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PERFORMANT CONNECTIONS – A MUST FOR VENEER-BASED PRODUCTS

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ABSTRACT: The structural use of high-strength veneer-based products requires the development of more performant connections, than those actually used. Great development is going on with glued-in bars. Besides high efficiency, adequate ductility may be achieved, resulting in robust structural components. The presentation will focus in the application of glued-in bars inserted parallel to the grain. Generally individual glued-in bars show a very brittle behaviour. Through special shaping of the steel rod and controlled application of ductile steels, ductile connections with groups of glued-in rods are now realistic. This is shown in typical applications like tension joints, bending joints in beams and trusses. By extending the ductility requirements, plastic design of such connections will now be possible. This opens the way for more performant design of complex structures.

KEY WORDS: LVL, beech, glued-in rods, ductility, robustness, group of connectors, plastic design, trusses

1 INTRODUCTION

Veneer based products show not only more uniform but generally higher physical and mechanical properties than similar glued laminated products built up from the same wood species. Furthermore – through the application of cross veneers – the properties may better be adapted to specific requirements.

A major problem of wood products is their brittle behaviour; this hinders them to develop plastic deformations before failure. Connections must therefore have adequate ductility to compensate this fact. Unfortunately no indications about how to achieve ductile connections will be found in Eurocode 5 – Design of timber structures. The word “ductility” appears only once, in section 5 – Basis of structural design: For structures able to redistribute the internal forces via connections of adequate ductility, elastic-plastic methods may be used for the calculation of internal forces in the members.

High-strength veneer-based products are indicated for use in large and more complex structures (here in direct competition with steel solutions) with a need for ductile connections to enable desirable load redistribution. At the same time the inherent properties of the new beech veneer based products require connections with adequate performance. As a result we need performant and simultaneously ductile connections.

In the last years more attention – at least in the academic field – was given to the ductile behaviour of connections, in particular about dowel-type fasteners in shear. We know better how to define ductility and to express the non-linear load-displacement or moment-rotation relations. But finally we have to ensure that timber components are always stronger than the connections. This may be the case by using low performance but ductile connectors (considered as weak points). A major problem is to define how weak the connector should be, to ensure that plastic deformation will occur in the connection before possible failure in the timber components.

Performant connections may be achieved with glued-in rods. The following approach is therefore adjusted to the use of glued-in rods following the GSA-technology, a connection system with reliable and ductile load-deformation behaviour.

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2 PERFORMANCE

2.1 EFFICIENCY OF A CONNECTION

The simplest way to express the efficiency of a connection is to relate the load-carrying capacities of the connection to the timber element. This is shown in Figure 1.

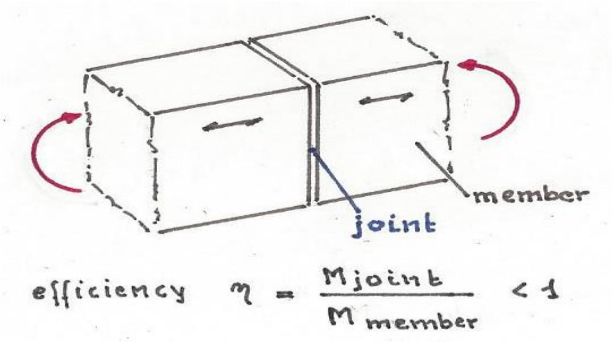

***Figure 1:** Grade of efficiency η of a joint*

The efficiency of most mechanically connections is restricted, mostly due to the great amount section reduction, i.e. the case for dowel-type systems. Values of η = 0.6 to 0.65 may hardly be achieved. By using glued-in rods a value of η = 0.8, based on design values, may be reached.

2.2 TYPE OF LOAD PATH

Highest performance may be achieved where the flux of strains or forces shows the smallest deviation. From Figure 2 it is easily understandable the better performance of glued-in rods compared to dowels in shear.

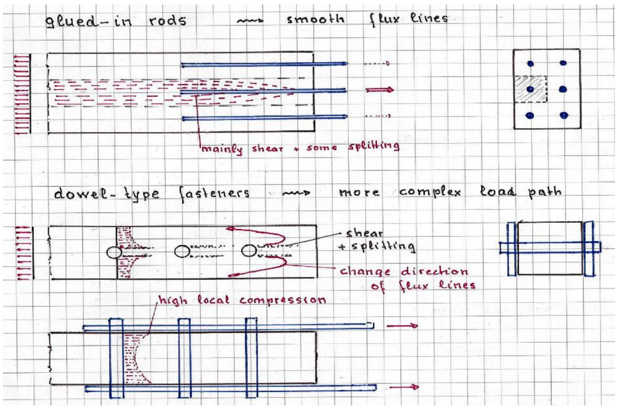

***Figure 2:** Load-path of glued-in rod and of dowel in shear*

To each glued-in rod a section of the member to be jointed can be assigned. In the case of a connection with dowel-type fasteners there is always a superposition with severe strain peaks.

3 DUCTILITY

3.1 PRINCIPLE

Joints in timber elements are normally the weak points of the construction. Joints may show besides low strength also a small deformation capacity. The failure mode is therefore brittle and likely load transfers are quite excluded. The whole system will than act as a chain and the ultimate load is determined by the weakest chain-link. If compatible with the connection in consideration, systems with high deformation capacity should be preferred.

3.2 FINGER-JOINT

Finger-jointing shows highest strength with only small reduction of stiffness (compared with an unjointed member). Joints behave pronounced brittle. Due to the high strength this effect plays a minor role, but in connection with low strength i.e. due to defective manufacture this may have a catastrophic effect.

3.3 MECHANICAL JOINTS

Conventional mechanical joints have, in general, a lower strength and reduced stiffness. Furthermore the most used connector, the dowel-type connector shows – when using the standard design specifications according to Eurocode 5 – a failure mode with generally very small deformation. To overcame this and ensure a more robust connection, joints have to be designed to a considerable lower strength level, to take in account the large scatter or variation of strength values.
Instead of a reduction, the reciprocal condition – a so-called over-strength factor – may be introduced, resulting in any case in a lower load-carrying capacity and therefore to a lower efficiency of the connection (see Figure 3).

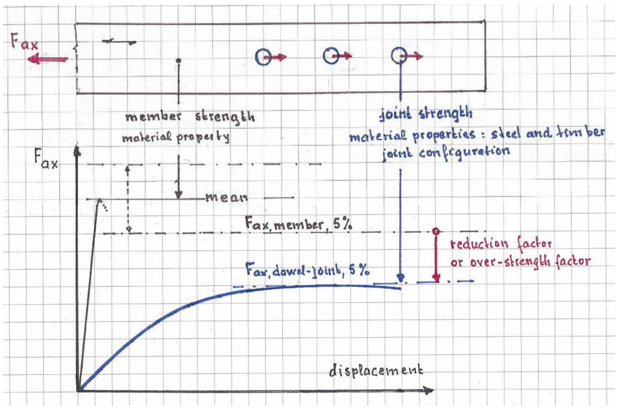

***Figure 3:** Condition for a reliable and robust dowel-type connection*

Only through additionally measures, like local reinforcements of the timber in the connection zone, to avoid premature splitting failure, the reduction or the over-strength factor may be decreased.

3.4 GLUED-IN RODS

By using glued-in rods following the GSA-technology, there is a clear allocation between the gluing of the rod to the timber member and the behaviour of the rod:

Glued connection: stiff, strong, but brittle
Load-carrying capacity governed – by using adequate adhesive – only by the shearing strength of the member, a property strong related to other material properties of the member (see Figure 4). Failure mode: in the wood adjacent to the glue-line. The transfer from the adhesive to the profiled rod is assumed purely mechanical.

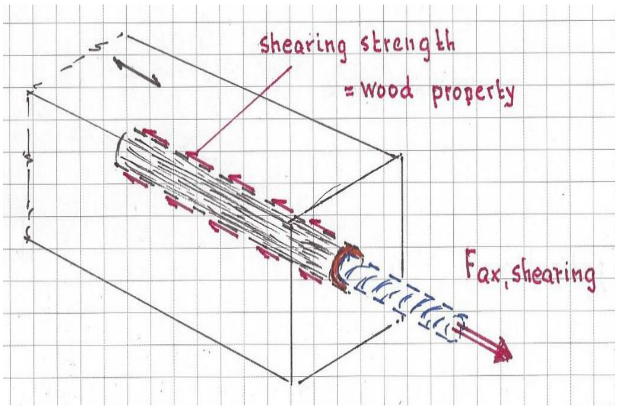

Figure 4: *Shearing strength = wood property*

GSA-rod: steel rod with special shaping and use of adequate and controlled strength properties (see Figure 5). Quality control guarantees small scatter or variation between $F_{ax,rod}^{95\%}$ and $F_{ax,rod}^{5\%}$.

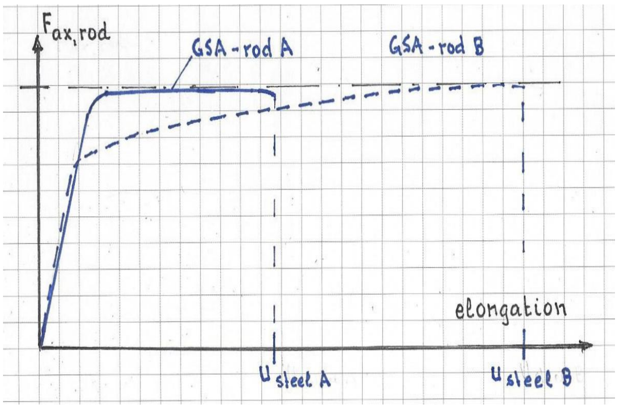

Figure 5: *GSA-rods with same load-carrying capacity but different load-elongation behaviour*

The shearing strength or the brittle pull-out strength of the GSA-rod and the ductile steel behaviour are in certain limits independent. Therefore the condition

$$F_{ax,shearing,5\%} > F_{ax,rod,95\%}$$

can be fulfilled, as long correct knowledge of the pull-out capacity (to be established under reliable practical conditions) and efficient control of rod strength. The result is shown in Figure 6.

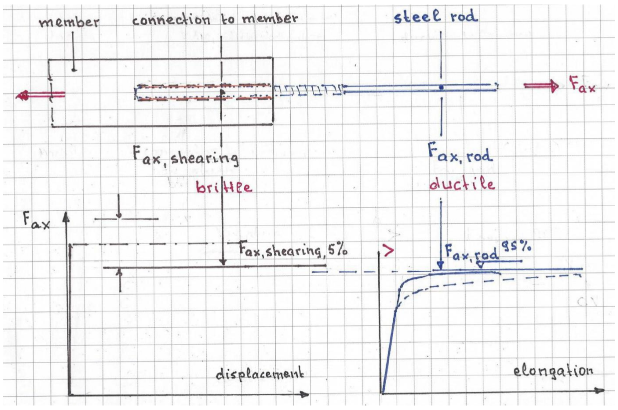

Figure 6: *Condition for a reliable and robust glued-in rod connection*

Compared to the dowel-type connection, since reliable basis for both failure modes exist – at least for the GSA-system – the margin may be kept small.

4 DUCTILE BEHAVIOUR OF GROUP OF GLUED-IN RODS

4.1 GROUP EFFECT

The group effect, i.e. the reduction of load-carrying capacity of an individual fastener when acting in a group or acting in a row parallel to the grain direction is well known and considered in most actual codes. Less known is that the reduction can be avoided when a ductile behaviour of the connection is provided.
For n dowels acting in a row parallel to the grain EC5 considers a reduction factor $k_{red} = n^{-0.1}(a_1/a_y)^{0.25}$ with a_1=distance between fasteners and a_y = distance above which no interaction of neighbouring fasteners is assumed (for softwoods a_y = 13 to 15d; for hardwoods a_y = 9 to 10d).
For n axially loaded screws or glued-in rods in a connection k_{red} is usually taken as: $k_{red} = n^{-0.1}$.
By using fasteners with adequate ductility k_{red} can be taken equal to 1, i.e. that force redistribution among the fasteners is ensured.

4.2 CASE OF GSA-RODS PARALLEL TO GRAIN

Assuming the relationship of the pull-out strength is empirically known, i.e. $F_{ax,shearing} = \alpha \cdot A_{ef}^{\beta}$ with the effective shearing surface $A_{ef} = \pi \cdot d_{hole} \cdot \ell_{ad}$ (ℓ_{ad}=partial length of rod glued-in). For each combination of member material and GSA-rod this relationship has to be established experimentally. For the combination of LVL-beech (BauBuche) and GSA the result is shown in Figure 7.

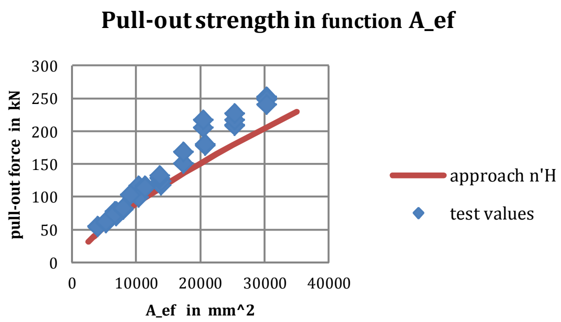

Figure 7: *Approach by n'H and experimental values*

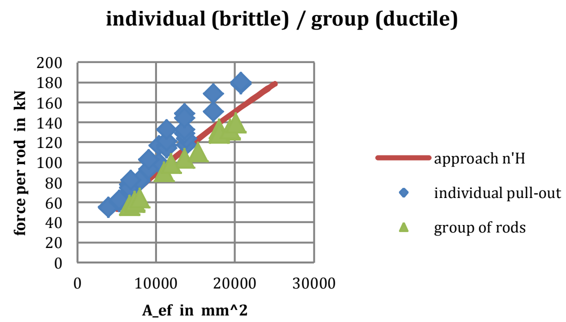

Figure 9: *Comparison of individual pull-out strengths to groups of glued-in rods (values per rod) with ductile behaviour*

Tests with different diameters and groups from 4 up to 10 glued-in rods in one connection, designed just below $F_{ax,shearing,5\%}$, have shown the adequacy of the procedure (see Figures 8 and 9).

Figure 8: *Testing of an assembly with two equal connections*

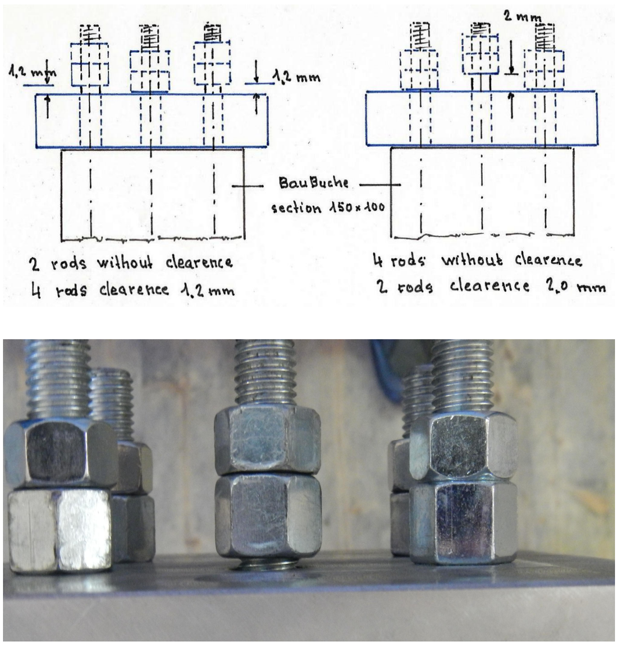

Figure 10: *Included deviations: group of 6 rods*

All the tests with groups of rods presented large displacements (above 5 mm) and exactly the same load-elongation curves as an individual tested steel rod. Tests were stopped, since expensive testing of steel properties! The achieved large ductility allows considerable fabrication tolerances. Some connections were provided with larger "errors" or deviations (see Figure 10).

As can be seen in Figure 11, the same load-carrying has been achieved as a similar connection with correct fastened rods (no clearance); only part of the plastic deformation was activated to compensate the clearances provided.

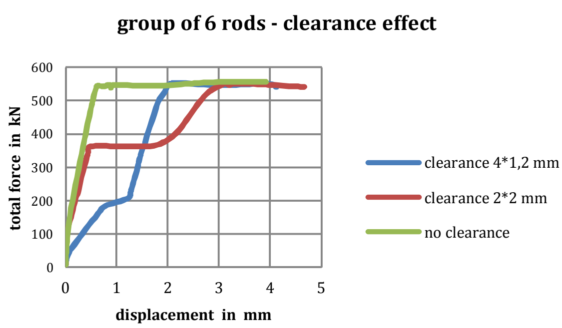

Figure 11: *Load-displacement curves for connections with large fabrication tolerances*

5 PLASTIC DESIGN

5.1 TIMBER AND PLASTIC DESIGN

Unlike steel who shows a pronounced plastic behaviour which may be used in the design procedure of structures or structural elements, timber presents a strong brittle behaviour for quite all strain conditions.

As a result the design of timber structures or structural assemblies is actually based on linear elastic models. When connections with adequate ductility are used, elastic-plastic are allowed. In such a case redistribution of internal forces is possible. Here the main problem consists in the lack of reliable information about deformation properties of the connectors. Reliable design requires therefore consideration of large so-called over-strength factors respectively introducing connections with reduced or low efficiency.

Another way is presented when applying glued-in rods according to the GSA-technology.

5.2 GSA-TECHNOLOGY AND PLASTIC DESIGN

As shown before (see section 4), as long as the condition $F_{ax,rod,95\%} < F_{ax,shearing,5\%}$ is fulfilled, the joints will behave like steel elements. Therefore the well-known steel-plastic design methods may be applied for the design of such joints. We have only to assure that the rods have appropriate strength level and ductility. This is area of responsibility of the GSA-technology.

The validity of this approach will be illustrated for the case of pure bending joint in a timber beam using GSA-rods. The following simplifies requirements are used:

Linear stress-strain relationship (validity of Hook) up to yield (f_y) and then plastic plateau (see Figure 12).
Sections remain plane, also in the plastic range.

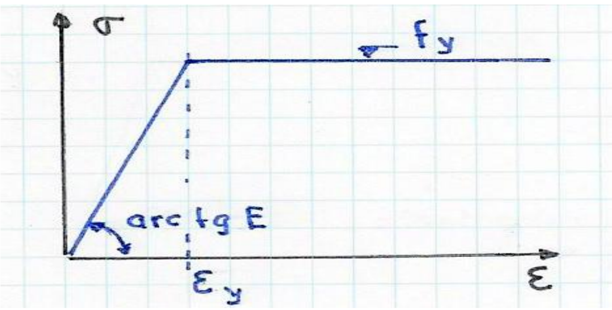

Figure 12: *Assumed stress-strain relationship*

Two possible conditions (see Figure 13) were considered:

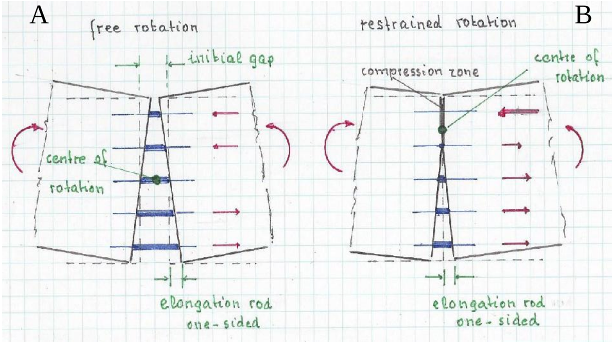

Figure 13: *Possible design conditions*

A Free rotation: only steel rods effective (assumption of substantial gap).

B Restrained rotation: with additional compression zone active (normal case).

5.3 CASE STUDY: ONLY RODS EFFECTIVE

For the case of a moment joint where only the rods are active (assume for that a gap between the timber members to be jointed), we obtain – depending of the load level – the following deformations (see Figure 14) and the corresponding forces in the rods.

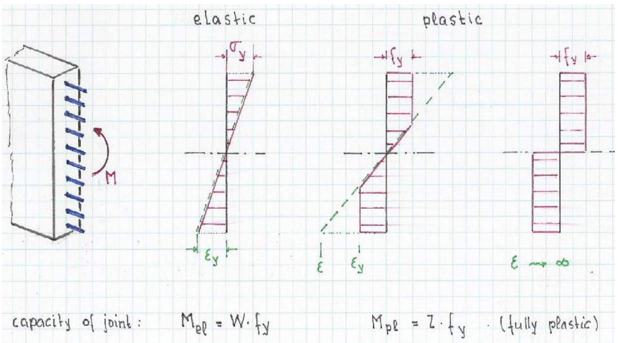

Figure 14: *Typical deformations and forces in the glued-in rods*

Depending on the steel section considered, the ratio W_{pl}/W_{el} or Z/W is given in Figure 15.

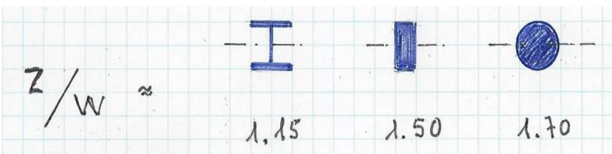

Figure 15: *Ratio of plastic to elastic moment of resistance*

For joints with glued-in rods (assimilate the singular rods to a rectangular section or steel plate of equivalent thickness) a ratio of about 1.5 should be possible. This was proved by testing a beam joint (120/310 mm in BauBuche) with glued-in rods type GSA16.8. Displacements were measured over the beam depth (length over the joint = 300 mm), as presented in Figure 16.

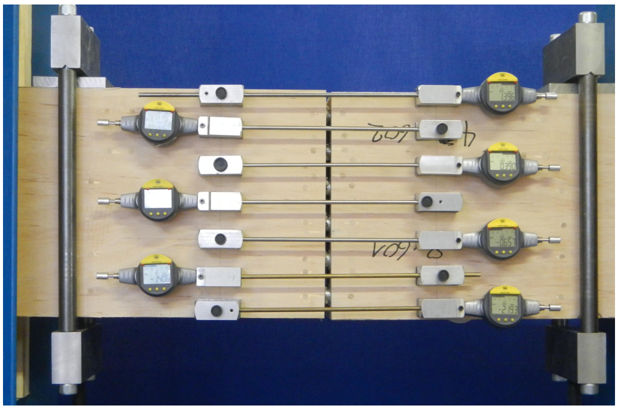

Figure 16: *Joint with gap of 8 mm; measurement system*

In Figure 17 are presented the beam rotation (over a length of 300 mm without joint) and the moment-rotation including the steel joint (deformation of the steel rods).
Also the calculated values (based on the properties of the rods) of M_{el} and M_{pl} are compared to the measured values:

$M_{el,cal}$ = 81.6 kNm $M_{el,test}$ = 82 kNm
$M_{pl,cal}$ = 116 kNm $M_{pl,test}$ = 121 kNm

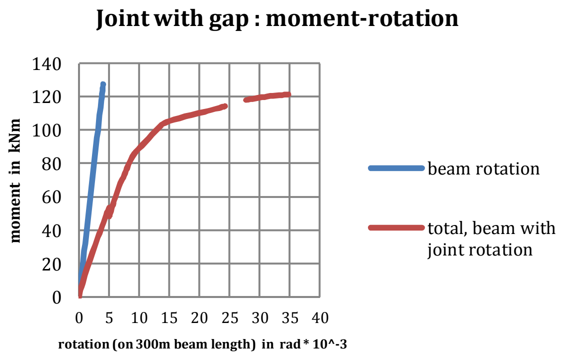

Figure 17: *Moment-rotation based on beam length of 300 mm*

5.4 CASE STUDY: JOINT WITH TIMBER COMPRESSION ZONE

This represents normal joint configuration. Through the creation of a compressive zone the rotation will be hindered and the resistance increased (see Figure 13, right).

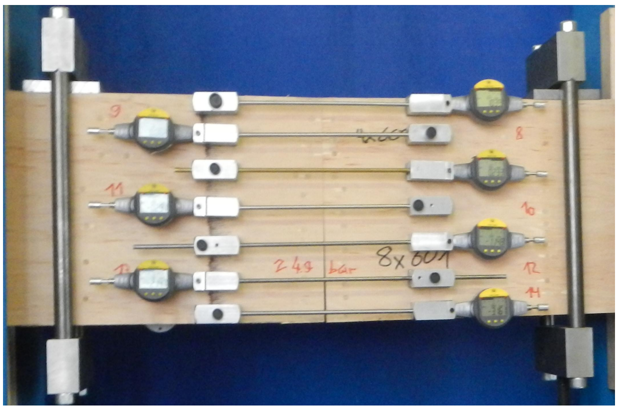

Figure 18: *Joint without gap (with compression zone)*

In Figure 19 are presented the beam rotation (over a length of 300 mm without joint) and the moment-rotation including the steel joint (deformation of the steel rods).

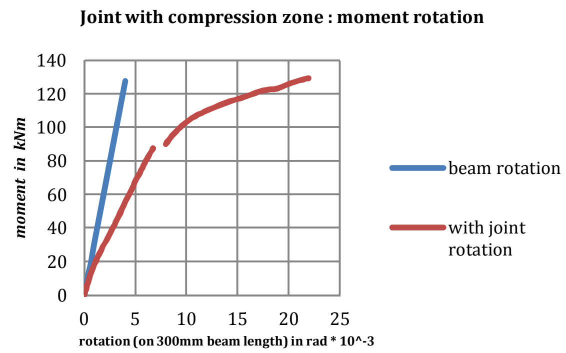

Figure 19: *Moment-rotation (restrained joint)*

Also the calculated values (based on the properties of the rods and assuming a contact zone of about 0.25 h_{beam}) of M_{el} and M_{pl} are compared to the measured values:

$M_{el,cal}$ = 90.8 kNm $M_{el,test}$ = 91 kNm
$M_{pl,cal}$ = 127 kNm $M_{pl,test}$ = 137 kNm

5.5 TO SUM UP

For the plastic design of a bending joint two approaches are possible:

A – Use of the very simple conservative approach for free rotation (only steel rods active).
B – Assume a realistic position of the resultant compression (reaction) force; calculate with the now known (geometric given) lever arms the plastic moment.

Note: The moment-rotation (restrained rotation) leads to a smaller rotation capacity; furthermore the ductility requirements are higher for this case.
The efficiency of glued-in rods in GSA-technology is high; the characteristic bending strength of an unjointed beam (for BauBuche with $f_{m,g,k}$ = 70 N/mm^2) is of same magnitude: $M_{beam,k}$ = 135 kNm!

6 CASE STUDY: TRUSSES

6.1 USE OF HARDWOODS

For long span structures trusses are the more indicated structural type. The use of glued-in rods for the connections goes back to the early 90^{ties}. In 2003 a large heavy loaded truss was built-up from glued-laminated hardwood (ash) components using glued-in rods in GSA-technology (see Figure 20).

Figure 20: *Truss girder: hardwood components connected with glued-in rods (2003)*

Since then components of glued-laminated hardwood were regularly applied. New is now the use of higher strength LVL-beech components.

6.2 TRUSSES BUILT-UP FROM LVL-BEECH

First were investigated the load-carrying capacity of glued-in rods acting parallel to the grain. Based on pull-out tests (see section 4) an optimized design of the glued-in rods based on the GSA-technology was used.
As a result of this procedure we obtained the same deformation capacity: in the steel rod; in an individual glued-in rod and as well as in a group of rods. The load-displacement curves were always governed by the geometry and material properties of the rod (load-elongation relationship).

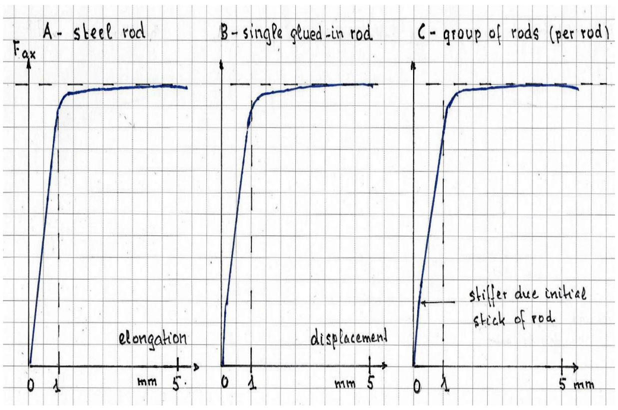

Figure 21: *Load-displacement curves:*
A – rod alone (steel elongation)
B – individual glued-in rod
C – group of glued-in rods (per rod)

In a second step the behaviour of a typical connection in a truss was analysed (see Figure 22) and tested.

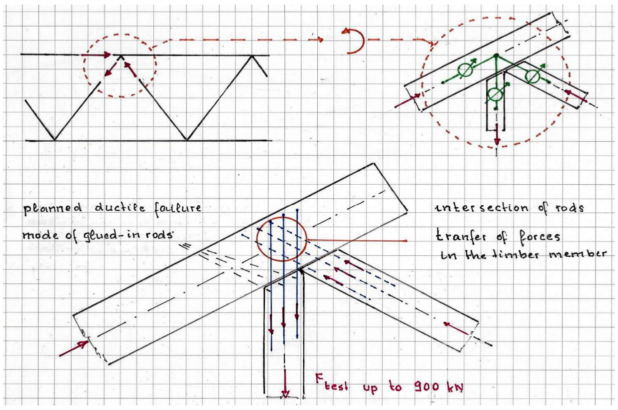

Figure 22: *Typical connection in a truss with acting forces and derivation of test procedure with similar strain situation*

Figure 23: *Test specimen of typical connection in a truss with measurement device of tension and compression joint*

The tested connections showed a similar ductile behaviour, as can be seen in Figure 24. As a result: when the glued-in bars start to flow the end moments tend to disappear; the connection behaves like an articulation (hinge). The diagonals of the truss (and their connections) may therefore be designed for normal forces only.

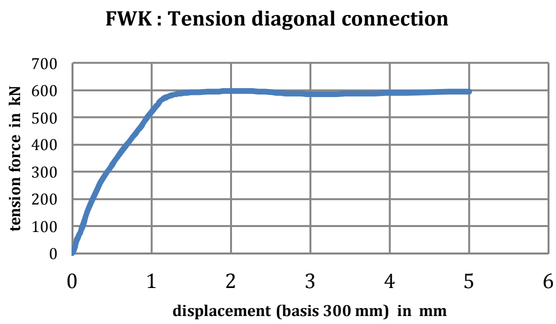

Figure 24: *Load-displacement curve of tension connection (measurement based on 300 mm length)*

Figure 25: *Aspect of connection at the beginning of plastic deformation*

Figure 26: *Failure of the steel rods after plastic deformation of more than 5 mm (no pull-out failure = no wood failure)*

In a third step full truss-girders were tested. They showed up a high stiffness, governed mainly by the sections area and modulus of elasticity of LVL-beech; the joint deformations made only about 15% of the total truss deflection. Furthermore – as expected – the load-deflection curve was elastic and linear up to 90% of the load-capacity (see Figure 29).

Figure 27: *Test of a truss girder with depth of 1 m and span of 7.2 m. Upper and lower cord section 160/180 mm, diagonals with section 100/160 mm. (Built in LVL-beech)*

Figure 28: *Measuring deformations of diagonals and of the connections.*

The displacement of a diagonal connection is compared with the earlier measurements made on same glued-in rod configuration (see Figure 29) and tested individually. Truss test was stopped at an elastic stage; deflection of the steel beam was about 4 times deflection of truss girder creating therefore a dangerous spring action.

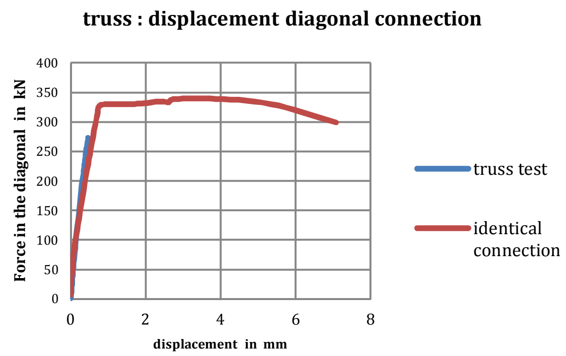

Figure 29: *Displacement of diagonal connection*

6.3 OUT-COME

The design of trusses with components of LVL-beech and GSA-technology leads to stiff and ductile structures. Through adequate ductility of the glued-in connections the diagonals may be designed as with hinged conditions. Any end-moments will – when the connection starts plasticization – disappear, before the steel failure (at higher level) will occur.

7 CONCLUSIONS

Through an optimized combination of high-strength beech veneer-based components with more homogeneous properties and of glued-in rods type GSA (especially tailored and adjusted to avoid brittle pull-out failures in the timber) with large deformation capacity, extremely efficient and performant connections are now available.

The result is a ductile behaviour of the connections and therefore of more robust structures or structural elements, like truss girders. The application of high ductile steels allows even the use of plastic design methods. This leads into an increased load-carrying capacity or into a more efficient utilization of the resource wood.

ACKNOWLEDGEMENT

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