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Innovation in Structural Timber Design with Prestressed Timber Joints

Projet de constructions en bois avec des assemblages précontraints

Erneuerung von Holzkonstruktionen mit verstärkten Holzverbindungen

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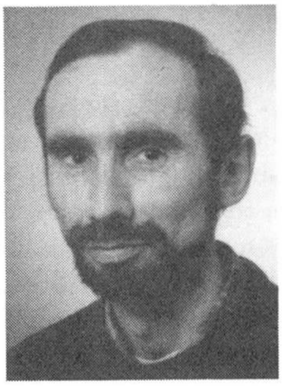

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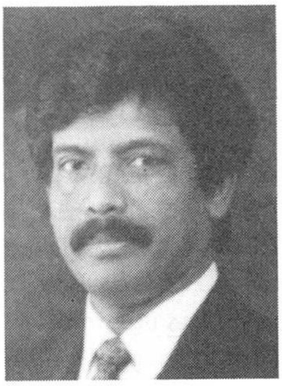

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SUMMARY

A timber joint is presented with a new type of prestressing connector. The timber is locally reinforced with densified veneer wood. The high strength and stiffness of the joint is combined with excellent ductile properties. This enables structural timber to be applied much more efficiently than with traditional joints. It is shown that timber savings of up to 30% can be realised.

RÉSUMÉ

Un nouvel assemblage pour le bois est présenté avec un nouveau type de connecteur précontraint. Le bois est renforcé localement avec du bois lamellé. Une grande résistance et une grande rigidité de l'assemblage sont combinées à une excellente ductilité. Ceci permet à la structure en bois d'être utilisée plus efficacement que lorsqu'elle comporte des assemblages traditionnels. Il en résulte une économie de bois de 30%.

ZUSAMMENFASSUNG

Eine neue Holzverbindung mit einem neuartigen Verbindungsmittel wird vorgestellt. Das Holz ist im Bereich der Verbindungen mit Presssperrholz verstärkt. Die Verbindungen zeigen neben aussergewöhnlich hohen Tragfähigkeiten und Steifigkeiten auch ein exzellentes plastisches Verhalten. Aus diesen Eigenschaften der Verbindung ergeben sich neue Möglichkeiten für wirtschaftliche Holzkonstruktionen. Holzeinsparungen bis zu 30% sind möglich.

1 INTRODUCTION

In many cases timber structures suffer due to the low strength, stiffness and splitting of timber joints. Although in essence the timber joints with mechanical fasteners like bolts and dowels behave in a ductile manner the unpredictable appearence of splitting cracks which initiate failure does not allow designers to take any plasticity or non–linear behaviour into account. In fact, due to splitting, the moment capacity of the joint will never be higher than about 40% of the bending capacity of the timber member. On the other hand, the spacing requirements of the dowel type fasteners in a joint frequently govern the dimensions of the timber members. The application of plastic theory in structural timber design with traditional joints is hindered because of the unreliable cracking. All together, mechanical timber joints limit the efficient use of timber as a structural material. Investigations aimed at improving the reliability of strength and stiffness of joints have been a research topic at the Delft University of Technology for many years.

2 REINFORCED JOINTS WITH DENSIFIED VENEER WOOD

It was Robert Stoeckhart, who first patented the densification of solid wood in Leipzig, Germany, in 1886. Finally in 1922 the Austrian Pfleumer brothers found a more effective method by trial and error. Since then this material is commercially available mainly in Europe. The main thought behind the densification is that the mechanical properties change proportionally with density. In a nutshell, the densification is described as follows. Solid wood or stacks of veneers are heated up to 145°C and compressed, perpendicular to the grain, to 20 MPa. This forces the outer cell wall to become plasticized, allowing the cell to drift and move within the conglomerate of cells so as to close all veins. For poplar, this process is indicated in figure 1. When the fibres are settled, a rapid temperature drop will freez this situation. Only immersion in water for a long time will activate the material memory. The maximum density obtained is about 1380 kg/m^3. Although many wood species can be densified, the highest mechanical properties are obtained with beech. Tension and compression strength values of maximum 300 MPa can be achieved [1]. For practical application a minimum density is usually specified. As densified veneer wood (dvw) consists of cross–layered veneer sheets, the mechanical properties are less grain direction dependent than for wood. No special precautions are required to glue this material to the timber.

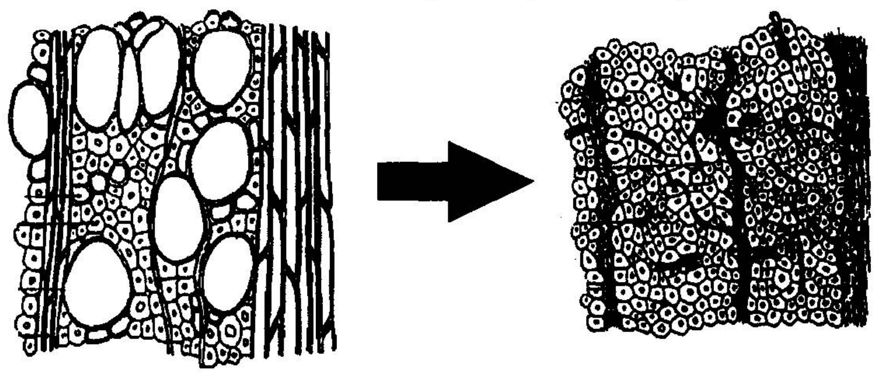

Figure 1: Poplar before and after densification.

The dvw is glued to the surface of the timber members where high concentrated loads are introduced by the fasteners to prevent splitting. The embedding or bearing strength of the dvw is about 130 MPa compared to 20–25 MPa for spruce [1].

3 THE EXPANDING TUBE DOWEL

One of the major problems in timber joints with mechanical fasteners is to eliminate the clearance space. Although tight fitting holes lead to a reduced clearance, the fasteners are in that case hard to drive in. When the holes are slightly unequally spaced, splitting can already be initiated at that stage. Therefore, very precise drilling equipment is required. To overcome this, there are efforts to drill wide holes and to use injection resin as in steel structures [2]. However, this method is rather expensive while quality control is difficult and doubtful.

To solve all these problems, an innovative new idea was developed and tested. Why not fit in a tube as dowel type fastener in wide holes and expand the tube by pressing the tube ends together? A central rod prevents any inward movement of the tube. This method has proved to satisfy all requirements easily. The clearance is completely removed. Due to this expansion procedure, the hole diameter is enlarged and the dvw and timber prestressed, which lead to an increased stiffness at the initial loading stage, see figure 2. On the other hand, the physics of a tube allows very large plastic deformations. The tube material is every cheap; galvanized welded gaspipe Fe360 (according to DIN 2440/ ISO 65). Diameters of 17.2 to 33.7 mm have been used. Details about production requirements are available on request. There are no patents that hinder the application commercially.

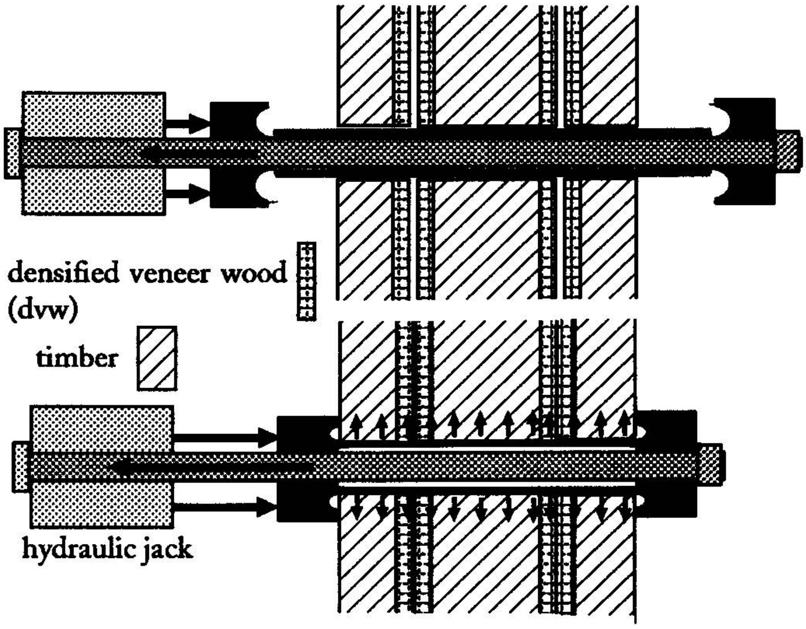

Figure 2: The principle of the prestressing procedure

4 TEST RESULTS

To show the capacity of this joint, portal frame corners were tested and the results are presented in figure 3. The moment–rotation characteristics of two test series are given. The difference is, the spacing of the fasteners. Each joint has four 35 mm diameter tube–dowels at the corner and the dvw thickness is 18 mm density 1300 kg/m^3. At the right hand side of the graph the bending stress in the glued laminated members of 600x110 mm is given as well. The data of test 3.5d187 should not be considered as the joint was tested twice due a computer break down. All tests ended because the stroke length of the jack was reached without any timber failure.

5 FRAME DESIGN EXAMPLES

In what follows, the application of such joints is indicated in a single storey and three–storey timber frame. The main objective is to determine the potential improvements in design that could be achieved by using the reinforced joints, especially in terms of the timber (cost) saving ability and the question of rotation capacity required at the ultimate limit state.

5.1 Program SWANSA

The structural design analysis was carried out using the computer program *SWANSA*, which takes into account material and geometrical nonlinearities, together with nonlinear semi–rigid behaviour of connections. The background theory is explained in more detail in [3]. The structural analysis is initiated with assumed cross–sectional geometry and connection characteristics, for combinations of dead, imposed and wind loads at ultimate (ULS) and serviceability limit state (SLS) conditions.

5.2 Geometry of the structures

The portal frame (Structure 1) considered in this analysis is idealised as shown in figure 4. In the structure as built, the frame consists of two 56 x 550 mm deep members and a single column. For

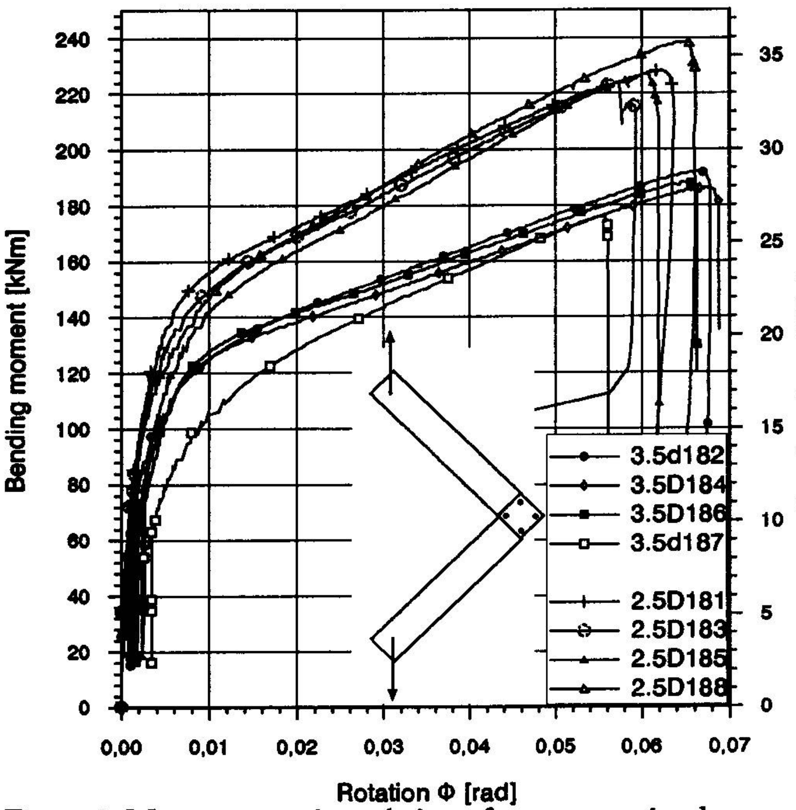

Figure 3: Moment–rotation relation of two tests series dvw reinforced prestressed timber joints, taken from [2].

purposes of present analysis, the beam is idealised as a single member of size 112 x 550 mm. The beam is connected to either column using four tube–dowels of 35 mm diameter set in a square pattern in the connection zone. The columns which are also of uniform cross–section are fixed to the foundation, using a connection detail similar to the beam to column connection at the top of the column. The spacing of the frames is taken as 5 m.

The three–storey frame (Structure 2) is idealised as shown in figure 5. The beams and columns are of uniform cross–section, and are connected to the columns using four 35 mm diameter tubes set in a square pattern in the connection zone. The connection detail is, in fact, identical to that of Structure 1.

5.3 Material Properties

The structures are made of glued laminated timber of strength class GL30, with a characteristic bending strength of 30 MPa. The design bending strength is 21.2 MPa, according to Eurocode 5. The modulus of elasticity is 12000 MPa for SLS and 6800 MPa for the ULS calculation.

5.4 Moment rotation characteristic of the connection

For the calculations with the traditional joints, the stiffness and strength values are used in accordance with EC5. Dowels ranging from 12 to 20 mm in diameter were chosen. The moment rotation characteristic of the traditional joints is linear elastic. The design moment and rotation capacity is given in Table 1. The moment–rotation relations of the reinforced joint, required in the frame analysis with semi–rigid joints, are derived from figure 3. The moment capacity of the beams is 121 kNm for Structure 1 and 130 kNm for Structure 2.

6 LOADING AND LOADING COMBINATIONS

The Permanent load, Variable load and Wind load used in the calculations for both structures are shown in Table 2. The structures were analysed for five load combinations, factored in accordance with Eurocode 1 clauses on the combination of actions, as shown in Table 3 below.

Load type	*Structure 1*	*Structure 2*
Permanent load (DL)	*1.5 kN/m*	*9.36 kN/m*
Variable load (LL)	*2.5 kN/m*	*6.00 kN/m*
Wind load (WL)	*12.9 kN/m*	*1.704 kN/m*

Table 2: Loading

Load Combination	*Limit State*	*Combination Formulae*
1	*Ultimate*	*DLx1.1 + LLx1.5*
2	*Ultimate*	*DLx1.1 + LLx1.5 +WLx1.5x0.6*
3	*Ultimate*	*DLx1.1 + LLx1.5x0.7 +WLx1.5*
4	*Serviceability*	*DLx1.0 + LLx1.0*
5	*Serviceability*	*DLx1.0 + LLx1.0 +WLx1.0*

Table 3: Load Combination factores Eurocode 1

Traditional joints with dowels			
Diam [mm]	*number*	*Mmax. [kNm]*	*Rot.max. [rad]*
15 mm	*22*	*31.3*	*0.0036*
16 mm	*16*	*33.6*	*0.0040*
20 mm	*13*	*38.3*	*0.0045*

Table 1: Moment rotation data

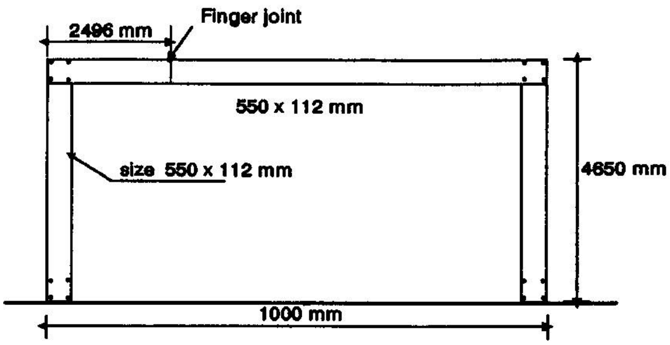

Figure 4: Structure 1

In the ultimate limit state calculations, the load factor on live load is varied, while the other load factors are kept constant. The maximum value of the live load factor obtained from the computations is compared with the code specified load factor. The serviceability calculations are made for the specified load factors. The principal objective of serviceability calculations is to check for limiting deflections. When the live load factor is substantially more than the value of 1.5 required for the ultimate limit state, substantial safety margins are available. For these cases the beam sizes have been reduced until comparable safety margins are obtained as with traditional design.

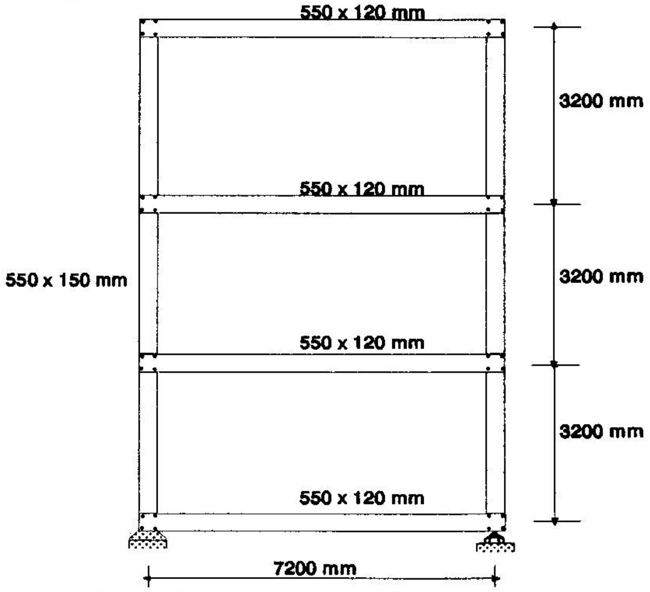

Figure 5: Structure 2

7 RESULTS

In all three ULS load combinations (1–3), the computations indicate failure at the beam midspan for Structures 1 and top storey beam of Structure 2, when the extreme fibre stress reaches the maximum design value of 21.2 MPa. In Table 4a, 4b and 5 the maximum load factors on live load for Structures 1 and 2 are presented for ULS design as well as for the serviceability limit conditions (SLS).

STRUCTURE 1							
Traditional design U.L.S.				Reinforced design U.L.S.			
Member sizes	*num. of dowels*	*Load Comb.*	*LL factor*	*Member sizes*	*num. of dowels*	*Load Comb.*	*L.L. factor*
550x112 mm	*13 of 20 mm*	*1*	*2.38*	*550x112 mm*	*4 tubes 35mm*	*1*	*5.85*
"	*16 of 16 mm*	*1*	*2.00*	"	"	*2*	*6.78*
"	*22 of 12 mm*	*1*	*1.82*	"	"	*3*	*9.52*
				500x100mm	"	*1*	*5.42*
				480x100mm	"	*1*	*4.68*
				450x100mm	"	*1*	*3.94*
				400x90 mm	"	*1*	*2.69*

Table 4a: Overview of Live Load factors for Structure 1, ULS.

Reinforced design SLS

Member sizes	*num.of dowels*	*Load Comb.*	*Vertical defl.*	*Vert.defl. limit*	*Load Comb.*	*Lateral defl.*	*Lat.defl.limit*
550x112 mm	*4 tubes 35mm*	*4*	*8.23mm*	*30mm*	*5*	*5.7mm*	*8.75mm*
500x100mm	"				*5*	*8.0mm*	*8.75mm*
480x100mm	"				*5*	*10.0mm*	*8.75mm*
Vertical deflection limit is 0.003xspan; Lataral deflection limit is h/500							

Table 4b: Overview of Live Load factors for Structure 1, SLS.

STRUCTURE 2							
Reinforced design ULS							
sizes	*num. of dowels*	*Load Comb.*	*LL factor*				
550x120 mm	*4 tubes 35mm*	*1*	*3.99*				
550x120 mm	"	*2*	*3.92*				
550x120 mm	"	*3*	*5.51*				
Reinforced design SLS							
sizes	*num,of dowels*	*Load Comb.*	*Vertical defl.*	*Vert.defl. limit*	*Load Comb.*	*Lateral. defl.*	*Lat.defl. limit*
550x120 mm	*4 tubes 35mm*	*4*	*11mm*	*21mm*	*5*	*14.7mm*	*19.2mm*
500x100mm	"	–	–	–	*5*	*20.9mm*	*19.2mm*

Table 5: Overview of Live Load factors for Structure 2.

The maximum value of the joint rotation obtained anywhere in the structures is 0.02543 radians. The maximum rotation in Structure 2 is about 10% higher than that for Structure 1, but is again well within the maximum rotation deduced from tests for this type of joint. Without any reduction of safety the dimensions of the timber beams can be reduced from 550x120mm in the traditional design to even 480x120mm for the prestressed dvw reinforced joint. About 30% of timber is saved which more than balances the production cost of the reinforced joint and is therefore of commercial interest.

8 CONCLUSIONS

It has been shown that the application of the prestressed dvw reinforced joint instead of the traditional joints with dowels opens new frontiers in structural timber design. The bending capacity of timber joints which traditionally is maximum 40% of the bending capacity of the timber members is increased to at least 100%. Combined with the semi–rigid behaviour of this new innovative joint, timber structures can be designed much more more efficiently. Timber saving of up to 30% is possible when applied in portal frames. The bending capacity of the timber is in all cases still the governing factor for ULS design.

9 ACKNOWLEDGEMENT

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