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Effect of vertical interlaminar shear slip and butt joints in narrow stress-laminated-timber bridge decks

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ABSTRACT

Interlaminar slip occurs in stress-laminated-timber (SLT) decks subjected to concentrated loads, such as vehicles. Butt joints in SLT decks can be regarded as local discontinuities with increased load transfer resulting in increased frictional forces. Multiple tests were performed with different combinations of pre-stress level, number of loads, span-to-depth ratio, beam width and butt-joint configurations. The results of the tests have been analysed and compared with non-linear finite element analyses using solid elements and contact properties. The experimental results and the analysis showed that, in the case of a high span-to-depth ratio in the deck and without butt joints, there is little or no interlaminar slip. Test elements without butt joints showed little slip at pre-stress levels of 300 kPa or higher. A significant reduction in post-slip stiffness was observed for the test elements with butt joints.

1. Introduction

Stress-laminated-timber (SLT) decks are an alternative to conventional building material for short- to medium-span bridges. The advantages include their low weight and excellent flexibility that enable a high prefabrication rate and quick assembly on site. The use of glulam beams that are butt jointed makes it possible to construct long, continuous decks over several supports with a short construction time, which may be highly desirable in some cases.

The principal idea of SLT decks is to create a plate by compressing several beams positioned together side by side. A load distribution is obtained when concentrated loads are distributed to adjacent laminations using friction. This is usually achieved using equally spaced high-strength steel rods positioned transversely to the longitudinal direction of the beams. The concept was developed as a means of rehabilitating old nail-laminated timber bridges some decades ago. Several researchers and engineers [1–10] worked on this type of structure during the 1980s and 1990s in both North America and Australia. During this period, the most common material for SLT decks was sawn structural timber. However, during the last decade, it has become more common in Sweden and Europe to build these bridges with planed glulam beams instead of sawn timber. A deck constructed with glulam normally has a higher load-bearing capacity than a deck with sawn timber, but it also has a lower friction capacity for load distribution due to the lower coefficient of friction (COF) for planed surfaces compared to sawn surfaces. This development in the construction of SLT, together with increased design loads and larger concentrated forces on SLT decks, has highlighted the issue of interlaminar slip, where the beams slip in relation to one another. Both longitudinal and vertical slip has been observed in several full-scale tests on SLT decks intended for highway traffic and successfully modelled using non-linear FE analysis [11–14].

Interlaminar slip in SLT decks causes stress redistribution within the deck and generally results in higher stresses and larger deflections. Decks constructed with butt joints are normally subjected to more vertical slip, since the butt joints themselves can be seen as imperfections in the decks, with high stress concentrations as a result.

In most cases, the design of timber bridges in Sweden and Europe is based on the Eurocode Standards EN 1995-2 [15], together with EN 1995-1-1 [16] and EN 1991-2 [17]. EN 1995-2 states that the pre-stress force after a long period of time should be of such a magnitude that slip between deck laminations is prevented. The previously mentioned full-scale tests have shown that it might be very difficult to prevent all types of slip or displacement in laminations. EN 1995-2 states that the requirement for

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interlaminar slip, $F_{v,Ed} < \mu_d\ \sigma_{p,min}\ h$, should be met, where $F_{v,Ed}$ is the design shear force per unit length, caused by vertical and horizontal loads, μ_d is the coefficient of friction, $\sigma_{p,min}$ is the minimum long-term compressive pre-stress and h is the height of the deck. Values for μ_d (depending on surface roughness, moisture content and direction relative to the grain) are stated in EN 1995-2. It is also stated in EN 1995-2 that the long-term pre-stress should be at least 0.35 MPa in areas subjected to concentrated loads. It is also stated in EN 1995-2 that the pre-stress can be considered to be larger than 0.35 MPa given that the following requirements are fulfilled.

1. The initial pre-stress should be at least 1.0 MPa.
2. The moisture content of the deck laminations should be less than 16% at the time of assembly.
3. The variation in moisture content is limited using a suitable protection such as a waterproof membrane.

EN 1995-2 does not provide any guidance on how the requirement for interlaminar slip should be fulfilled. A requirement for the longitudinal spacing of butt joints is stated in EN 1995-2. The longitudinal distance between two adjacent butt joints l_1 should be calculated according to Eq. (1) [15]. Where d is the spacing of the pre-stressing bars and t is the width of the laminations in the deck.

$$l_1 = \min \begin{cases} 2d \\ 30t \\ 1.2m \end{cases} \tag{1}$$

EN 1995-2 states that the strength reduction of an SLT deck with butt joints should be taken in proportion to the number of butt joints within a distance of four times the width of the laminations.

The aim of this paper is to present the results of an extensive laboratory test series, together with the results of non-linear numerical finite element analysis (FEA) performed on the tested elements. The results of the tests are independent of any design code (such as Eurocode or AASTHO), due to the fact that the test elements were not designed to fulfil the requirements of any such design code. The influence of varying compressive pre-stress levels, span-length ratios and butt-joint configurations was tested and can be compared with other results from the test and the numerical analysis. The results of this study can be used to develop a better understanding of the causes of interlaminar slip, develop improved design models and establish more accurate design requirements in future versions of design codes, such as the Eurocode Standards.

2. Materials and method

Experimental tests and numerical analyses of stress-laminated timber decks were performed in this study. Load–deflection values from both experimental tests and numerical analyses can be compared with one another in order to determine the accuracy of the numerical model. The experimental tests provide an actual failure load and failure mode, while the numerical analysis provides further information on current stress states and stress redistribution due to interlaminar slip.

2.1. Experimental test

A total of 29 configurations were tested on 12 unique stress-laminated-timber test elements, as shown in Table 1. Some tests were repeated several times in order to study the influence of repeated loading. An external load was applied with the aim of generating interlaminar slip in all the tests. In 11 of the tests, the load was increased further until the failure of at least one beam in the element was observed. The test elements were narrow in comparison to the length in order to reduce the effects of transverse bending, thereby focusing on the vertical interlaminar slip. Fig. 1 shows a principle sketch of the test elements.

2.1.1. Material and dimensions

The test elements were made of Norway spruce (*Picea abies*) glue-laminated timber (glulam) beams. The glulam beams were manufactured to fulfil the requirements of the Swedish CE L40c glulam class, meaning that the two top and bottom laminations

Table 1
Comparison of tests and variables.

Element no.	Test no.	Pre-stress (kPa)	Height (mm)	Width (mm)	Load pos.	Butt joints/joint distance (mm)	Ultimate load test
1	1	100	180	90	B	No	No
1	2	200	180	90	B	No	No
1	3	300	180	90	B	No	Yes
2	4	600	180	90	B	No	Yes
3	5	100	270	90	B	No	No
3	6	200	270	90	B	No	No
3	7	300	270	90	B	No	Yes
4	8	600	270	90	B	No	Yes
5	9	100	180	90	A	No	No
5	10	200	180	90	A	No	No
5	11	300	180	90	A	No	Yes
6	12	600	180	90	A	No	Yes
8	13	100	270	90	A	No	No
8	14	200	270	90	A	No	No
8	15	300	270	90	A	No	Yes
7	16	600	270	90	A	No	Yes
9	17	300	270	90	C	No	No
10	21	200	270	90	B	Yes/900	No
10	22	300	270	90	B	Yes/900	No
10	23	600	270	90	B	Yes/900	Yes
11	24	200	270	42	B	Yes/900	No
11	25	300	270	42	B	Yes/900	No
11	26	600	270	42	B	Yes/900	Yes
12	27	200	270	90	B	Yes/1350	No
12	28	300	270	90	B	Yes/1350	No
12	29	600	270	90	B	Yes/1350	Yes