Assessment of the shear strength of glued-laminated timber in existing structures

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Abstract

Civil engineering codes and standards reflect the knowledge in designing new structures. But when it comes to the assessment of existing structures, the engineers are often left with little guidance regarding their remaining structural performance. One example is glued-laminated timber; for new material, there are standard methods such as the shear test of glue-lines according to EN 392 and codes for the performance requirements of products such as EN 386. These codes are also applied when evaluating the remaining structural integrity of aged or damaged components of existing structures.

This paper reports on experimental and statistical research regarding the problematic of making inference on the performance of glue-lam beams based on the shear strength of glue-lines. Since the quality of the glue-line can vary significantly within and between members, multiple samples must to be taken to account for these effects and to get global estimations of mechanical beam properties. Structural scale specimens were taken from timber beams of a decommissioned skating rink in Switzerland. A total of 20 bending and 128 shear tests were carried out on representative large scale; additionally, 608 shear tests on small scale core samples were conducted. The results demonstrate that core samples can be used to derive the shear strength of glue-lines; however, no correlation with the shear and bending strength of adjacent large scale specimens was found. The results demonstrate that the common practise of deriving the strength of glued laminated timber based on the glue-line strength of core samples has to be re-evaluated.

1 Introduction

1.1 On site evaluation of timber structures

Timber has been a structural material for centuries, and numerous examples throughout the world demonstrate its durability. The advantages of glued laminated timber, including its suitability for long spans, diverse shapes and attractive appearance make it the preferred material in wide span timber structures. But timber is biodegradable, and damage attributed to deterioration decreases the capacity of structural members. At best, replacement of damaged members is an acceptable option; at worst, decommissioning of the complete structure is necessary.

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Methods for assessing the condition of timber can be non-destructive (NDT); such techniques are useful for rapid screening for potential problem areas. NDT are best suited for the necessary qualitative assessment of structures. But for strength prediction, a drawback of NDT is the relatively poor correlation between the measured quantity and material strength (Kasal & Anthony 2004).

Semi-destructive techniques (SDT) bridge the gap between indirect non-destructive and direct fully destructive methods of strength measurement. SDT often require the extraction of small specimens for subsequent testing to determine elastic and strength parameters while preserving the integrity of the member. The weakness of SDT is the necessarily small size of specimens that leads to increased variability in test observations.

1.2 Shear test of glue-lines

The strength of glue-lines in glued-laminated timber elements can be derived by shear tests on circular core samples according to EN 392 or ASTM D 905-03. Such core samples (Figure 1 left), although they provide only a local property value, are often used to make inferences on the member strength. But the quality of the glue-line can vary significantly within and between members; therefore to get reliable global estimations of a member’s properties, multiple samples must be taken to account for the effects of irregularities.

For testing, the specimens are placed into the shear test apparatus with the glue-line oriented parallel to the loading direction (Figure 1 right). The maximum shear force value is used to calculate the average shear strength (f_S) of the tested glue-line.

In addition to the strength, the percentage wood failure (PWF) has to be determined after testing. PWF is a critical index to determine the quality of a bond and is usually measured by visual examination. Depending on PWF, different requirements on the strength of glue-lines exist (specified in EN 386 or ASTM D 5266); a higher percentage of glue failure leads to higher requirements on the strength.

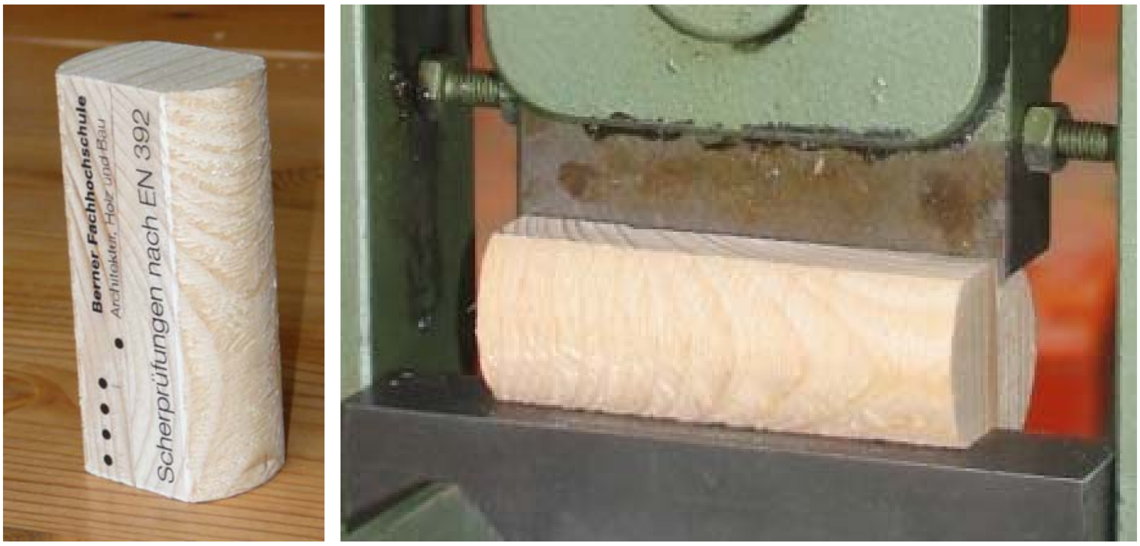

Figure 1: Shear core sample (left) and specimen in test fixture (right)

Since the core specified in EN 392 needs machining to produce two parallel faces for applying the load and only one glue-line is assessed in each drilling, Gaspar *et al.* [2008] evaluated alternatives. For in-situ evaluation, specimens may also be drilled perpendicular to the glue-lines, reaching several glue-lines with minimal impact on the strength of the member to be inspected. Alternative drill cores may also be tested with their cylindrical shape, thus avoiding extra time and cost consuming operations.

Already Selbo [1962] proposed cylindrical specimens extracted perpendicularly to the glue-lines and developed drilling and testing equipment. The results indicated that the shear strength was approximately 14% lower than the one obtained with the standard block specimen according ASTM D 905-03. The tolerance required in the hole of shear tool to insert the specimen resulted in combined stresses, nevertheless, the method was sufficiently promising to test glued laminated timber in service. Outinen and Koponen [2001] developed another method for specimens extracted perpendicularly to the glue-lines, to be tested in an identical device like the one used for block specimens. Shear strength values of drilled specimens, however, were significantly higher (30% to 70%) than the results obtained with block specimens.

Gaspar *et al* [2008] showed that average shear strength and standard deviation of both glue-lines and wood on block specimens increase with the decreasing dimension of the cores. Shear strength of glue-lines were similar to the shear strength of the wood, except in the case of preservative treated pine where a low PWF led to a poorer correlation between wood and glue-line shear strength. Furthermore, good correlation was found between shear strength of cores parallel (EN 392) and perpendicular to the glue-line.

The extraction of core samples has been described as often unnecessary, as experts can recognize whether the wood or the glue-line is damaged and with the core tests, only the quality of the wood is examined while the glue-lines often show sufficient strength (Brüninghoff 2007). Furthermore, the shear stresses in typical test fixtures are not evenly distributed, no pure condition of shear stress can be created, and the PWF measurements are subjective, making it difficult to compare test results (Steiger *et al* 2007).

1.3 Objective

Alike other materials, glued laminated timber members need to be regularly inspected to prevent premature degradation and avoid structural failures. However, apart from visual inspection, there is a lack of reliable methods to assess the integrity of members in service and to evaluate the quality of glue-lines. The objective of the presented work is to evaluate the application of shear tests of glue-lines in the assessment of existing timber structures.

2 Case study

2.1 Decommissioned ice rink

At the beginning of 2006, many timber structures in Central Europe collapsed, mostly due to heavy snow loads. As a consequence, existing timber structures were being monitored more closely. One examined structure was the roof of an ice rink in Switzerland, built in 1982 with seating for 4500 people. The main load bearing elements were glued laminated timber beams with a length of 14 m, consisting of two parallel members (Figure 2 left) 1.4 m high and 0.2 m deep for the three centre beams and 0.15 m deep for the side beams, respectively. In order to improve the interior conditions, the originally open south facade was closed in 1992; since then, due to lower air circulation, the relative humidity and consequently the timber moisture content (MC) increased.

At the time of first inspection in winter 2007/08, the MC was determined to be partially above 30% allowing the growth of wood destroying fungi. Visual inspections showed local fungi infestations but no cracks. Since the secondary structure was significantly damaged, it was recommended as an initial measure of safety to close the rink to public when high snow loads occurred. Core samples on glue-lines were extracted; and from four samples taken, two did not fulfil the requirements according to EN 386; therefore in summer 2008 a second round of investigations was carried out.

Contrary to the first inspection, and due to the lower MC, large cracks were observed, some more than 2 m long and up to 90 mm deep (Figure 2 right). From 40 shear core samples taken, 19 did not fulfil the requirements, in five of them less than 20% remaining strength was obtained. The average shear strength was determined to 5.8 N/mm^2 and the 5% quantile value to 1.9 N/mm^2.

The complete assessment demonstrated that the roof structure did no longer fulfil safety requirements and it was decided to decommission it. Individual parts (3 m long sections of each main beam) were transported to the timber & composite lab of the Bern University of Applied Sciences for further tests.

Figure 2: Main beam of roof structure (left) and crack in glue-line (right)

2.2 Material

A total of 10 beam segments were cut into smaller parts. From each 200 mm wide beam segment, 2 bending test specimen, 16 large scale shear specimen and 60 core samples were cut, see Figure 3. From the 150 mm wide beam segments, 2 bending test specimen, 8 shear specimen and 30 core samples were cut. To study the variation of shear strength within one glue-line, eight additional cores were takes from 4 glue-lines each. Therefore a total of 20 bending, 128 large scale shear and 608 core samples were extracted.

The bending specimen were 3 m long and 300 mm high; the large scale shear specimen were 600 mm long and 300 mm high, and the small scale core samples followed the requirements of EN 392. The core samples were taken from strips which were located between the large scale shear specimens in order to facilitate correlating the strength of the core samples to the strength of the large scale shear samples within one segment. Five cores were taken from each strip, four of those with glue-lines and one without a glue-line.

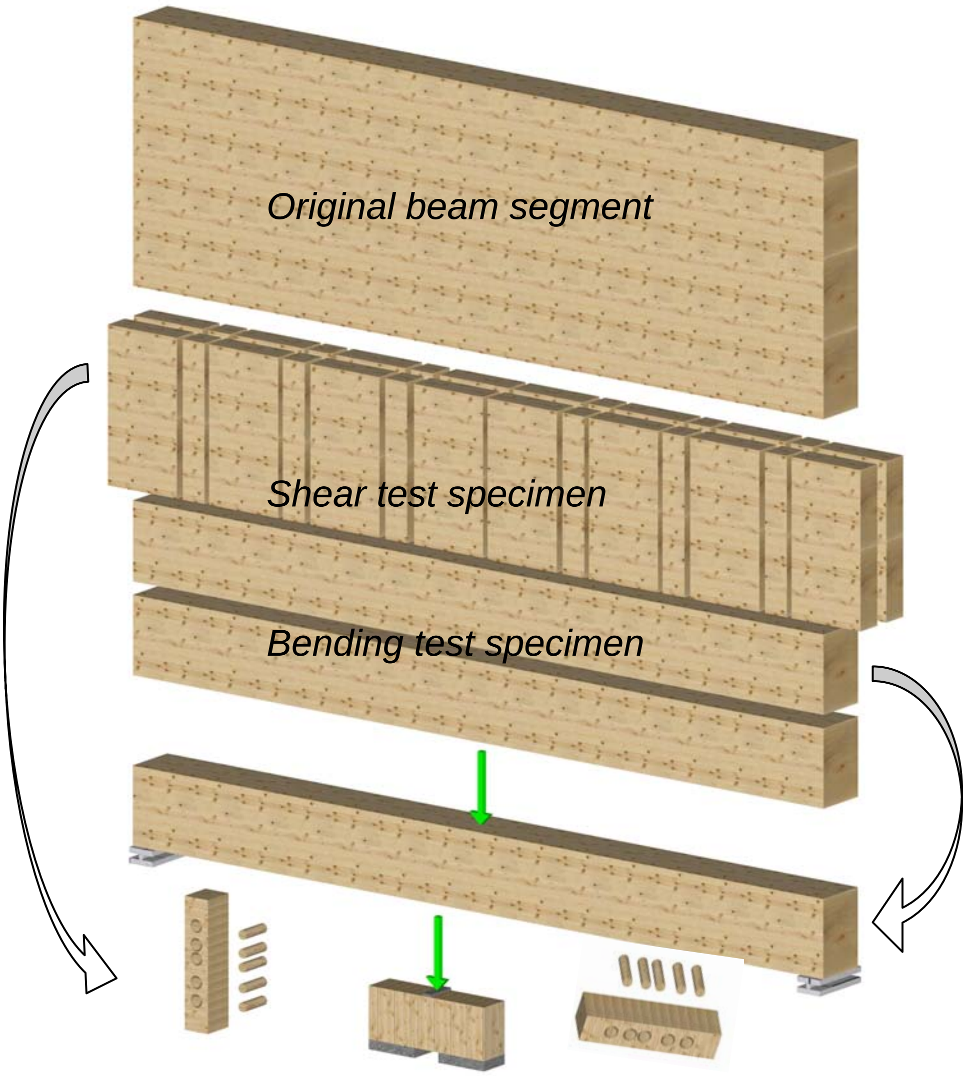

Figure 3: Test specimens cut from beam segments

2.3 Methods

The bending tests were carried out as three-point tests in a loading frame with a free span between the supports of 2.6 m. The specimens were stored in laboratory environment where they reached an equilibrium moisture content of approximately 12%. The quasi-static tests were performed under displacement-control at a constant loading rate of 10 mm/min. The exact dimensions and the maximum loads were recorded and the bending strength f_B was computed for each specimen.

For the large scale shear tests, the specimens were loaded with three glue-lines being exposed to the shear stress between the support and the loaded steel plate. The tests were performed under displacement-control at a constant loading rate of 3 mm/min. Again, the dimensions and the maximum loads were recorded and the shear strengths $f_{S,I}$ were computed for each specimen.

The tests on the core samples were performed according to EN 392; the specimens were conditioned to 12% MC prior to cutting and then again stored in constant climate until testing. The maximum load was recorded and the shear strengths $f_{S,II}$ (for samples without glue-lines) and $f_{S,III}$ (for samples with glue-lines) were computed.

2.4 Results

The test results for the individual beam segments are summarized in Table 1, with the average values and the coefficients of variations (CV - in parenthesis). The correlation between the shear strength of the glue-lines with the other recorded strength values is illustrated in Figure 4.

Table 1: Summary of test results

Beam segment	f_B [N/mm^2]	$f_{S,I}$ [N/mm^2]	$f_{S,II}$ [N/mm^2]	$f_{S,III}$ [N/mm^2]
200-I	43.3 (18%)	5.4 (47%)	10.9 (15%)	8.5 (20%)
200-II	41.1 (29%)	7.0 (52%)	10.0 (11%)	8.6 (16%)
200-III	38.6 (19%)	7.5 (53%)	11.4 (13%)	8.4 (20%)
200-IV	38.2 (10%)	5.1 (55%)	10.5 (15%)	8.1 (19%)
200-V	35.2 (25%)	6.5 (48%)	11.4 (11%)	8.6 (24%)
200-VI	44.6 (25%)	7.2 (51%)	10.5 (23%)	8.8 (20%)
150-I	45.4	4.9 (55%)	10.9 (5%)	8.4 (18%)
150-II	45.3 (9%)	6.6 (43%)	11.4 (13%)	7.9 (23%)
150-III	38.1 (17%)	7.0 (37%)	11.3 (11%)	8.8 (13%)
150-IV	43.8 (20%)	4.8 (51%)	11.1 (11%)	8.5 (27%)
Average	41.4 (19%)	6.2 (49%)	11.0 (11%)	8.4 (20%)

The bending strength (f_B) of the large scale specimens averaged 41.4 N/mm^2 with moderate variation between the beam segments (9%) but showed large variation between the two specimens cut from the same beam segment with values around 19%. The shear strength of the large scale specimens ($f_{S,I}$) averaged 6.2 N/mm^2 with 17% variation between beam segments but with an extremely large variation within segments (on average 49%).

The shear strength of the core samples without glue-lines ($f_{S,II}$) was on average 11.0 N/mm^2 with very small variation between the beam segments (3%) and moderate variation within segments (11%). A significant size effect in shear strength is observed; small scale specimens have a strength that is 36% higher (11.0 N/mm^2 vs. 6.2 N/mm^2) than large size specimens.

The shear strength of the glue-lines ($f_{S,III}$) was on average 8.4 N/mm^2, with very small variation between the beam segments (4%) but very large variation (20%) within segments. The glue-line shear strength was for all beam segments lower than the shear strength of the core samples without glue-lines.

The variation within beam segments was much larger for all strength parameters than the variation between beam segments. This indicates that the local estimates, by testing single glue-lines (core samples) or few glue-lines (large scale shear samples), are not representative for a large scale specimens.

The correlation of the investigated strength values for all beam segments is shown in Figure 4. It can clearly be observed that almost no correlation exists between the shear strength of glue-lines and the other strength values.

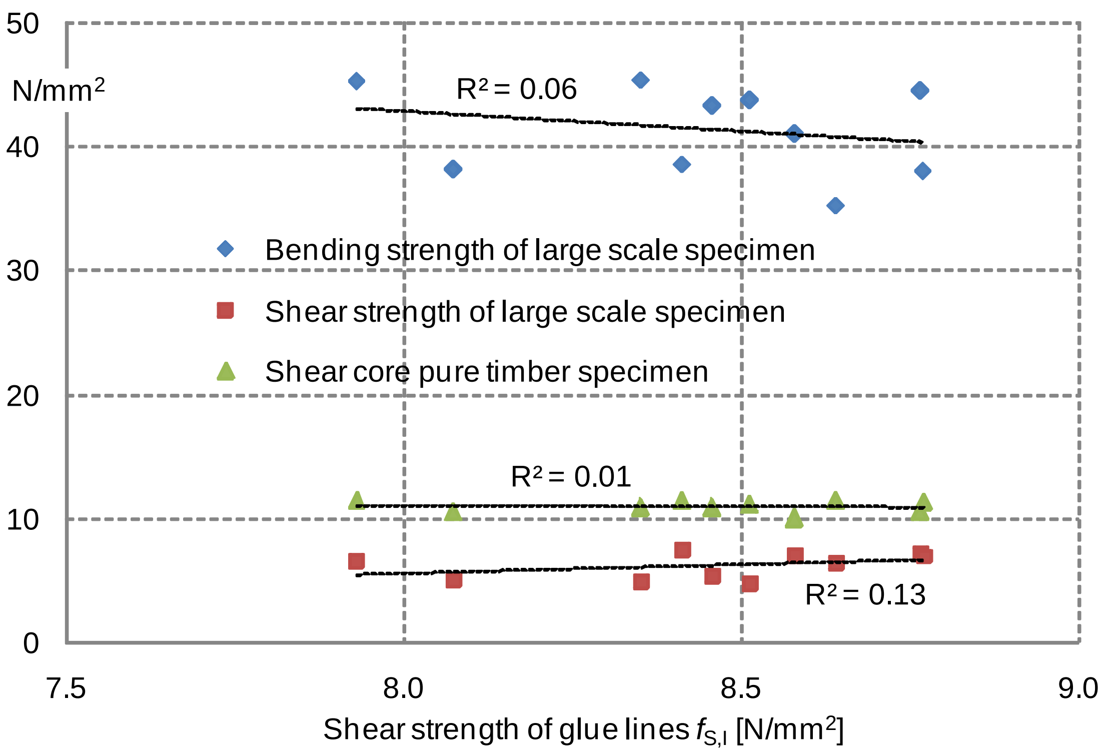

Figure 4: Correlation between glue-line shear strength and timber strengths

The tests on eight core elements taken from within the same glue-line revealed a much smaller variation (on average 11%) than the variation of glue-line strength for all samples taken from one segment (20%). Table 2 shows the results on samples taken from the same glue-lines.

Table 2: Summary of test results

Beam segment	Glue-line 1 $f_{S,II}$ [N/mm^2]	Glue-line 2 $f_{S,II}$ [N/mm^2]	Glue-line 3 $f_{S,II}$ [N/mm^2]	Glue-line 4 $f_{S,II}$ [N/mm^2]
150-I	9.1 (11%)	6.5 (10%)	8.8 (7%)	10.1 (8%)
150-II	8.0 (8%)	9.7 (6%)	8.8 (11%)	9.8 (11%)
150-III	10.1 (14%)	8.9 (13%)	8.9 (14%)	7.4 (14%)
150-IV	9.8 (12%)	10.8 (13%)	7.5 (14%)	8.5 (14%)

3 Conclusions

This paper reports on experimental investigations and a subsequent statistical analysis regarding the problematic of making inference on the performance of glued laminated timber beams based on the shear strength of glue-lines. The results can be summarized as follows:

1. Tests on core samples can be used to determine the shear strength of glue-lines; however, as with any technique that utilizes small specimens, the samples give only information about the specific location which they were taken from.
2. No significant correlation between the shear strength of glue-lines and the strength of gluelam beams can be established; this is valid for the bending strength and the shear strength of the beams.
3. The variation in shear strength of samples taken from the same glue-line is significantly smaller than that from samples taken from different glue-lines.
4. As a consequence of the aforementioned, the common practise of deriving the strength of glued laminated timber beams based on the glue-line strength of core samples tested according to EN 392 and evaluated according to EN 396 has to be seriously questioned.
5. Since the results from visual inspections give a clear indication on the state of existing timber structures, the extraction of cores is often unnecessary; if strength estimates are necessary, samples should be taken from the section were either damage is visible or large stresses are expected.

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