure of 400%. The CR was 0.5 mm thick with a density of 1.30 g/cm^3, tensile strength $f_t \geqslant 13$ MPa and an elongation at failure of ⩾ 250% according to ISO standards. The hardness was the same as for the SBR/NR.

The resilient adhesive SikaTack Move IT is a 1C PUR with a shear modulus of 65 shore A (1.4 MPa), a shear strength of 5 MPa and an elongation at failure of 300%. Collano RESA HLP-H is a 2C PUR casting resin with granular additive, being the softest and weakest material tested with a shear modulus of 30 shore A (0.4 MPa), a tensile strength of 0.8 MPa and an elongation at failure of approximately 260%.

Table 1 Specimen and bond line specifications

Specimen	Joint length (mm)	Rubber	Adhesive	No. tests
SBR-200	200	SBR/NR, 3.5 mm	SikaForce 7710 + hardener 7020	4
SBR-400	400	SBR/NR, 3.5 mm	SikaForce 7710 + hardener 7020	4
SBR-700	700	SBR/NR, 3.5 mm	SikaForce 7710 + hardener 7020	6
PUR-200	200	–	SikaForce 7710 + hardener 7020	4
PUR-400	400	–	SikaForce 7710 + hardener 7020	4
PUR-700	700	–	SikaForce 7710 + hardener 7020	4
CR-700	700	CR, 0.5 mm	SikaForce 7710 + hardener 7020	2
IT-700	700	–	SikaTack Move IT, 2 mm + Sika Primer-3 N	2
CO-700	700	–	Collano RESA HLP-H, 1.5 mm	2
SBR-700 s	700	SBR/NR, 3.5 mm	SikaForce 7710 + hardener 7020	1
PUR-700 s	700	–	SikaForce 7710 + hardener 7020	1

In comparison, the shear stiffness of conventional bond line is approximately 1000 MPa (Wernersson 1990).

2.1.2 Rubber-adhesive bonding

The generally low surface energy of rubber is problematic in terms of adhesion as the adhesive used must have an even lower surface energy in order to achieve a strong bond (Dillard and Pocius 2002). However, this is seldom the case and poor adhesion, or no adhesion at all, follows.

It is a relative difference in surface energy that has to be obtained, which can be done by modifying either the rubber or the adhesive. In this study, the surface energy of the rubber was increased by sanding and etching in concentrated sulphuric acid. Clean surfaces were obtained by rinsing the specimens in water and ethanol. To obtain the best possible results of the test series, additional tests were conducted to investigate the influence of the rubber treatment. Simple rubber-adhesive-rubber peel tests were conducted according to Fig. 2 using 3.5 mm SBR/NR rubber and 2C PUR adhesive with a thickness less than 0.5 mm. Using two nominally equal test specimens, the effect of each process step was investigated: water rinsing, ethanol rinsing, sanding and acid etching. Two different time durations of sanding and etching were tested. The acid etching was conducted with 97% sulphuric acid at room temperature.

Fig. 2 Rubber-adhesive adhesion tensile test. Bonded area was 50×50 mm^2

2.1.3 Manufacturing

Glued laminated timber (GLT) of strength class GL30c (Norway spruce) with a cross-sectional depth of 225 mm was paired using SikaBond 545 to obtain the required dimensions shown in Fig. 1. The thickness of the laminations was 45 mm. The test setup introduces eccentricity which gives rise to perpendicular to grain tensile stress within the centre member with possible premature splitting. To avoid possible splitting and to minimize possible secondary effects on the bond line the largest specimens were reinforced by means of 2–3 6.5×220 mm screws inserted perpendicular to grain at the low end. The density of the tested GLT was 440–460 kg/m^3 at an average moisture content of 8.7% during testing.

The manufacturing method used for the bond line was dependent on the bond line material, and all methods were verified by tests. The method used for the SBR/NR is presented in detail in Gustafsson (2007), which involves sulphuric acid treatment of the rubber prior to application of the adhesive according to the results of the rubber-adhesive bonding tests. The same gluing technique was used for the SBR/NR specimens as for the PUR specimens. The GLT was planed within 2 h prior to bond line gluing. All adhesive was applied to the GLT surfaces, one-sided for each bond, and cured at room temperature with manually applied curing pressure using 4–6 sash clamps. Dependent on the adhesive used, the pressure was typically applied for 24 h and the specimens stored for a minimum of one week prior to testing.

The manufacturer of the CR recommended the use of CR-based contact adhesive for application, but pre-testing indicated low strength. To obtain the best result, the CR was also treated with sulphuric acid according to Gustafsson (2007) and 2-component PUR adhesive was used.

The resilient adhesive in the IT specimens was applied using a motorized mobile caulking gun after application of the primer. A maze of adhesive strings was applied to the wood surface, which were flattened out by applying compression between the two adherends. The thickness of the bond line was ensured by 2.0 mm rubber distances. Due to the manual string-wise application, the bond line was not entirely continuous making the nominal bond line area smaller than intended with typically 90–95% coverage. The low viscosity of Collano RESA HLP-H enabled pouring of the adhesive on to the substrate, ensuring 100% coverage if the 1.5 mm rubber distances are disregarded. The CO specimens were stored for one month prior to testing to ensure proper hardening.

2.1.4 Setup and loading procedure

The experimental test setup is shown in Fig. 1. The test is designed to primarily fail in shear, in which the horizontal shackle at the base of the specimen reduces the effect of leg splitting during the displacement controlled quasi-static loading. The shackle was made of up to UPE 80 beams and 8.8 M16 rods. Steel plates were used in order to uniformly distribute the bearing stress between the points of load application and the end grain.

The loading procedure was conducted according to the European Standard EN 26891 for timber structures. The load is applied up to 40% of the estimated failure load F_{est}, then reduced to 0.1 F_{est} before loaded to failure at an actuator speed of 1.1 and 1.5 mm/min for non-resilient and resilient bond lines, respectively. The relative shear displacement over the bond line was measured centrically on both sides using four LVDTs with 140 mm length of stroke. The measurement points were located 25 mm from the bond line on either side. The load was measured internally in the hydraulic press, which was calibrated up to 500 kN with a maximum error less than approximately 2%.

Possible failure modes include bond line failure in the wood/adhesive interface, rubber/adhesive interface, rubber failure, wood failure close to bond line by shear/peel stress interaction and wood tensile crack perpendicular to grain along the centreline of the specimen due to leg splitting. Except rubber failure, all these failure modes were visible in the experimental study. However, only wood failure close to bond line by shear/peel stress interaction is studied in the numerical analyses as further discussed in the following section.

In addition to the test setup shown in Fig. 1, the influence of support conditions was experimentally investigated. The main part of the study was conducted using steel plates covering the entire end-grain area of the specimens where the forces were applied. The steel plates to some extent prevent failure due to block shear. The test specimens SBR-700s and PUR-700s were made to experimentally evaluate this restriction by reducing the end grain area covered by the steel plate. The steel plate covering the end grain of the top member was reduced in width, allowing 40 mm free end grain on each side.

2.2 Numerical strength analysis

Numerical analyses with linear and non-linear fracture modelling were performed to determine a general length to load bearing capacity behaviour for resilient and non-resilient bond lines, respectively. The simulations were performed in plane stress 2D by means of finite element modelling using the commercial general-purpose FE software Abaqus. The model consists of wood and a bond line, which is represented by a cohesive layer with a single element in the thickness direction. The bond line thus represents either (1) the adhesive or (2) the adhesive and the rubber foil; including the material interfaces. As fracture softening is important for common adhesives while negligible for rubber materials, two separate approaches were used to model the bond line.

The load carrying capacity of the conventional stiff adhesive bond line is highly dependent on the softening behaviour (Serrano and Gustafsson 2006), and was thus modelled with bilinear softening illustrated for pure shear in Fig. 3, as typical for structural adhesives (Wernersson 1990). The initiation of damage was predicted by means of a quadratic Norris criterion (Norris 1962), for which a one parameter damage evolution was defined as a function of the effective shear and normal displacement (Larsson et al. 2016).

Characteristic for the rubber and rubber-like materials used in the resilient bond lines is the brittle failure at large shear displacements, which limits the influence of the softening behaviour (Austrell 1997). The resilient bond line is further simplified to a linear elastic material, as shown in Fig. 3. As shear is the dominant mode in this setup, this approximation is reasonable. In both bond line types, the strength is represented by wood failure while the shear modulus used was according to Sect. 2.1.1 for resilient and non-resilient bond lines, respectively.

The wood body is represented by a linear elastic rectilinear orthotropic material model, for which the 2D parameters are given in Table 2. Wood parameters were used in a stochastic fashion, where normal distribution was found for all parameters except for the stiffness (Berblom Dahl 2009). Fracture softening of wood adhesive bonds has been studied

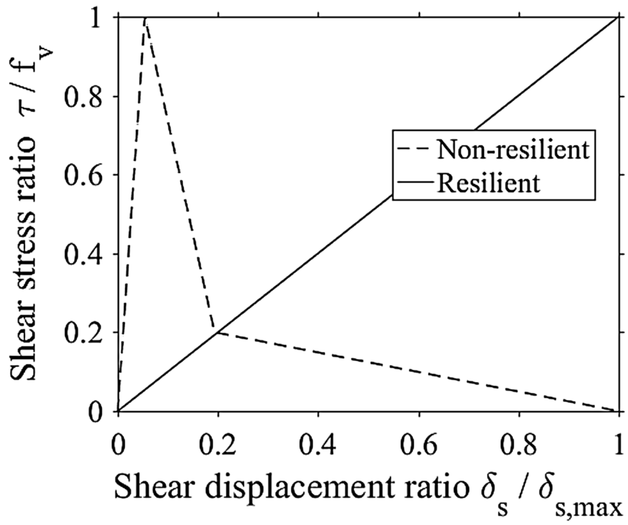

Fig. 3 A linear shear stress-displacement behaviour was used for the resilient bond lines, while a bilinear model was used for the non-resilient

Table 2 Adopted material parameters for wood (Berblom Dahl 2009). Parameters are given in MPa and [-] with corresponding coefficient of variation (CV). Fracture energies are given in Nm/m^2 representing PUR adhesives in wood lap joints (Wernersson 1990)

	Direction	Mean	CV
Young's modulus // grain[a]	E_L	9040	0.38
Young's modulus ⊥ grain	E_R	790	0.28
Shear modulus	G_{TL}	600	0.30
Poisson's ratio	υ_{TL}	0.06	0.07
Shear strength	f_v	4.4	0.38
Tensile strength	$f_{t,90}$	4.9	0.15
Tensile fracture energy	$G_{f,I}$	230	0.14
Shear fracture energy	$G_{f,II}$	850	0.10

[a]Lognormal distribution

by Wernersson (1990), from whom relevant fracture energy values are found.

A load controlled analysis without artificial stabilization was used in the numerical simulations. Symmetry was regarded on the geometry built up by first order plane stress solid elements with 4 nodes and full integration. Cohesive elements were used for the bond line. Failure was evaluated using a stress based Norris failure criterion (Norris 1962) for the resilient bond line while the maximum strength of the propagating fracture was adopted for the non-resilient bond line. Two sets of numerical analyses were conducted:

1. Numerical shear strength comparison between resilient and non-resilient bond lines. The boundary conditions were set in order to achieve a dominant shear action in the lap joint by restricting the horizontal movement of the specimen legs. In comparison to the boundary conditions illustrated in Fig. 1, roller supports are in this set replaced by fixed supports and thus the shackle does not need to be included. A bond line thickness of 1 mm was used regardless of bond line type. The experimental geometry was otherwise reproduced.
2. Detailed comparison to the tests. Comparison to test results are made with the more realistic boundary conditions according to Fig. 1 as presented in Sect. 3.2 using a horizontal linear elastic spring to represent the shackle ($k = 35$ kN/mm).

A screening process for important factors was conducted using a two-level fractional factorial 2^{9-4}_{IV} design for the resilient and non-resilient model individually (Box et al. 1978). The analysis included 9 geometric and material parameters with a variation of $\pm 10\%$ including failure strengths, fracture energies and axial stiffness of the members. A full factorial 3^4 design was then conducted to discover possible non-linear responses and interactions between analysed factors, which is not possible in a common one-factor-at-the-time sensitivity analysis. The four most influential material parameters were then inserted as stochastic variables in order to possibly verify a strength increase of the resilient bond line regardless of the natural variability of wood.

2.3 Analytical study

2.3.1 Shear stress distribution

The analytical expression used for determination of the shear stress distribution and bond line strength is based upon the Volkersen theory (Volkersen 1938) as presented in Gustafsson (2008). For the compression–compression load configuration used in the test, but neglecting bending, the 1D shear stress distribution of the bond line τ_3 is found being

$$\tau_3(x) = C_1 \cosh(\omega x) + C_2 \sinh(\omega x)$$

$$C_1 = \frac{PG_3}{t_3\omega}\left(\frac{1}{E_1A_1\tanh(\omega L)} + \frac{1}{E_2A_2\sinh(\omega L)}\right) \quad (1)$$

$$C_2 = \frac{PG_3}{t_3\omega}\left(\frac{-1}{E_1A_1}\right)$$

$$\omega L = L\sqrt{\frac{G_3 b_3(1+\alpha)}{t_3E_1A_1}} \quad \alpha = \frac{E_1A_1}{E_2A_2} \leqslant 1.0$$

The shear stress distribution of the bond line (index 3) is thus governed by the properties of the two adherends (index 1 and 2) and the bond line properties: cross-sectional area A, longitudinal stiffness E, bond line length L, width b_3, thickness t_3 and shear stiffness G_3.

By identifying the maximum shear stress at $x = 0$ and introducing the material shear strength, the load carrying capacity P_f can be determined by

$$P_f = b_3 L f_v \frac{(1+\alpha)\sinh(\omega L)\tanh(\omega L)}{\omega L(\sinh(\omega L) + \alpha \tanh(\omega L))} \quad (2)$$

As $\tanh(\omega L) \rightarrow 1.0$ for large ωL, i.e. for large lap lengths, Eq. (2) can be reduced to

$$P_f \approx b_3 L f_v \frac{(1+\alpha)}{\omega L} \quad (3)$$

The approximation deviates less than 0.5% from the exact solution for $\omega L \geqslant 6$. The Volkersen theory does not include bending, which however does occur in the test setup. Equation (1) is plotted for increasing lap length in Fig. 5.

2.3.2 Definition of a 'long' lap joint

The study presented in this paper argues for the benefits of a resilient bond line in long lap joints. Although the term 'long lap joint' is used in literature, a definition of what can be considered a long lap joint is lacking. As hinted by Volkersen theory above, the definition of a long lap joint must be put into perspective of the adherends and the bond line. To obtain an estimate of the length needed for positive influence of a resilient bond line, the brittleness ratio of lap joints λ can be used. (Gustafsson 1987).

The normalized mean shear stress at failure is governed by the brittleness ratio λ of lap joints. To achieve a high utilization ratio of the bonded area, it is important to have a low brittleness ratio. Using the strength limits of ideal plasticity and linear elastic fracture mechanics (LEFM), it is possible to identify an approximation of the recommended maximum value of λ which allows for a high efficient lap joint as

$$\lambda = \frac{l^2 f_v^2}{t_1 E_1 G_f} \leqslant 2(1+\alpha) \quad (4)$$

where α is defined in Eq. (1) and t_1 is the thickness of element 1. If a resilient bond line is used, then $G_f = f_v^2/2G_3$. The limitations of LEFM should be noted as well as the fact that bending is not included in Eq. (4). To meet the recommended brittleness ratio, a reorganisation of Eq. (4) suggests that a resilient bond line should be used for lap lengths over 420 mm for the geometry used in the experimental study ($\alpha = 0.61$).

3 Test results

The experimental results are presented, starting with the parameter study of the rubber-adhesive bonding. The optimal rubber treatment method was then used for the main study of the influence of lap length on the load carrying capacity of the joint. The section also includes results from the tests of different boundary conditions as well as the different means of achieving a resilient bond line.

3.1 Bonding between rubber and adhesive

Table 3 summarizes the load at failure of the rubber specimens treated by different methods in order to increase the surface energy. The importance of an adequate rubber treatment prior to bonding cannot be underestimated as this simple test suggests a strength increase of up to 60 times by using a combination of 30 s of acid etching after rigorous sanding. In order to achieve a strong bond of the SBR/NR rubber, the initially shiny surface must be sanded until a matt surface is obtained.

3.2 Lap length series

The strengths of the non-resilient PUR-series and the resilient SBR-series were compared for increasing lap lengths and the results are compiled in Table 4, also including the two specimens with smaller steel plates on member ends. It is found that this experimental study shows no significant strength increase by using a low stiffness bond line.

All non-resilient specimens showed a brittle failure in wood close to the bond line. Two types of failure modes

Table 3 The effect of rubber processing steps on tensile strength

Category	Treatment				Average force at failure (N)
	Water	Ethanol	Sanding[a]	Etching[b]	
1	–	–	–	–	0
2	x	–	–	–	5
3	x	x	–	–	5
4	x	x	+	–	15
5	x	x	++	–	50
6	x	x	+	+	140
7	x	x	+	++	130
8	x	x	++	+	310
9	x	x	++	++	90
10	x	x	–	++	30

[a]+ Corresponds to 5 s by belt sander while ++ is 30 s (results in a matt surface)

[b]+ Corresponds to 30 s submerged in concentrated sulphuric acid while ++ is 3 min

Table 4 Failure load and strength from experimental tests for conventional non-resilient adhesive and the low stiffness resilient SBR/NR with increasing lap length. Strength is the average shear stress at failure and the coefficient of variation of the average is found in parenthesis

Length, mm	Test	Non-resilient (PUR-series)			Resilient (SBR-series)		
		Failure mode[a]	Failure load, kN	Strength, MPa	Failure mode	Failure load, kN	Strength, MPa
200	1	1	359	3.99	1	490	5.45
	2	1	373	4.15	2	420	4.67
	3	1	461	5.12	2	361	4.01
	4	1	441	4.90	1	400	4.44
	Avg		410 (0.12)	4.5		420 (0.13)	4.6
400	1	1	941	5.23	1	687	3.82
	2	1	940	5.22	1	769	4.27
	3	1	716	3.98	1	759	4.22
	4				1	814	4.52
	Avg		870 (0.15)	4.8		760 (0.07)	4.2
700	1	1	1168	3.71	2	911	2.89
	2	1	1285	4.08	2	692	2.20
	3	1	1242	3.94	2	912	2.89
	4	1	1480	4.70	1	1172	3.72
	5				1	1169	3.71
	6				1	1537	4.88
	Avg		1290 (0.10)	4.1		1070 (0.28)	3.4
700 s	1	1	790	2.52	1	1150	3.65

[a] 1: Wood failure close to the bond line, 2: Premature failure in glue-rubber interface

were visible in the resilient specimens. Some resilient specimens failed in similar wood bond line failure to the non-resilient specimens, while others failed prematurely in the adhesive-rubber interface as indicated in Table 4. In these cases, visual inspection subsequent to failure indicates poor rubber treatment, in which some rubber areas were of type category 6 instead of the intended category 8 (Table 3) which is believed to initiate the premature failure. Excluding the premature failures from the SBR-700-series results in an average failure load of 1290 kN, the same as for the PUR-700-series.

For a vast majority of the test specimens, a tensile crack perpendicular to grain was formed centrically in the low end of the middle member (prior to final failure due to shear at the bond line) due to perpendicular-to-grain tensile stresses, at the location of the reinforcement screws. The crack did not influence the global behaviour of the lap although an irregularity in the displacement plot was observed, for example at approximately 700 kN for SBR-700-4 in Fig. 4.

A comparison of the deformation of the resilient and non-resilient bond lines are found in Fig. 4. By introducing the 3.5 mm thick SBR/NR sheet, the measured stiffness over the bond line was reduced by a factor of approximately 30. The test results regarding the influence of boundary conditions indicate a greater sensitivity in the non-resilient specimen than in the resilient one.

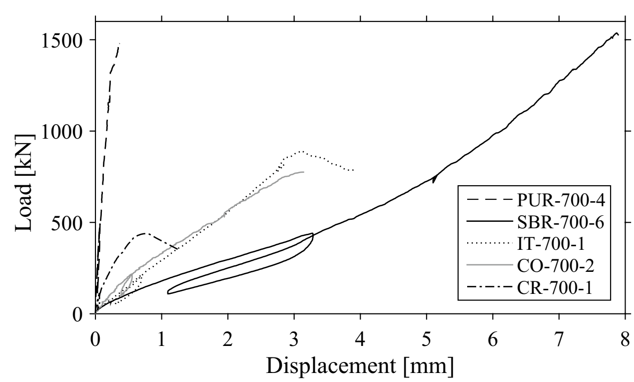

Fig. 4 Load–displacement comparison between the different types of bond lines investigated

3.3 Type of resilient bond line

To investigate the possibility of simplified manufacturing, the SBR/NR was experimentally compared to CR, Move IT and CO, in which the latter was supposedly more easily manufactured than the former.

The results shown in Table 5 suggest that the CR was not as strong as the SBR/NR. The resilient adhesives Move IT and RESA HLP-H enabled very simple production, although

Table 5 Four resilient bond lines compared also to common adhesive using a lap length of 700 mm. Failure load, strength and stiffness with coefficients of variations are presented. *n* is the number of specimens, *t* is the bond line thickness and premature SBR specimens are excluded

Type	n	t, mm	Failure mode[a]	Failure load, kN	Strength, MPa	Stiffness, kN/mm
SBR/NR	3	3.5	1	1290 (0.16)	4.1	230 (0.07)
CR	2	0.5	2	360 (0.30)	1.2	720 (0.11)
IT	2	2	2	760 (0.25)	2.4	270 (0.03)
CO	2	1.5	2	730 (0.09)	2.3	260 (0.18)
PUR	4	0.1	1	1290 (0.10)	4.1	5470 (0.10)

[a]1: Wood failure close to the bond line, 2: Premature failure

it was difficult to obtain a uniform bond line using Move IT due to the high viscosity. Both the CO and IT specimens also showed premature failure, now in the adhesive/wood interface.

The stiffness of the resilient bond lines is to a large extent dependent on the thickness of the layer, which depends on the type of bond method. Figure 4 compares typical load-deformation curves of the different bond lines investigated in this study.

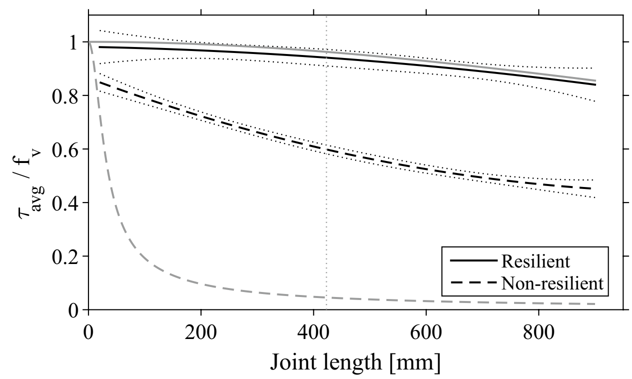

Fig. 5 Normalized shear stress at failure for increasing joint length. Quadratic polynomial fit to numerical stochastic analysis is indicated by black lines according to legend with corresponding 95% confidence dotted adjacent ($R^2_{resi} = 0.034, R^2_{n.resi} = 0.498$). Analytical results according to Volkersen theory in grey where a good resemblance is found for the resilient bond line while very poor for the non-resilient. The vertical dotted line represents the suggested lap length limit according to Eq. (4)

4 Numerical analysis

The results of this study comprise numerical and experimental analyses comparing resilient to non-resilient bond lines, as well as influencing parameters. In this section, two sets of boundary conditions have been used according to Sect. 2.2, presented in the different subsections.

The numerical analyses indicate an increasing strength difference in favour of the resilient bond line as the lap length increases, which however is in disagreement with the presented experimental results. However, it is the authors' belief that the discrepancy between the results is due to possible inadequateness of boundary conditions adopted in the laboratory tests and production difficulties.

4.1 Double lap joints with minimal bending influence

Boundary conditions were set in order to minimize the bending effects in the specimen according to type 1 in Sect. 2.2. For the double lap joint geometry shown in Fig. 1 using deterministically increasing length, independent stochastic material parameters were inserted in a numerical strength analysis. The stochastic material parameters were the shear strength f_v, shear fracture energy G_f, normal stiffness of wood E_L and tensile strength perpendicular to grain $f_{t,90}$. The results of 700 stochastic numerical simulations are shown in Fig. 5 using a 2nd order polynomial fit with corresponding 95% confidence interval. A decreasing average shear stress at failure is visible for both the conventional and the bond lines with low stiffness for increasing lap length, although the effect is less pronounced in the latter case.

To evaluate the applicability of the Volkersen theory on this specific design, a comparison is made to the numerical analysis in Fig. 5. A good agreement is found between analytical and numerical results for a resilient bond line, while very poor agreement for non-resilient bond lines primarily due to the fact that fracture softening is not taken into account in the Volkersen theory.

The numerical analysis indicates that damage is initiated in the non-resilient design at approximately 70% of maximum load, while no damage is modelled for the resilient bond lines.

To obtain a better understanding of the parameters influencing the strength of adhesive lap joints, a factorial design study was conducted. Out of nine material and geometrical parameters analysed, the four most influential were further studied in a full 3^4 factorial design from which the results are presented in Fig. 6. The analysis was conducted for a base bond line length of 500 mm, and all parameters were independently varied ±10% from the reference values discussed in Sect. 2.2. The numerical analysis is based upon an

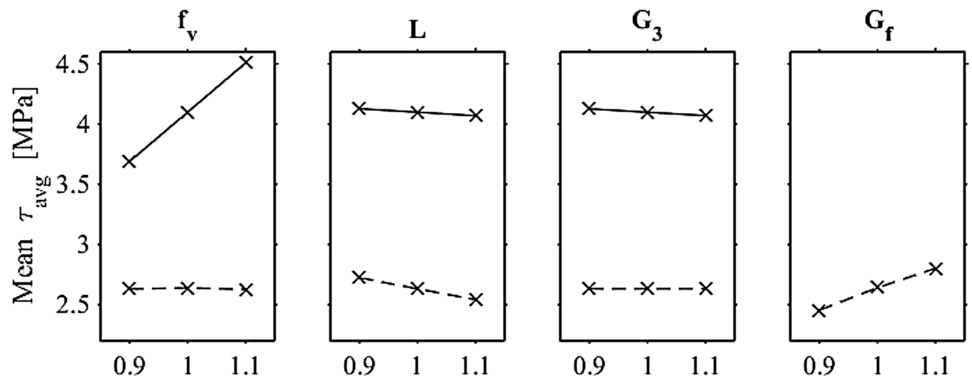

Fig. 6 Parameters that significantly influence the average shear stress at failure according to full factorial 3^4 design using a ± 10% variation of reference values: shear strength f_v, lap joint length L, stiffness of the bond line G_3 and shear fracture energy G_f. Resilient bond line as solid line while non-resilient as dashed line. Reference values are found in Sect. 2.2

ideal lap joint comparing geometrically similar resilient and non-resilient bond lines.

The factorial design clearly highlights the fundamental differences between resilient and non-resilient bond lines. Due to high stress concentrations in the stiff non-resilient bond line, a shear strength increase does not influence the load carrying capacity, which is more dependent on the fracture energy. Although to some extent proportional, these material properties have been considered individually in this analysis for illustration purposes. Resilient bond lines have a strength advantage when used in long lap joints, as the average shear stress at failure does not drop at the same rate as for non-resilient bond lines for increased lap length as shown in Fig. 6. Low stiffness, by either using a less stiff or thicker bond line, increases the load carrying capacity at the expense of a decreased joint stiffness. As the stiffness of the bond line approaches zero, the strength approaches the theory of perfect plasticity.

The factorial design analysis does not suggest any parameter interaction for the resilient bond line in the analysed parameter region in terms of average shear stress over the lap area. It does however suggest a slight interaction in case of non-resilient bond line between lap length and shear strength, as well as between fracture energy and shear strength.

4.2 Comparison to test results

The numerical results in Fig. 5 indicate a considerably larger difference in load carrying capacity than found in the experimental study. To investigate this discrepancy, additional numerical simulations were conducted with boundary conditions according to the test setup. Roller supports were used, the shackle represented by a linear spring ($k = 35$ kN/mm) and bond line thicknesses of 0.1 and 3.6 mm were used for non-resilient and resilient bond line, respectively. It was found that the resilient SBR specimens were somewhat more sensitive to the shackle stiffness than the non-resilient PUR specimens, while shorter specimens were significantly more sensitive than longer ones. In comparison to the results

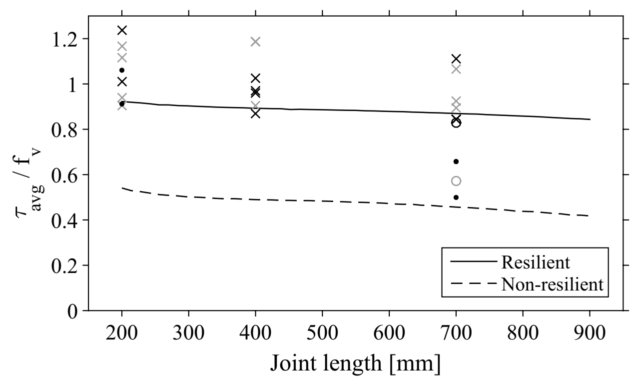

Fig. 7 Numerical results of experimental setup compared to experimental data: resilient in black while non-resilient in grey. Wood close to bondline is marked with "x", dot marks premature failures and results of the test with smaller steel plates are marked with "o"

shown in Fig. 5, the use of the shackle with finite stiffness causes a strength decrease of both types of bond lines as seen in Fig. 7. This is especially relevant for shorter lap lengths as these are subjected to larger bending moments. A general strength increase using a resilient bond line is also found in this analysis, which was however not visible in the tests.

5 Discussion

It is very difficult to achieve a uniform shear stress distribution in a lap joint due to different axial strains in the adherends at a given point of the bonded area. The consequences of this difference can however be minimized by introducing a resilient bond line, which allows the adherends to deform more independently. This conclusion is drawn from the presented numerical analysis as well as previous studies (Gustafsson 2007; Yang et al. 2015). The experimental results are however not as simple to interpret due to different failure modes and unexpected influence of boundary conditions, but the data do not falsify the numerical results.

In comparison to previous experience and the conducted numerical analysis, the high strength of the non-resilient bond lines is found interesting. All GLT specimens were manufactured and delivered at the same time. The test specimens were further produced similarly and also stored together, suggesting that the material parameters are similar for all. The parameters used in the numerical analysis are however based upon literature values rather than measured on the tests themselves. Hence it is possible that the material parameters do not necessarily consider the specific boundary conditions of this test. The load carrying capacity of non-resilient bond lines is also influenced by the fracture energy. The presented shear fracture energy of 0.85 kNm/m^2 was found at a shear failure of 3.56 MPa (Wernersson 1990), which possibly could be higher if a higher shear strength is used. The normal distribution of the shear strength suggests a 95th percentile strength of up to 7.5 MPa, which would increase the numerical load carrying capacities. However, numerical analysis indicates that this effect alone cannot explain the high strength of the non-resilient bond lines.

A large variance in the experimental results of the resilient SBR/NR was found due to premature bond line failure in the rubber/adhesive interface. The results highlight a sensitivity to rubber treatment, in which local differences are likely to initiate failure. However, this problem can be avoided by a simple but detailed visual inspection and does thus not necessarily imply a large variance in the load carrying capacity in an established production method.

A similar double lap joint test setup using resilient bond lines was included in the large resilient bond line test series presented in Gustafsson (2007). Using close to identical production method, an average shear stress at failure of 4.6 MPa was recorded for a lap area of 600×223 mm^2, which is higher than measured in this study. However, the failure also included bending failure of the two outer members of the double lap joints due to their slenderness, possibly influencing the results negatively. The higher strength is probably due to the influence of different boundary conditions.

Comparison between numerical and analytical findings suggests that the Volkersen theory is suitable for hand calculations of lap joints if (1) a resilient bond line is applied and (2) boundary conditions are such that they limit the influence of peel stress interaction in the joint design. The numerical findings of the given geometry also suggest that a strength increase by introducing a resilient bond line can be achieved at shorter lap lengths than the analytical estimate suggests.

The additional testing of smaller steel plates at end grain suggests that the non-resilient bond line is more sensitive to boundary conditions than the resilient one. The same shear stress in the bond line occurs regardless of end plate boundary conditions at a given load, resulting in insignificant influence on the numerical model in which a stress based failure criterion is implemented in the bond line. The fundamental difference is found in the wood body, where the wood volume experiencing a shear stress level close to the shear strength is considerably larger than in the case of smaller end plate. This, in combination with the weakest link theory (volume effect), is a plausible explanation for the decrease in average shear stress at failure from 4.1 to 2.5 MPa for non-resilient joints. The same reasoning is also valid for the insensitivity of the resilient bond line as no significant stress concentrations occur. When the shear stress approaches the strength of the material, nearly simultaneously for the whole lap joint, the weakest link theory predicts failure at some point regardless of end grain support.

Compared to the rubber based resilient bond lines, the manufacturing process of the IT and CO series was considerably more effective. If proper adhesion can be obtained to wood, a resilient adhesive is recommended in wood–wood lap joints. Similar to rubber based resilient bond lines, a low shear stiffness and high shear strength are important parameters for the strength of the joint. Furthermore, manufacturing is more effective if the resilient adhesive also has a high viscosity and only in need of a low curing pressure.

Redundancies should be promoted in structural design. Therefore, not only strength but also the stiffness of the connection is relevant to consider in a design phase in order to ensure the intended load path. The stiffness and slip are also decisive when several types of connectors are used in a single connection, in which simultaneous action requires similar behaviour. By using a resilient bond line, the stiffness can be designed specifically to match other connectors by varying the shear modulus of rubber and/or thickness, thus enabling the addition of strengths for different connectors.

6 Conclusion

The presented research concludes the following findings:

- Resilient bond lines can be achieved by means of adhesives with low stiffness or rubber.
- The experimental study indicates the difficulty of achieving a strong bond between rubber and adhesive, and thus a clear and reliable production method must be established.
- The experimental study shows that a long non-resilient bond line can be stronger than resilient bond line in certain conditions.
- The stiffness of lap joints with resilient bond lines can be designed with great variety.
- Numerical analysis shows that an increased load carrying capacity of lap joints can be achieved by introducing a resilient bond line due to a more uniform shear stress distribution.

- Volkersen theory is applicable to lap joints with resilient bond lines.
- An analytical relation is proposed as definition of a long lap joint.

Despite the somewhat contradictory experimental results, the authors conclude that properly manufactured resilient bond lines do increase the load carrying capacity of long lap joints.

The use of resilient bond lines is not limited to wood–wood configurations. The study is conducted within a project regarding the "Shear plate dowel joint" (SPDJ), which uses the resilient bond line technique in a wood-steel configuration with intended use in heavy timber structures.

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References

Austrell P-E (1997) Modeling of elasticity and damping for filled elastomers. PhD thesis, Lund: Lund University

Berblom Dahl K (2009) Mechanical properties of clear wood from Norway spruce. PhD thesis ISBN 978–82-471-1911-2 ed. Trondheim, Norway: Norwegian University of Science and Technology

Box GEP, Hunter WG, Hunter JS (1978) Statistics for experimenters. Wiley, New York

Danielsson H, Björnsson P (2005) Strength and creep analysis of glued rubber foil timber joints, s.l.. Master thesis, Lund University

Dillard D, Pocius A (2002) The mechanics of adhesion. s.l.. Elsevier, Amsterdam

Gustafsson PJ (1987) Analysis of generalized Volkersen joints in terms of non-linear fracture mechanics. In: Proc of European Mechanics Colloquium 227 "Mechanical behavior of adhesive joints", pp 323–338

Gustafsson PJ (2007) Tests of full size rubber foil adhesive joints, s.l.: Structural Mechanics, Lund University

Gustafsson PJ (2008) Tests of wooden cleats oriented along fibre, structural mechanics. Lund University, Lund

Larsson G, Gustafsson PJ, Serrano E, Crocetti R (2016) Bond line models of glued wood-to-steel plate joints. Eng Struct 121:160–169

Norris CB (1962) Stength of orthotropic materials subjected to combined stresses. U.S. Department of Agriculture, report No. 1816, Madison

Serrano E, Gustafsson PJ (2006) Fracture mechanics in timber engineering—strength analyses of components and joints. Mater Struct 40:87–96

Sumiyoshi T, Matsui G (1991) Wood joints in classical Japanese architecture. Kajima Institute Publishing, Japan

Volkersen O (1938) Die Nietkraftverteilung in zugbeanspruchten Nietverbindungen mitkonstanten Laschenquerschnitten (The rivet load distribution in lap-joints with members of constant thickness subjected to tension) (In German). Luftfahrtvorschung 15:41–47

Wernersson (1990) Wood adhesive bonds, fracture softening properties in shear and in tension. s.n, Lund

Yang H, Crocetti R, Larsson G, Gustafsson P-J (2015) Experimental study on innovative connections for large span timber truss structures. In: Proceedings of the IASS Working Groups 12 + 18 International Colloquium 2015 International Association for Shell and Spatial Structures (IASS), Tokyo, Japan, s.n

Zwerger K (2000) Wood and wood joints, building traditions of Europe and Japan. Birkhäuser, Berlin