HJL/Draft 2004-09-28

COST E24 Probabilistic Model Code for Timber – Glued laminated timber

This paper gives a brief description of the behaviour of glued laminated timber beams as a basis for discussions about the glulam chapter in COST E24 Probabilistic Model Code for Timber structures. It leans heavily on the works of Erik Serrano, Division of structural engineering, Lund University, e.g. [Serrano, 2003], [Serrano et al., 2000] and [Serrano & Larsen,1999].

1. The components

Glulam beams are produced by gluing together laminations made by end jointing boards to the required length.

The glue has no influence on the strength and stiffness. The properties of glulam depend only on the strength and stiffness of the boards and the finger joints.

2. Lamination effects

It is generally assumed that the lamination results in a strength increase; that there is a lamination effect. There are various definitions of this effect. The one most commonly used is:

$$k_{lam} = \frac{f_m}{f_t}$$

Here f_m is the bending strength of the glulam corresponding to ordinary beam theory and f_t is the tensile strength of the outer lamination found from testing a long lamination free to deflect sideways due to uncentred knots and other defects and to unsymmetrical stiffness variations over the cross-section. Therefore, f_t corresponds not to a pure tensile failure but to failure caused by a combination of tensile and bending stresses. The tensile strength of a corresponding member restrained as in a glulam beam is higher. This effect is really not a lamination effect, but a “test procedure effect”.

The lamination effect is often explained by the following:

- In a glulam beam the defects are smeared out, resulting in a more homogeneous material than solid wood. The probability of a defect having a serious influence on the strength of the beam is less than for a single lamination. This is referred to as a “dispersion effect”.
- A lamination containing knots or other zones of low stiffness will be reinforced by adjacent laminations when it is contained in a glulam beam: the stiff and strong laminations take up a larger part of the tensile stresses. This is sometimes referred to as a “reinforcing effect”, a “bridging effect” or a “stress redistribution effect”.

Based on experience, the models for the strength of glulam take as reference the individual lamination – see below. This means that they a priori disregard the influence of the “dispersion effect” since typical lamination thicknesses are in the range of 20-50 mm and strength-reducing defects, such as knots, are of the same order of magnitude

3 The Karlsruhe model

There are several models for the strength of glulam beams. An overview is given in [Serrano, 2003]. The models may differ in details and level of sophistication, and linked to this in the calculation power required, but basically they are all based on the same principles. One of the best-known models is the so-called Karlsruhe model developed by Ehlbeck, Görlacher and especially Colling, see [Ehlbeck et al., 1985] and [Colling, 1990].

3.1 The model

The Karlsruhe model uses a subdivision of a glulam beam into cells. A cell corresponds to a 150 mm long part of a lamination. The lamination is assumed to consist of two “materials”: wood and finger-joints.

The model is based on two computer programs, one that simulates glulam beam lay-up, and one that performs finite element calculations.

The lay-up programme determines the position of the finger-joints by sampling from statistical distributions found by measuring the distances between finger-joints in glulam beams. It also assigns material properties to each cell along a lamination.

The basic parameters are density and the Knot Area Ratio (KAR). KAR is the area of all knots in a cell projected on a plane perpendicular to the lamination divided by the area of the cross-section. A section of a lamination between two finger-joints are assigned a density and a KAR-value This KAR-value is then used within the section to assign to each cell a specific KAR-value by multiplying the lamination-KAR-value by a factor, taken from statistical distributions, its aim being to simulate the influence of multiple knots within a limited zone (= the length of the cell) of the lamination. The specific KAR-value and the density value are then used to calculate the stiffness (modulus of elasticity) and the strength of a cell using regression equations containing random elements. This ensures that even if two cells are assigned the same KAR-value, their strength and stiffness values need not be the same. It should be noted that the strength is based on testing150 mm long specimens restrained against deflection, i.e. there is no “test procedure effect”.

The finger-joints are modelled in the same way as described above, but by assigning “finger-joint properties” instead of “wood properties” to the cells that contain a finger-joint.

The weak point in the model as in all other models is related to the failure criteria of the beam. In the Karlsruhe model four different failure criteria are used based on “experience gained during the calibration of the model to beam bending tests”:

1. If a finger-joint fails in the outer tension laminations, the beam is assumed to fail. This is motivated by the fact that finger-joints induce a failure across the complete lamination width, and not only a part of it as is the case for knots.
2. If two neighbour elements fail at the same stress level, the beam is assumed to fail. This simulates a brittle failure in tension.
3. If an element fails in tension within a predefined region (see Figure 1) around a previously failed element, the beam is assumed to fail. This simulates a failure due to to high shear stresses in that region, although the model does not include the shear strength of the wood as a parameter.
4. If none of the above criteria have been fulfilled, the beam is assumed to fail when the fifth element fails in tension.

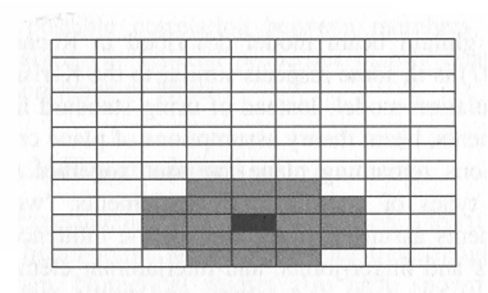

Figure 1. If an element fails close to (grey region) a previously failed element (black) the beam is assumed to fail (Coiling, 1990.

3.2 Effect of weak zones

The correlations used in the Karlsruhe model implies – at least for cells without finger-joints – that a zone of lower stiffness will be subjected to stresses of lesser magnitude, in line with the reduction in stiffness. Therefore, it is often assumed that a small zone (e.g., a knot) of lower strength will not have a severe effect on the global load-bearing capacity of a beam.

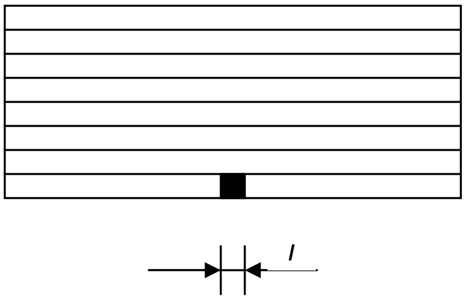

Figure 2. Beam with length L and a weak zone with length l in the middle.

Serrano & Larsen [1999] have checked up on this assumption. A beam section with length 600 mm and depth 315 mm with 7 laminations subjected to pure bending was analysed, see Figure 2. In the middle of the outer lamination there was a weak zone where the stiffness was reduced by 25-100 %.

Some results are shown in Figure 3 and 4 that are taken from [Serrano & Larsen, 1999]. The stress distributions shown in these figures all correspond to the same bending moment. The normalized stress shown is the stress divided by the maximum stress as calculated by ordinary beam theory.

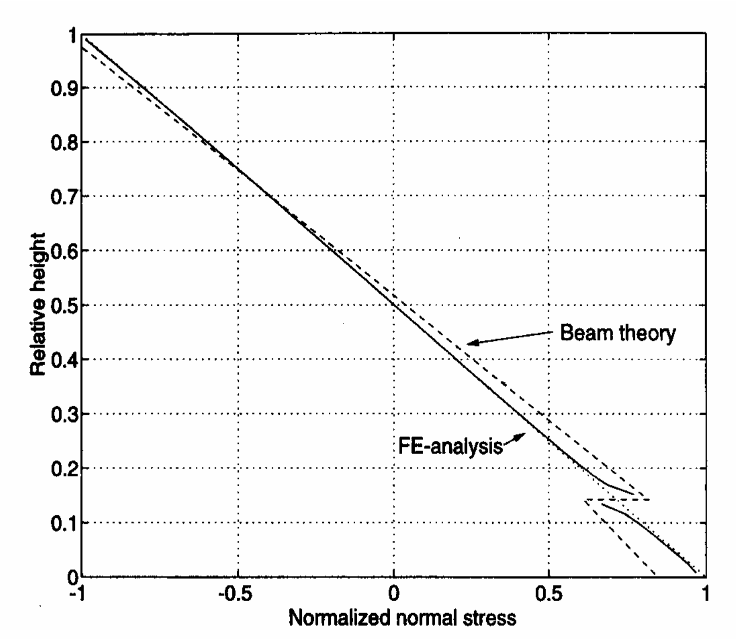

Figure 3. Stress distribution in the middle of the beam for a length of the weak zone (stiffness reduction 25 %) of 30 mm, calculated with beam theory and with finite elements

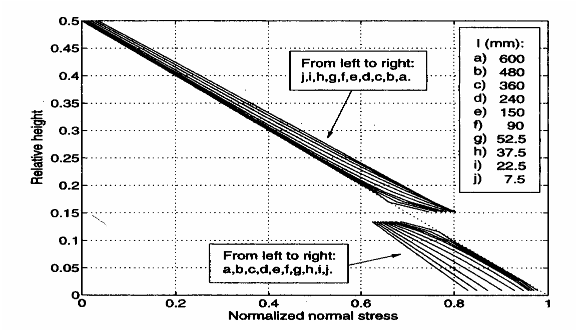

Figure 4. Influence of the length of the weak zone (stiffness reduction 25 %) on the stress distribution in the middle of the beam.

Fig. 3 shows the stress distribution in the mid-section of the beam for a length of the weak zone of 30 mm calculated by finite elements and by ordinary beam theory, i.e. assuming that plane cross sections of a beam that initially were perpendicular to the beam axis remain plane and perpendicular to the beam axis under loading. The reduction of the stresses in the weak zone is very local.

Fig. 4 shows the influence of the length of the weak zone. As expected, when the weak zone is as long as the beam, the stress distributions are linear, in accordance with beam theory. A reduction in the extension of the weak zone results in a redistribution of the axial stresses. In the limiting case, as the length of the weak zone approaches zero, the stress distribution is found to approach the linear one expected in a homogeneous cross section. According to beam theory, the length of the weak zone should not affect the stress distribution at all.

The analyses suggest that the simple assumption that a local and proportional reduction in stiffness and strength has only minor influence on beam strength is not valid for small zones such as knots and finger joints. Since the stress reduction in a small zone is far from proportional to the stiffness reduction, the stress is closer to the strength of the material in a small weak zone than one would expect by intuition.

3.3 Reinforcing effect

The models for the strength of glulam differ with regard to the failure criteria, bur generally it is assumed that after an initial failure in a lamination, the stresses in the failed lamination can be transferred to the neighbour laminations. Serrano et al [2000] have checked up on this possibility by analysing a beam with a failed outer lamination, see Figure 5.

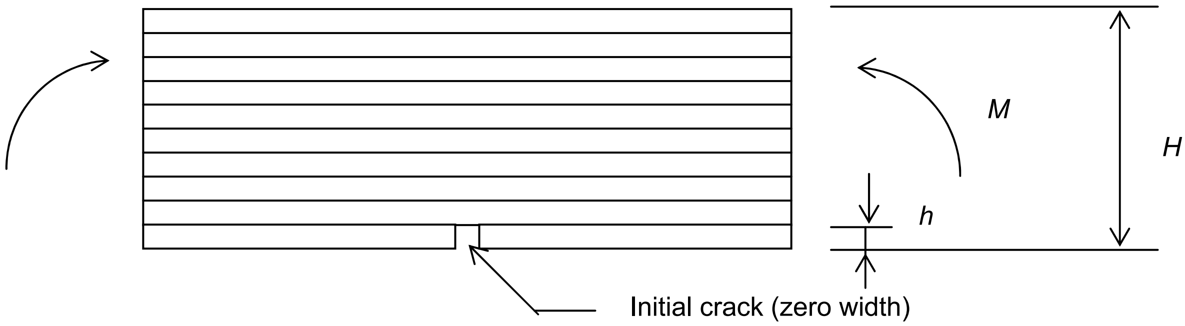

Figure 5. Beam subjected to bending with a failed outer lamination.

Based on the assumptions of linear fracture mechanics, Petersson [1994] derived an expression for the critical bending stress, i.e. the stress where an unstable crack will develop in the glue line between the failed lamination and the rest of the beam:

$$\sigma_{crit} = \frac{6M_{crit}}{bH^2} = \frac{1}{\sqrt{H}}\sqrt{\frac{6G_c E}{\left(H/(H-h)\right)^3 - 1}}$$

Here

G_c fracture energy at crack propagation. For pure mode-1 failure G_c varies between 200 and 400 N/m; for pure mode-2 failure G_c is about 3 times higher. For simplicity – giving a lower bound – a value of G_c = 400 N/m is used

E modulus of elasticity. A value of E = 15 000 MPa is assumed.

Figure 6 shows the critical stress as a function of the beam height, H, and the lamination thickness, h. Assuming a bending strength of 30 MPa, a local failure in the outer lamination will lead to total collapse if the lamination thickness is greater than about 12 mm, which in practice is always the case. These results are confirmed by [Larsen, 1982].

In LVL the “lamination thickness” is 3-4 mm, which explains the high strength, even though LVL is made with butt joints in the plies.

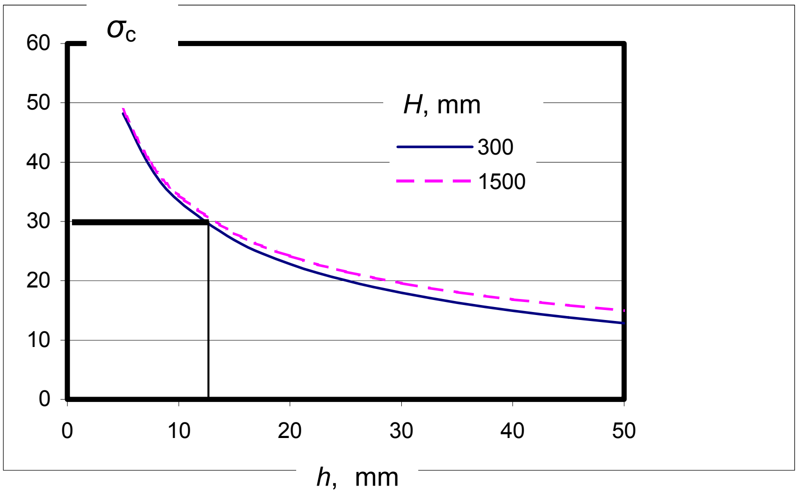

Figure 6. Critical stress.

3.4 Test results

Colling [1990] also gives results of tests with glulam beams. The test programme consisted of 6 series, each with 7 beams 100 x 600 x 7500 mm^3. The laminations were selected as shown in Table 1 where also the tests results are given. It is seen that except for series 1, about 60 per cent of the beams failed in a finger-joint but that these beams had strength above average.

Table 1.

Series	Laminations	Bending strength, test MPa		Proportion with finger joint failures
		All	Finger joint failure	
1	Large knots	34,7	-	0/7
2	Average knots	38,9	40,2	4/7
3	Small knots	40,3	41,1	5/7
4	High density	42,9	48,8	4/7
5	Stiff	43,8	46,9	4/7
6	Stiff and small knots	46,1	47,4	3/7

The test results and the theoretical load-carrying capacities are compared in Figure 7.

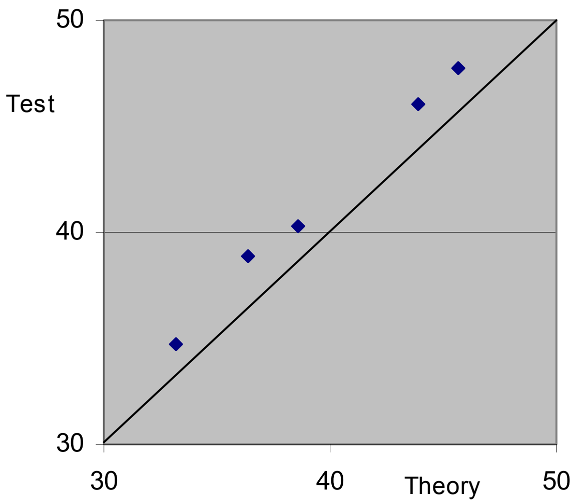

Figure 7. Theory and test results.

Figure 7 shows that the test results generally are higher than predicted by the theory. This is claimed to be due to the fact that the theory disregards the reinforcing effect in cases with finger joint failure. This is, however, contradicted by the fact that beams with finger joint failure had above average strength. It is not possible from the paper to estimate the influence of the reinforcing effect.

Aasheim et al. [1993] have compared the results from the model with the results from tests with about 100 glulam beams. The agreement was good

4 The EN model

The Karlsruhe model has not been used directly for the European design method described in EN 1194.

It was felt that it was too complicated and some of its implication – e.g. a strong depth effect independently of length - was not supported unambiguously by tests, see [Ehlbeck and Colling, 1988]. Instead a simpler model was chosen where the strength depends solely on the tensile strength of the outer lamination in the tension side. Arguments for this model may be found in [Gehri, 1992], [Gehri, 1992], [Larsen, 1982] and [Schickhofer, 1996].

According to the model the characteristic strength values shall be calculated from the conventional characteristic tensile strength $f_{t,0,l,k}$ and the mean modulus of elasticity $E_{l,mean}$ *of* the laminations as shown in Table 2.

Table 2. Characteristic properties in MPa of glued laminated timber

Property			Comments
Bending		$f_{m,,k} = 7 + 1.15\ f_{t,0,l,k}$	Some theoretical background
Tension	parallel to grain	$f_{t,0,k} = 5 + 0.8\ f_{t,0,l,k}$	Some theoretical background
	perpendicular to grain	$f_{t,90,k} = 0.2 + 0.015\ f_{t,0,l,k}$	Empirical
Compression	parallel to grain	$f_{c,0,k} = 7.2\ f_{t,0,l,k}^{0,45}$	Empirical
	perpendicular to grain	$f_{c0,g,k} = 0.7\ f_{t,0,l,k}^{0,5}$	Empirical
Shear	shear	$f_{v,k} = 0.32\ f_{t,0,l,k}^{0,8}$	Empirical
Modulus of elasticity	mean	$E_{mean} = 1.05\ E_{l,mean}$	Some theoretical background
	5-percentile	$E_{0,5} = 0.85\ E_{l,mean}$	Some theoretical background
Shear modulus		$G = 0.065\ E_{l,mean}$	Some theoretical background

For the characteristic tensile strength of the finger joints it is required that

$f_{t,fj,k} \geq f_{t,0,l,k} + 5$ MPa

The required overstrength of the finger joints shall take care of the brittle failure.

If the lamination quality in the outer and inner laminations (2/3 of the depth) the expressions are valid for each part although it is not in consistence with the assumptions of the decisive influence of the outer lamination. It is however permitted to calculate the bending properties with the strength of the outer laminations provided the tensile strength is not less than 75 % of the strength of the outer laminations.

5 Outline of the model code chapter on glulam

For a beam with a cross-section as shown in Figure 8, it is assumed that the strength depends only on the tensile strength of the outer tension lamination.

The tensile lamination consists of timber boards with length *a* jointed by finger joints.

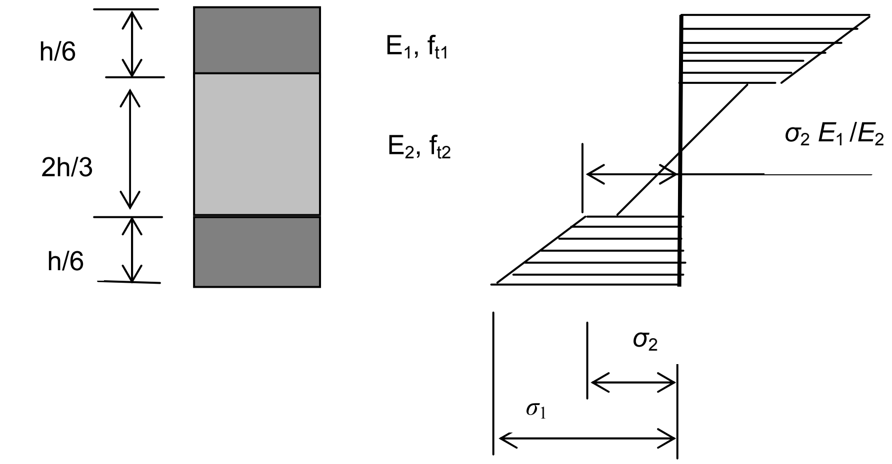

Figure 8. Cross-section and assumed stress distribution.

The length, *a*, is assumed to be Poisson distributed with parameters determined by measurements of lamination lengths in glulam factories. The possibility of having mixed distributions because some laminations are used directly while others have been crosscut to remove defects shall be taken into consideration, see Figure 9.

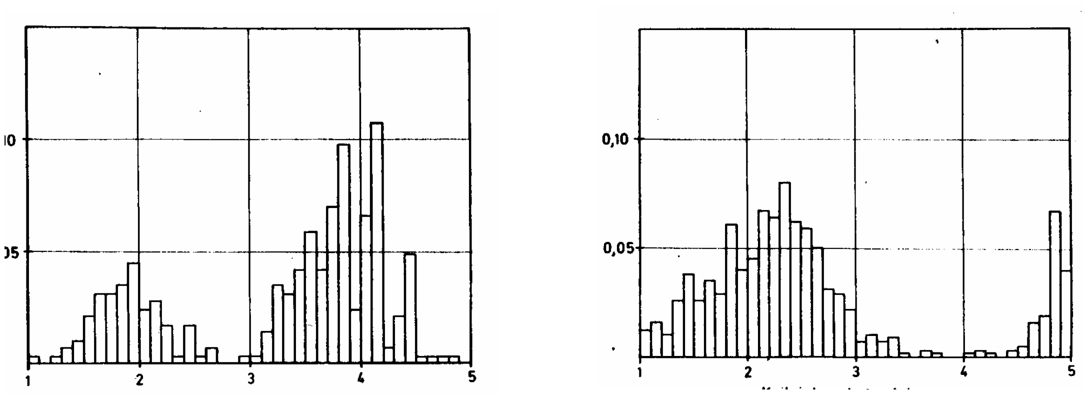

Figure 9. Distributions of lengths between finger joints for two glulam factories. After Colling, 1990].

The tensile strength, $f_{l,mean}$, of the boards between the finger joints and the modulus of elasticity, $E_{l,mean}$, shall be assumed to be constant and log normal distributed.

The tensile strength of the finger joints $f_{fj,mean}$ shall be assumed to be log normal distributed.

The mean bending strength $f_{m,mean}$ of a glulam beam shall be determined from:

$f_{m,mean}$ = min {9.3 MPa + 1.15 $f_{l,mean}$; 2.7 MPa + 1.15 $f_{fj,mean}$}

The other properties shall be determined from $f_{l,mean}$ by the expressions given in Table 3. They correspond to Table 2 but transformed to mean values assuming a coefficient of variation of 0.2 for strength values.

Table 3. Mean properties in MPa of glued laminated timber

Property		
Bending		$f_{m,,mean} = 9.3 + 1.15\, f_{l,mean}$
Tension	parallel to grain	$f_{t,0,k} = 6.7 + 0.8\, f_{l,mean}$
	perpendicular to grain	$f_{t,90,k} = 0.27 + 0.015\, f_{l,mean}$
Compression	parallel to grain	$f_{c,0,k} = 8\, f\, f_{l,mean}{}^{0,45}$
	perpendicular to grain	$f_{c0,g,k} = 0.75\, f_{l,mean}{}^{0,5}$
Shear	shear	$f_{v,k} = 0.23\, f_{l,mean}{}^{0,8}$

Modulus of elasticity mean	E_{mean} = 1.05 $E_{l,mean}$
Shear modulus	G_{mean} = 0.065 $E_{l,mean}$

6 References

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