Some thoughts on steel-to-timber connections particularly using dowels and hardwood

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1 Background

Design of connections is strongly dictated by chapter 8 – Connections with metal fasteners - of Eurocode 5 – Design of timber structures. It considers quite exclusively timber structures based on softwoods. In the last two decades the use of hardwoods started. The higher performance of glulam made of hardwood – mainly ash and beech – can only be of use with adequate performing connections. Instead of adapting existing codification from softwood to hardwood, it seemed appropriate to review the requirements starting from the needs of the user.

Steel-to-timber connections with dowels are universally used. It's an open system: dowels are available in quite all desirable properties from different manufactures. Production and workmanship control are easy. Only problem: need for a simple and reliable design in connection with hardwood. First realizations go back to the 80ties – where no codification was available. This left to a great freedom in design, but although the need for a better understanding of connection behavior.

Actually – 40 years latter – we can use advanced knowledge. My hope is, that research will be better orientated to the basic needs of the designer: helpful for simple and reliable design.

2 Theory and practical approach

The theoretical basis for timber-to-timber connections with dowels goes back to Johansen (1941/1949). Latter on – in the 80ties – took place the transition to steel-to-timber connection, named as European Yield Model (EYM).

Practical use and testing of multiple steel-to-timber dowel connections may go back to the 40ties**.** Konrad Sattler [1] published 1948 the results of his research and showed possible applications for truss-girders. I remember also – now missing – a Dutch publication from the yearly's 40ties, where an application was shown.

Practice was already orientated to multiple-steel-to-timber use. Unfortunately most testing and research is still based on a single plate connection!

3 Basic requirements

Here will only be considered the following basic requirements (important for the structural behavior): high efficiency in strength and stiffness, adequate robustness. Furthermore more simple and clear detailing of the connection is, the less is prone to errors.

3.1 High efficiency in strength and stiffness

That means to make best use of the member's properties which should be connected. In the connection area the flux of forces should be as smooth as possible; the force lines less disturbed (see Fig. 3-1).

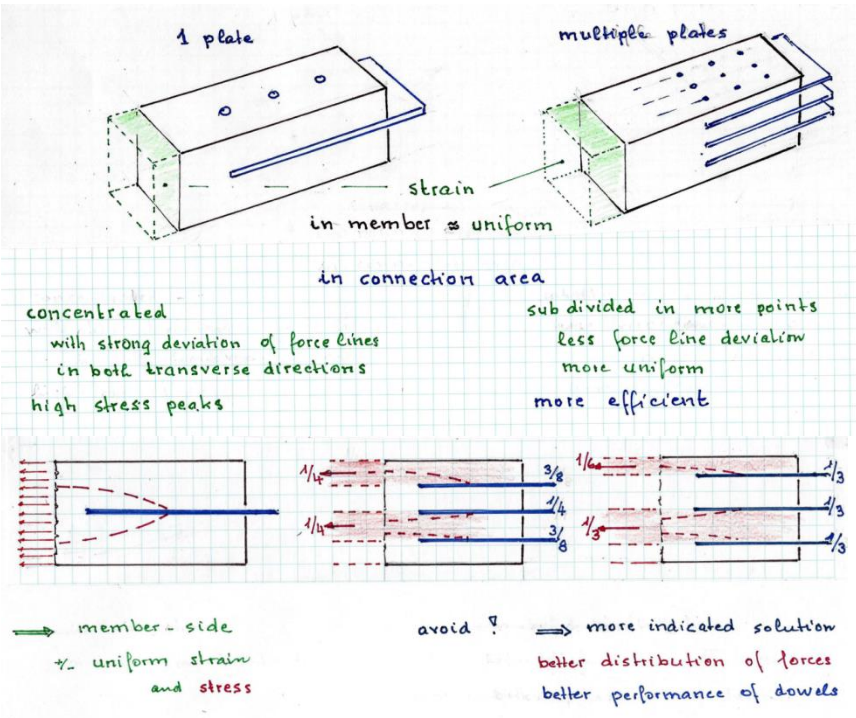


Figure 2-1: Flux of forces

With multiple steel plates – and automatically smaller dowel diameters - more uniform strain and stress conditions are effective in the connection area. Often are only regarded the conditions for the dowels.

3.2 Ductile structural behavior

Ductile behavior of a timber structure depends directly from the plastic deformation capacity of the connection areas. Plastic (bending) deformation of the dowel (see Fig. 3-2) is only possible when steel plate shows a certain displacement between steel plate and timber. The timber contact zone will follow the deformed shape of the dowel (timber will be crushed). The greater the dowel diameter, the greater the non-uniform deformed zone, and the lower the local resistance.

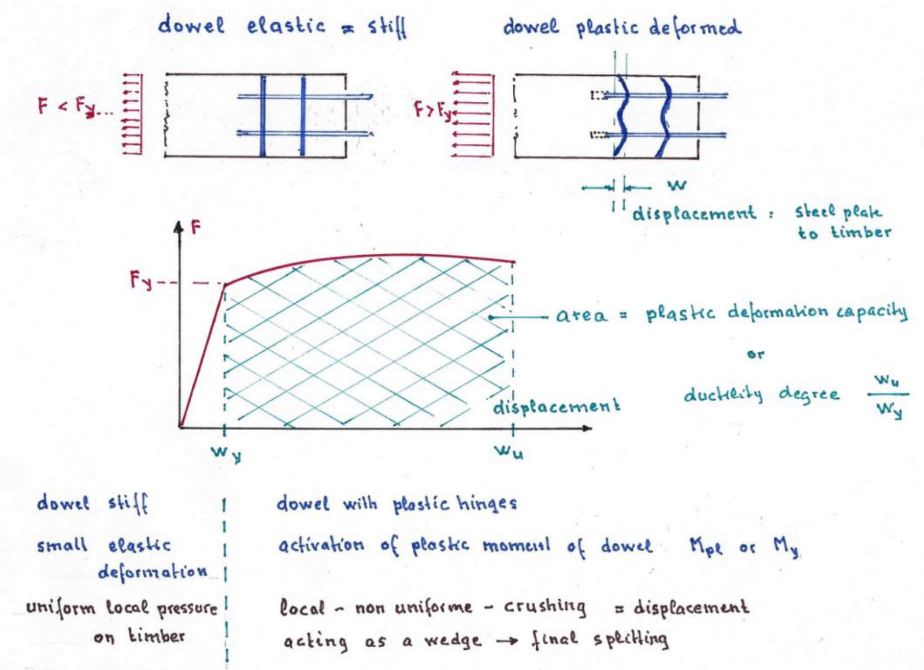


Figure 3-2: Plastic deformation capacity

As a result: to create plastic deformation into dowel an adequate plastic deformation capacity or a certain ductility degree will be required. This is a basic condition of Johansen theory; any other failure mode (splitting) must be avoided. This requires slender dowels. The slenderness required is function of the material properties and the supporting conditions. Practice has shown, that for ductile multiple steel-to-softwood connection a slenderness of the dowel of about t/d = 9 is needed.

3.3 Simple design

It's an interesting observation, that only few parameters are involved into the design of a dowelled connection: two material properties (each one for steel and for timber) and two geometric relations (both related to dowel size d).

only two material properties involved

- steel dowel **fy** or **fu** — derived Mplastic or My in f (d) — **size factor**
- wood density **ϱ** — derived: embedment strength fh in f (d) — **on Ø d**

geometric relations — all sizes related to dowel Ø d

- dowel slenderness **λ** = t / d → f (fy /ϱ) — **ductility**
- distance between dowels **a/d** → f (wood properties: par./perp.) — **no splitting**

Note: properties and dimensions are subjected to variations
furthermore tolerances of fabrication should be considered

Actually we are used - based on Johansen theory – to apply, instead of the material properties, the system strength values for the plastic bending moment M_y and for the embedment strength $f_{h,0}$. Note: the actual definition of those system strengths values was not known by Johansen.

4 M_y / f_h : material properties or system values?

Plastic moment of dowel M_y in EC 5 depends on: $M_y = 0{,}3 \cdot d^{2{,}6} \cdot f_u$
Bending angle α and r/d
Diameter d — size factor: $d^{-0{,}4}$
Stress-strain curve (f_y/f_u)

The embedment strength $f_{h,0}$ in EC 5 depends on: $f_{h,0} = 0{,}082\ (1-0{,}01 \cdot d) \cdot \varrho$
Test arrangement and procedure
Assessment criteria (compression/tension)
Diameter d
Density of wood ϱ (soft-/hardwood)

The equation in EC5 was established in the 80ties based on a linear approximation to test data; more indicated is an exponential function –with similar reliability – $f_{h,0} = 0{,}082\ (1{,}44 \cdot d^{-0{,}2}) \cdot \varrho$. This simplifies the well-known Johansen-equation $R_{Johansen} = \sqrt{4\, M_y f_{h,0} d}$ to $0{,}378\sqrt{f_u\, \rho}\ d^{1{,}7}$.

From the above it should be clear, that $R_{Johansen}$ may directly be written in function of the two properties f_u (tensile strength of steel) and ρ (density of timber) and by the diameter of the dowel d . The following will show that this simple approach is correct and reliable.

5 A practical case: concept with integral procedure

5.1 Decomposition into sub-assemblies

Since too complex: try to decompose into sub-assemblies with negligible interference (see Fig. 5-1).

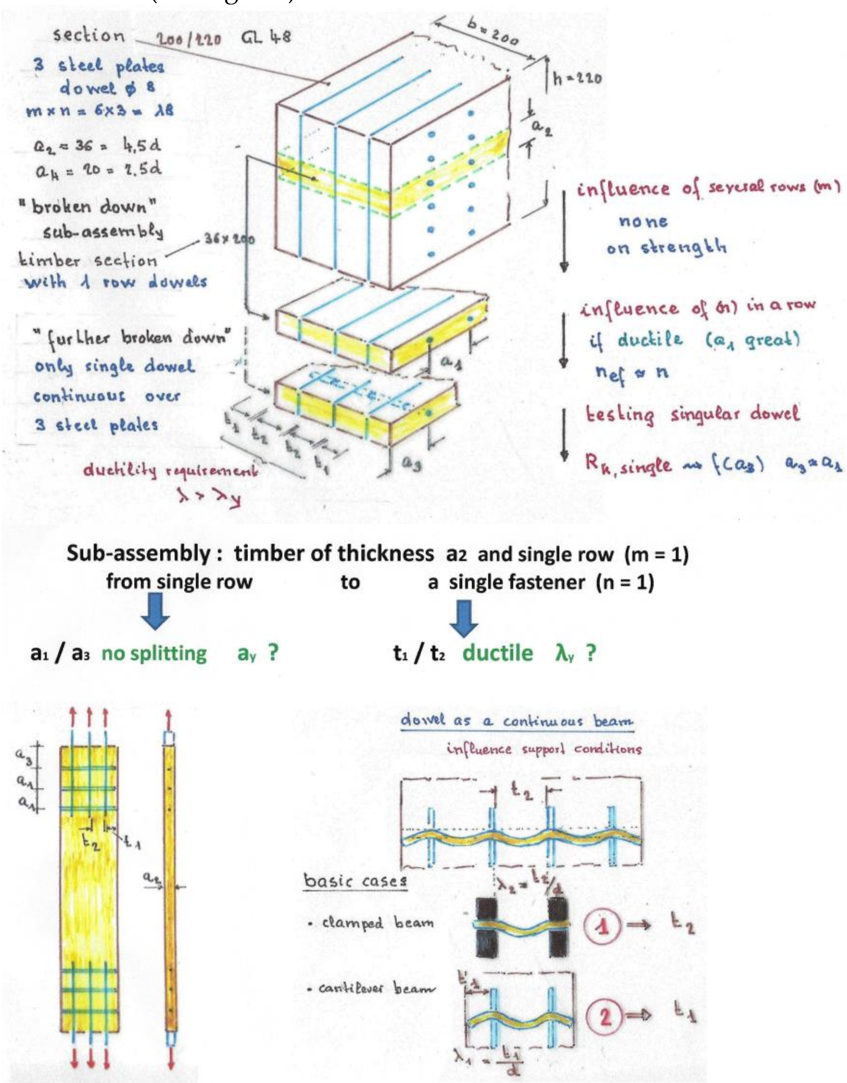


Figure 5-1: Decomposition into sub-assemblies

The proposed procedure allows breaking down more complex problems to sub-assemblies wich are easier to handle. Important: interference between sub-assemblies should be small or negligible. Finally – basic case – is a “beam” clamped on both sides. Wanted is the slenderness $\lambda_2 = t_2/d$ wich corresponds to the desired ductlity degree.

5.2 Assessment of λ_2 by test: case $\lambda_{2,y}$

The assessment by test is a very simple way. By varying the timber thickness t_2 we obtain directly – for the desired displacemt w = 5 mm – the value of $t_{2,y}$ at the point of intersection (see Fig. 5-2).

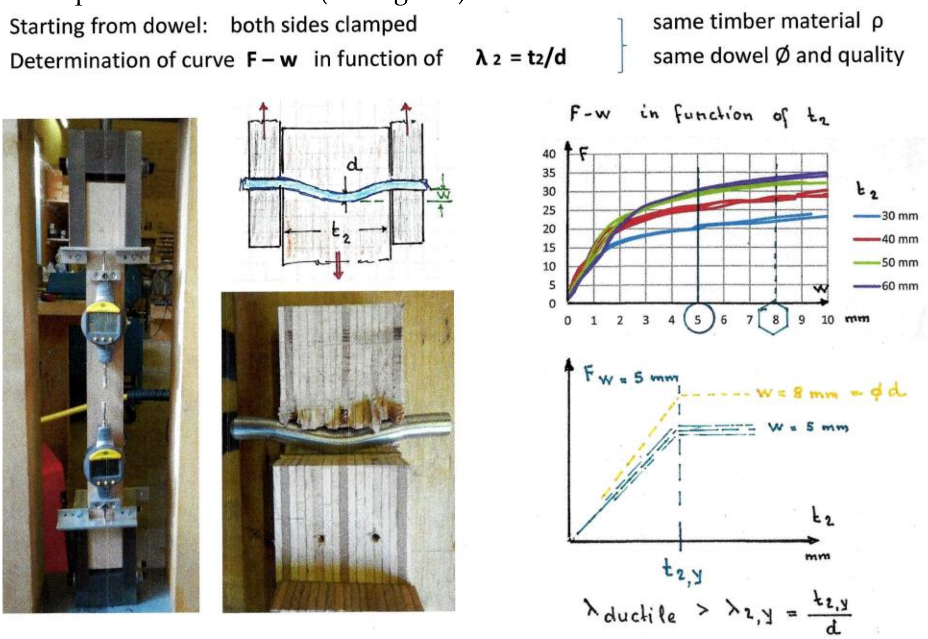


Figure 5-2: Test procedure for the assessment of $\lambda_{2,ductile}$

5.3 Tests on sub-assemblies

Next were made tests on sub-assemblies to define values for:

- Adequate slenderness λ_1 (compatible deformation)
- Distances a_1 and a_3 (avoid splitting)

Based on the results (see Fig. 5-3) of such sub-assemblies (3 dowels in a row) it was found that for beechwood no interference exists with a_1 about 9 d. This was considered by detailing the full size test specimens.

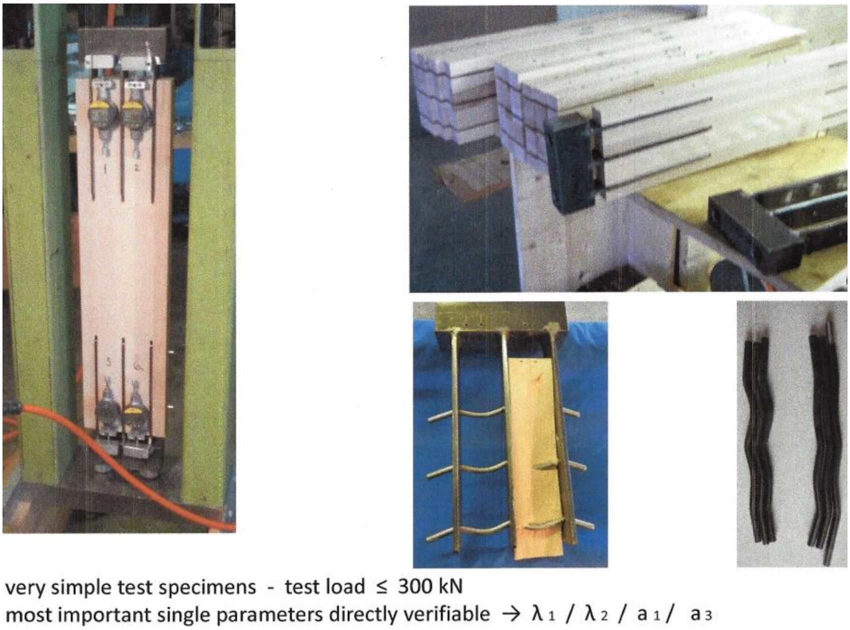


Figure 5-3: Test on sub-assemblies at the neue Holzbau (n'H)

5.4 Soundness of concept

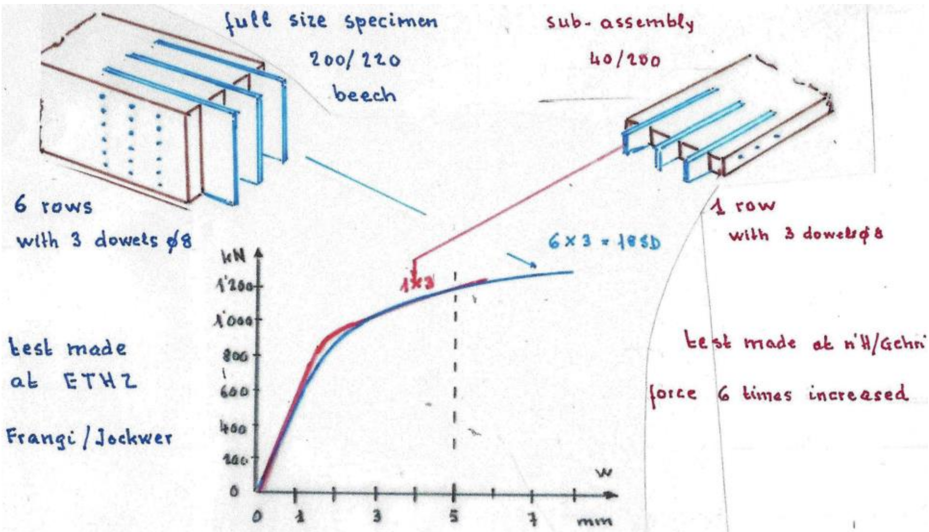
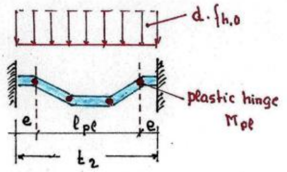


Figure 5-4: Comparison of full size test to partial approach

From Fig. 5-4 follows that the proposed procedure is acceptable and reliable.

5.5 Assessment by plastic hinge theory: case $\lambda_{2,y}$

Both, dowel slenderness and load-carrying capacity, may be estimated by applying the plastic hinge theory (see Fig. 5-5 and 5-6).



formation of **4 plastic zones** (so-called plastic hinges)

attention: EYM simplification (**hinges without extension**)

plastic hinge at the transition timber-to-steel plate

assume e ≈ d / 2

Basic assumptions of Johansen → here direct applied on **multiple steel plates**

– Equilibrium condition: $\frac{d \cdot f_{h,0} \cdot \ell_{pl}^2}{8} = 2 \cdot M_{pl} \longrightarrow \ell_{pl} = \sqrt{\frac{16\, M_{pl}}{f_{h,0} \cdot d}}$

– **Dowel slenderness:**

$$t_{2,y} = 2 \cdot e + \sqrt{\frac{16\, M_{pl}}{f_{h,0} \cdot d}} = d + \sqrt{\frac{16 \cdot 0{,}25 \cdot d^{2,7} \cdot f_u}{\underbrace{0{,}15}_{\text{for hardwood} \rightarrow 0{,}19} \cdot d^{0,7} \cdot \rho}}$$

$\lambda_{2,y}$: softwood $= 1 + 5{,}2\sqrt{f_u/\rho}$; hardwood $= 1 + 4{,}6\sqrt{f_u/\rho}$

Figure 5-5: Estimation of $\lambda_{2,y}$ based on M_y=0,25 $d^{2,7}$ f_u and $f_{h,0}$ = 0,15 $d^{-0,3}$ ϱ (according to Gehri/SIA 265:2003)

Note: for deign purposes – to be on the safe side and take in account variations of properties and dimension as well fabrication tolerances – the above dowel slenderness are increased to $\lambda_{2,design} \approx$ 1,2 to 1,25 · $\lambda_{2,y}$.

Load-carrying capacity:

$$R_{dowel/shear\ plane} = \frac{d^2}{2} \cdot f_{h,0} + \sqrt{4 \cdot M_y \cdot f_{h,0} \cdot d}$$

$$= \left[0{,}075 \cdot \rho + 0{,}38\sqrt{f_u \cdot \rho}\right] \cdot d^{1,7}$$

for softwood ≈ 1,16 × Johansen ≙ EYM

Figure 5-6: Estimation of load-carrying capacity based on properties f_u and ϱ

In principle, the plastic hinge theory provides the highest possible value of load-carrying capacity – when using correct properties. The increase – in EC5 – by a factor of 1,15 was therefore contested by the Author. By the introduction of the plastic hinges with a distance of about d/2 from the steel plate this contradiction desappears.

The application of a greather slenderness do not affect the load-carrying capacity; it makes only shure to reach adequate ductility.

6 Strength model for ductile configuration

6.1 Load-carrying capacity for singular dowel

Taking in account ductile detailing (adequate distance a_1, e.g. for beechwood about 9 d, and slenderness of the dowel λ) the load-carrying capacity for a singular dowel over multiple shear plates may be written to:

$$\mathbf{R_{k,shear\ plane} = factor \cdot d^{1,7}}$$

The factor Y is function of the material properties f_u and ϱ and of supporting conditions (continuos or clamped, cantilever). For hardwood beech with $\varrho \approx$ 700 kg/m³ and steel dowel with $f_u \approx$ 700 N/mm² the following values are proposed (see Fig. 6-1).

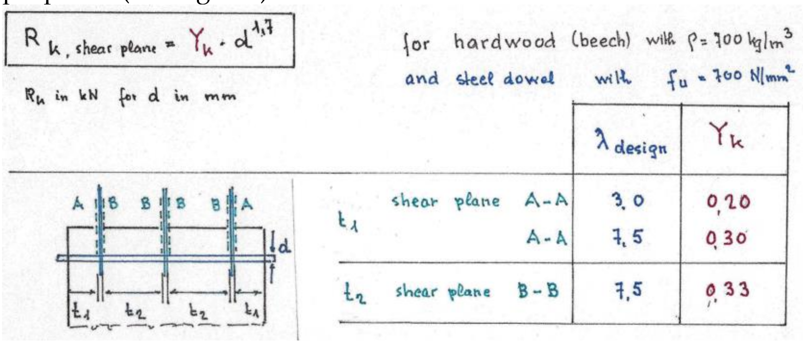


Figure 6-1: Proposed factors for characteristic load-carrying capacities

6.2 Validity of strength model

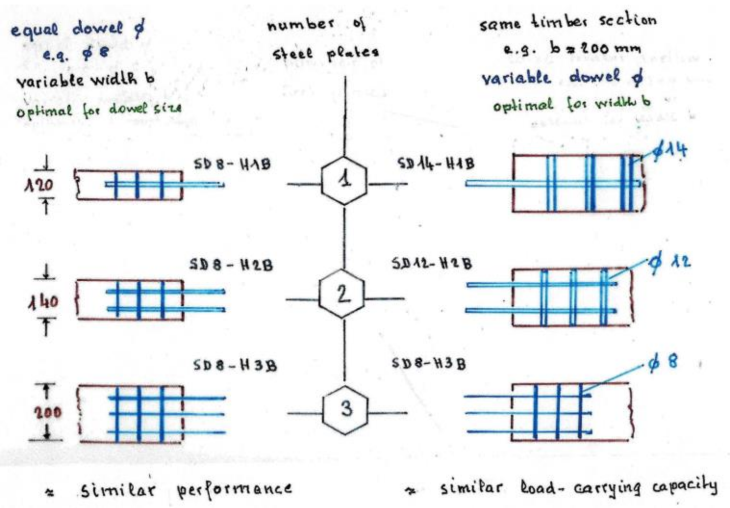


Figure 6-2: Variation of number of plates and dowel diameter

For the validation 15 full size specimens were foreseen and prepared, but only 10 specimens were tested. Fig. 6-3 shows a good approach: estimation to test results.

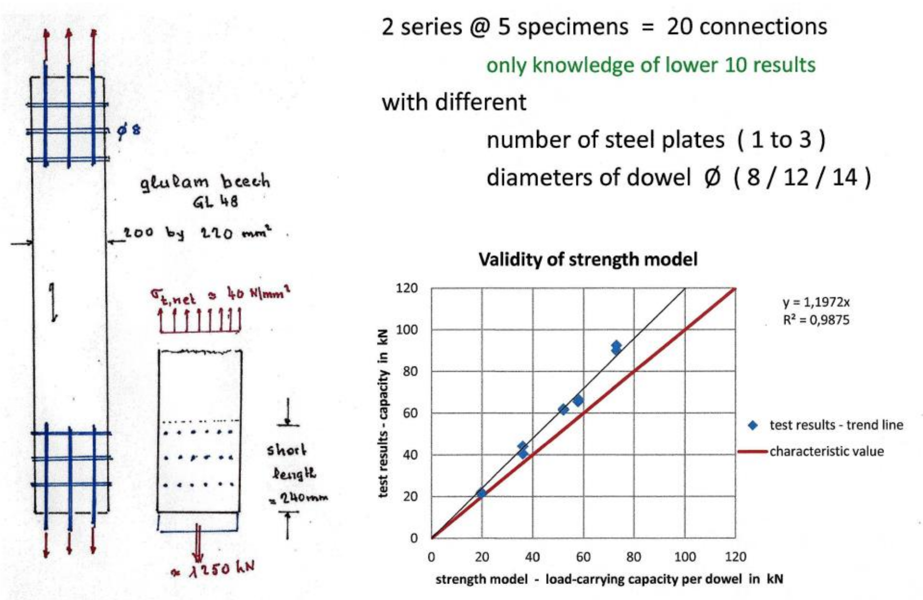


Figure 6-3: Estimation to test result

7 What is important to remind?

- Use multiple steel plates — single only for secondary work
- Ductility requirement $t = \lambda \cdot d$ ⬇ function of $\sqrt{f_u/\rho}$ — hardwood $\lambda_{2,design} = 7{,}5$
- Splitting requirement $a_1 \geq a_y$ — hardwood $a_y \approx 9 \cdot d$
- Strength function of $\sqrt{f_u \cdot \rho}$ and $d^{1{,}7}$

  simplification $R_{design/shearplane} = X \cdot d^{1{,}7}$

8 Literature

[1] K. Sattler, Hölzerne Tragwerke mit genagelten stählernen Stossblechen. Bautechnik, 1948, p. 53-59.