Joining Wood by Friction Welding – Fabrication of Multi-layered Components

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Summary

At the Chair of Timber Constructions of the EPFL tests were carried out to join wooden work pieces by friction welding without any additional welding deposit. It was determined that this kind of technology formerly used for thermoplastics and metal, can also be applied to the material wood.

The investigations showed that multi-layered wood compounds can be welded in very short time. The initial resistance obtained immediately after termination of the welding process is about 70 percent of the resistance reached after 15 minutes and at nearly ambient temperature of the interfacial zone. This result allows a continuous welding of multi-layered compounds without affecting the recently welded joints, which are not completely consolidated. The investigations led to the development of a new friction welding installation, which is especially adapted to wood and able to weld larger surface areas.

1 Introduction

Since the year 2000 [1] the laboratory of timber construction of the Swiss Federal Institute of Technology at Lausanne (EPFL) investigates the application of friction welding to wood. Traditional friction welding methods are used since decades industrially for metal and thermoplastic synthetics. Results showed that for different applications this method is promising for wood too. The process does not necessitate any additional material. Due to frictional heat the surfaces heat up to about 420-450°C [2]. At these for wood elevated temperatures the connections are realised based on a thermal conversion of the different wood compounds (lignin, cellulose, and polyoses) [3]. The following chapters deal with investigations concerning the consolidation time of the interfacial layer and its importance for the welding of multi-layered compounds.

The consolidation or curing of the heat-affected zone, and thus the development of the interfacial shear strength, is of major importance for friction welding of wood laminates. One of the process' advantages, compared to glued connections, is the short time necessary to realise a connection. Examinations concerning the curing behaviour of the welded joints were carried out to determine the evolution of the interfacial shear resistance and the time, which is necessary until a new layer of wood can be welded on the already finished layers. To realise multi-layered wood laminates by friction welding, the solidification time of the heat-affected zone is a decisive parameter. To weld continuously one layer to the others, the existing connection has to be strong enough to avoid damage by the newly introduced vibration. The development of the shear strength of welded wood connections is examined as a function of the solidification time and temperature.

Influencing parameters are the maximum interfacial temperature reached and the humidity of the samples, which has an influence on the conductivity.

2 Experimental

Seven test series of ten samples each from Norway spruce *(Picea abies)* were welded and tested with regard to the evolution of the shear strength of the connection. Compression shear tests were carried out at different times shortly after the termination of the welding process. Table 1 **s**hows a summary of the welding parameters, used for the fabrication of these samples.

Table 1: Welding parameters for shear strength examinations

Parameter	**Dimension**	**Value**
Amplitude	[mm]	0.95
Normal pressure	[MPa]	0.63
Frequency	[Hz]	130
Thickness specimens	[mm]	10
Welding displacement	[mm]	2
Cooling time	[s]	30
Cooling pressure	[MPa]	1.58

The direction of the annual rings of the specimens was perpendicular to the interface with a maximum deviance of the angle of $\pm 20°$. The following seven time steps were chosen:

30 seconds (2x)

60 seconds (2x)

90 seconds

210 seconds

330 seconds

630 seconds

930 seconds

The samples have the dimensions *6.5cm*5. cm*1.0cm*, the welded area amounts *5.0cm*5.0cm*. The cooling time, accompanied by a cooling pressure of 1.58 MPa, is set to 30 seconds. All samples were conditioned in a climatic chamber under a standard climate of 65% relative humidity and a temperature of 293 K. The moisture content equilibrium amounted to 12-13%.

For every time step, ten samples were tested. Two welds were defective (series SP04, SP09) due to slippage, which occurred between the holding fixture and the upper surface of the upper piece. This led to additional welding displacement, as the teeth of the jagged holding plates got carved into the surface. Thus, no weld could be achieved, as not enough material could be thermally decomposed to form the interfacial layer. These samples were not representative and thus not considered within the evaluation.

The tests were carried out at two different periods. The comparability of the results was proven by reference test series, tested at cooling times 30 seconds and 60 seconds after termination of the vibration. These two tests show similar results for both testing periods. (A certain deviation has to be accepted, as the material is quite inhomogeneous).

The resistance of the welded connections is tested by means of compression shear tests along the longitudinal direction of the samples, in the direction of the wood fibres.

The shear strength was evaluated by a special apparatus, which is designed to measure plane stress. This testing device is moveable and can be used as the measurement equipment, which is also used to verify welding force and temperature evolution. The apparatus is shown in Figure 1.

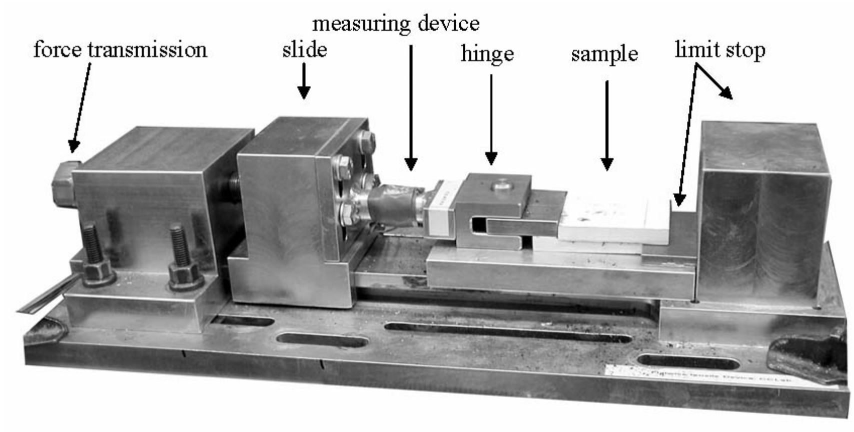

Figure 1: Hand-operated measuring device used to measure the compression shear strength during solidification of the interfacial layer with its main components

The load is applied by turning the bolt at the left of Figure 1 (force transmission) using an appropriate spanner. The suggested loading rate can only be defined by an angular speed: experience showed that a full twist per *20-30 seconds* is a good choice. This corresponds to a displacement controlled loading rate of around *4.5-3.0 mm/min*. As this device is hand-operated, the chart speed could not be kept exactly uniform over the whole force range.

The instrumentation consists of a strain gauge adherent in the mid-height of the round bar. The whole system of the apparatus was calibrated.

As the installation is hand driven, this kind of testing method is not in accordance with any standard. However, it is assumed an appropriate possibility to measure the connections' shear strength on site during the cooling stage of the heat-affected zone.

The shear strength is calculated by means of the compression force F_{shearC} applied and the welded surface A_{wl} and is indicated in MPa.

$$\tau_{\max} = \frac{F_{\mathrm{shearC}}}{A_{\mathrm{wl}}} \text{ [MPa]} \qquad \textbf{[1]}$$

3 Results and discussion

Figure 2 displays the average shear strength of seven test series of 10 samples each, measured during the fifteen minutes subsequent to the termination of the welding process.

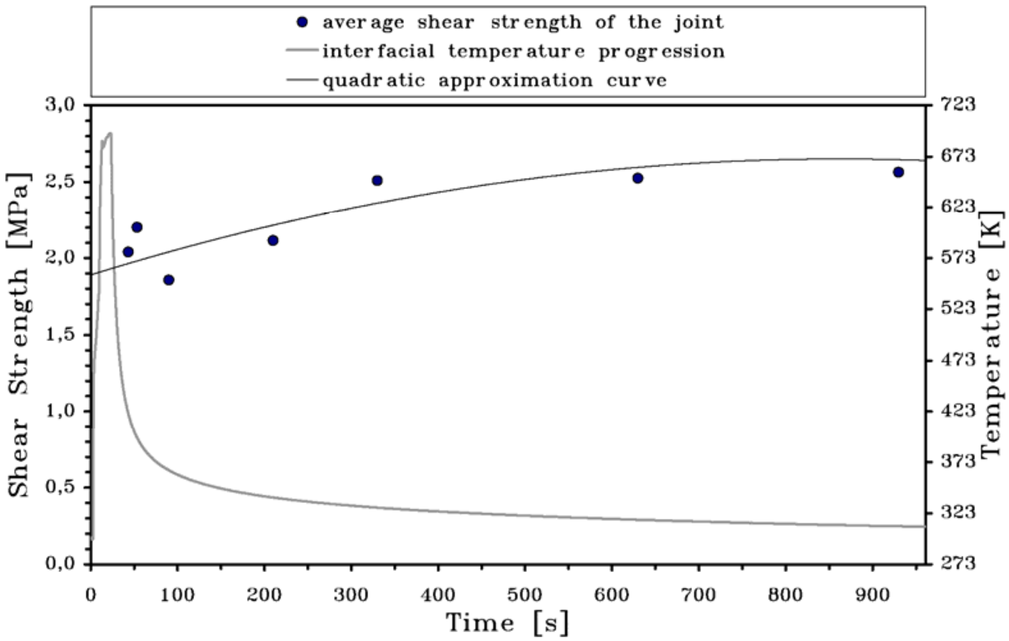

Figure 2: Shear strength of welded connections as a function of solidification time

During welding, the interfacial temperature reaches values between 673 K and 713 K. The temperature graph shown in Figure 2 is an exemplified one. However, as the maximum temperature varied only in a small range for all the tests carried out, this graph represents approximately the variation of the interfacial temperature as a function of solidification time. The temperature at the interface decreases during this period from nearly 700 K during the welding process, to less than 313 K after fifteen minutes. After 60 seconds, the interface temperature is already lower than 373 K. A summary of the results is shown in Table 2.

Table 2: Sample size, mean values and standard deviation (SD) of the test series

Series	**Time of testing s**	**Sample number**	**Mean value MPa**	**SD %**
SP01	20	10	2.04	13.9
SP02	30	10	2.20	18.5
SP06	30	10	1.95	14.5
SP03	60	10	1.86	20.9
SP07	60	10	2.05	14.7
SP08	180	10	2.12	16.6
SP04	300	9	2.51	15.0
SP09	600	9	2.66	19.6
SP05	900	10	2.57	19.2

One minute after the termination of the frictional movement, the joints show average shear strength of about 2 MPa. During the following fifteen minutes, the shear strength increases to about 2.6 MPa. This demonstrates that the shear strength obtained immediately after the interruption of the welding process, reaches about 70% of the maximum value, reached after fifteen minutes with nearly ambient temperature at the heat-affected zone.

According to measurement of the interfacial shear forces during welding, the maximum shear stress introduced by the machine vibration is approximately 0.5 MPa. Thus, the resistance of the connection reached immediately after termination of the cooling process under pressure (30 s) exceeds this value noticeably. This result is of major importance with regard to welding of multi-layered wood laminates. Such a rapid achievement of high shear strength allows continuous welding of several layers of wood with very short welding cycles, and without affecting the joints already completed. Figure 3 shows a parallelepiped consisting of eight alternating layers of spruce and beech woods, welded continuously.

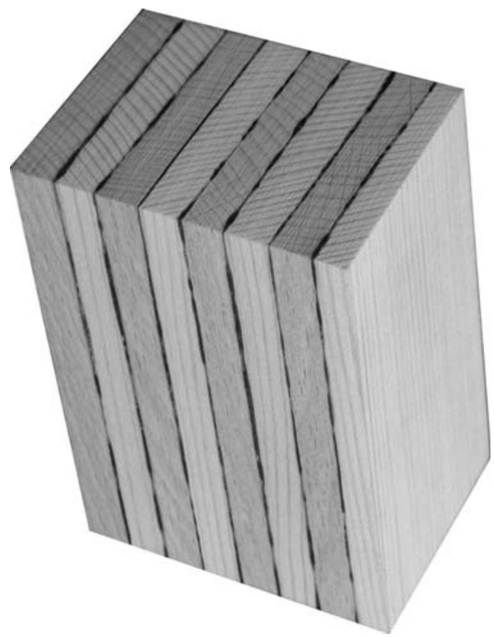

Figure 3: Multilayered wood laminate, built out of eight alternating layers of spruce and beech boards; beech shows a darker colour.

The interval between the different welding steps was about one minute. The thermally altered wood, which forms the bond at the interface, can be seen as a dark line. The surfaces of the parallelepiped have been cut and sanded after welding. Its dimensions are 6.3cm*4.5cm*9.1cm.

During the fabrication of this multi-layered laminate, only the lowest layer and the newly welded layer were held by jagged metal plates, as schematically shown in Figure 4.

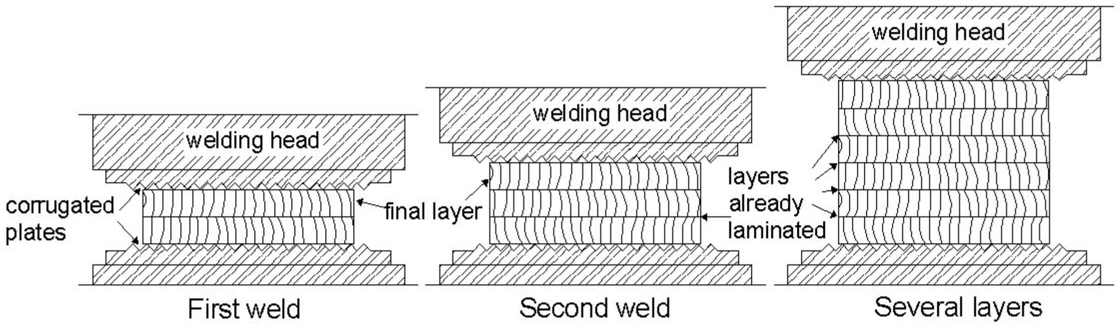

Figure 4: Method of welding of multi-layered laminates. One layer is continuously welded on the already existing layers with only short breaks between the welding steps.

In so doing, it is difficult to weld laminates with more than a few layers (8 layers in this case). Increasing height of the laminate leads to an increase of the elastic deformation in the horizontal direction. This effect reduces the generation of thermal energy. At a certain limit, the heat is no longer sufficient to realise a weld. A horizontal fixation of the latest layer helps to avoid this problem preventing the transmission of the frictional force to deeper layers.

4 Conclusions

The results show that the welded connections have relatively high initial shear strength. This attribute is the major advantage in comparison to glued connections. At the actual stage the resistance of the welded connection is less strong than connections realised by modern wood glues. This is on the one hand due to the machinery used for these experiments. It is designed for the welding of thermoplastics and metal. On the other hand testing showed that the circular vibration seems to be not ideal for friction welding of wood. But as the initial shear resistance exceeds the shear stress applied by the vibration, continuous welding of wood laminates, composed of various layers, is possible.

In addition other examinations have revealed that the orientation of the annual rings within the welded samples influences the welding process in a significant manner if a circular movement is applied. Therefore, circular friction welding is likely not to be the most appropriate method with regard to this material. GFELLER et al. [4] showed that high shear strength up to 10 MPa is achievable for beech joints using linear friction welding technology. An application of linear friction welding could help to prevent the inhibiting effects. As the two methods have not been directly compared this is only an assumption confirmed by bibliographical data.

5 Perspectives

In spite of the rather low shear strength obtained for welded spruce wood samples, the method could potentially be applied to the lamination of wooden slabs by timber planks (mainly spruce) forming solid wall and ceiling elements. Up to now these elements are nailed or screwed together. The distance between the nails is about 30 to 40 cm. Thus, the shear strength of those elements is very low. Therefore welding could be an alternative method. Welding of these elements would lead to relative airtightness of the bonds in comparison to nailed joints. Advantages are also seen with regard to machining of these slabs where metal connectors pose a problem (additional openings). A disadvantage is the very poor resistance to water [5], which is limiting the application range to interior use.

Due to the use of pure wood, the waste disposal or recycling of such elements would not pose an environmental problem in comparison to traditional wood connections.

The experimentation carried out dealt with small surfaces of mainly 25 cm². However, the results gained led to the development of a new friction welding machine, conceived to be able to weld significantly larger surface areas and to be more appropriate for the material than traditional machines. The vibrational movement can be switched between linear and circular movement to investigate the differences between these two and to determine advantages and disadvantages. A specially conceived fixation enables the installation to realise multilayered components.

An image of the new installation is shown in Figure 5.

Figure 5 : Friction welding machine conceived especially for wood during a welding test. Welding is accompanied by smoke generation.

6 Acknowledgements

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