WG2

Stress perpendicular to grain in glued laminated timber girders with special shapes

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Summary

- The paper presents the results of few researches in Croatia in the field of stress perpendicular to grain analysis inside glued laminated timber girders with special shapes.
- Researches include experimental part, analysis of parametrically prepared FE models, comparison of test results and theory, as well as results of design with various European codes and FEA.
- Also, as the result of this works the advises for the design and geometry limitation for the engineers in praxis are given for the most common shape types of glued laminated beams.

Most common shapes of glulam beams

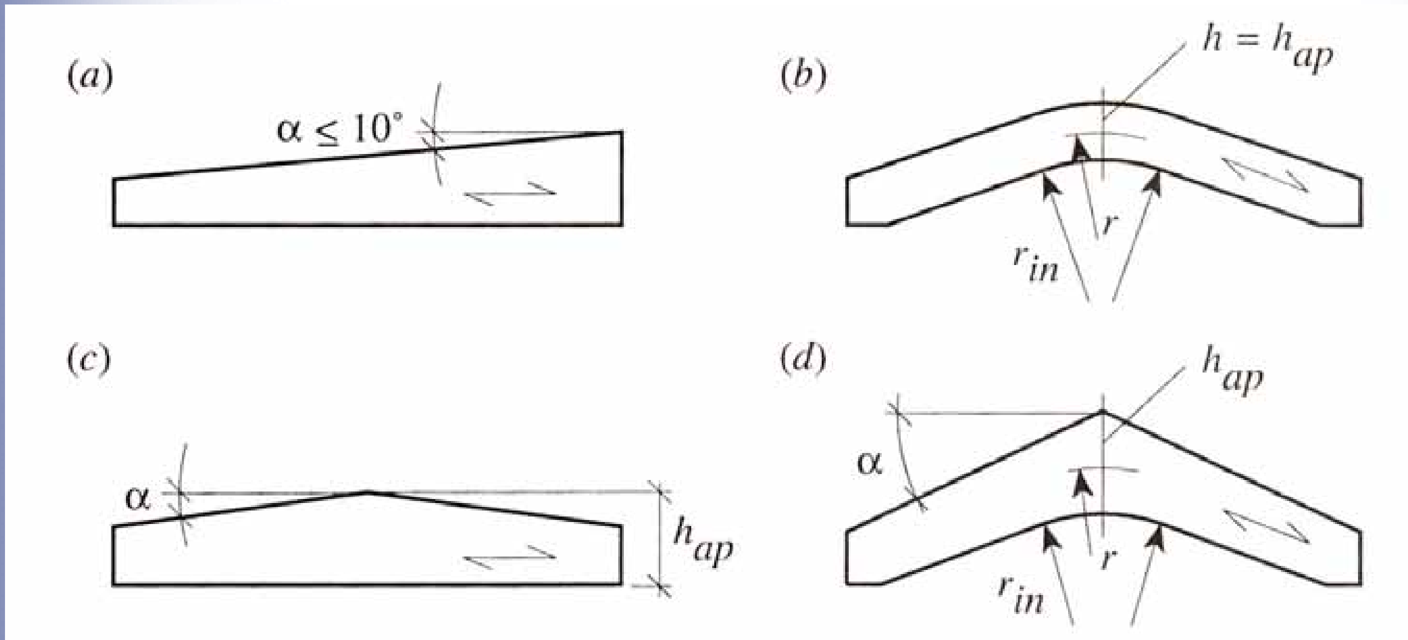
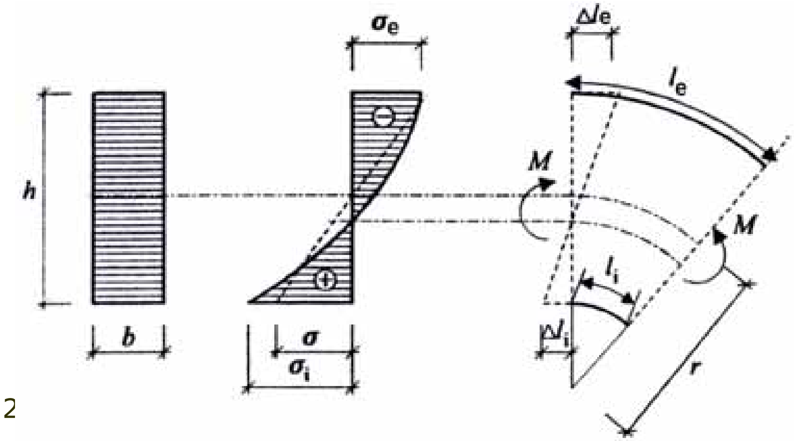


Figure a) single tapered beam,b) double tapered beam, c) curved beam with constant cross-section d) pitched cambered beam

Distribution of bending stress

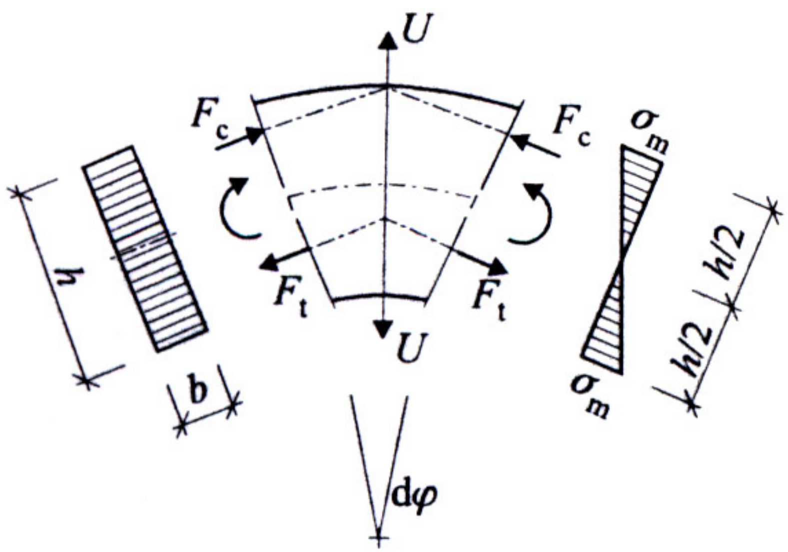
- The distribution of bending stress in tapered beams is non-linear and therefore should be calculated using the theory of thin anisotropic plates, taking into account the ratios of E_0/E_{90} and E_{90}/G and Poisson's ratio.

- Theory of the curved beam bending is based on the presumption that cross sections stay narrow after bending and perpendicular to the longitudinal axis of the beam after deformation. They have only relative rotation.



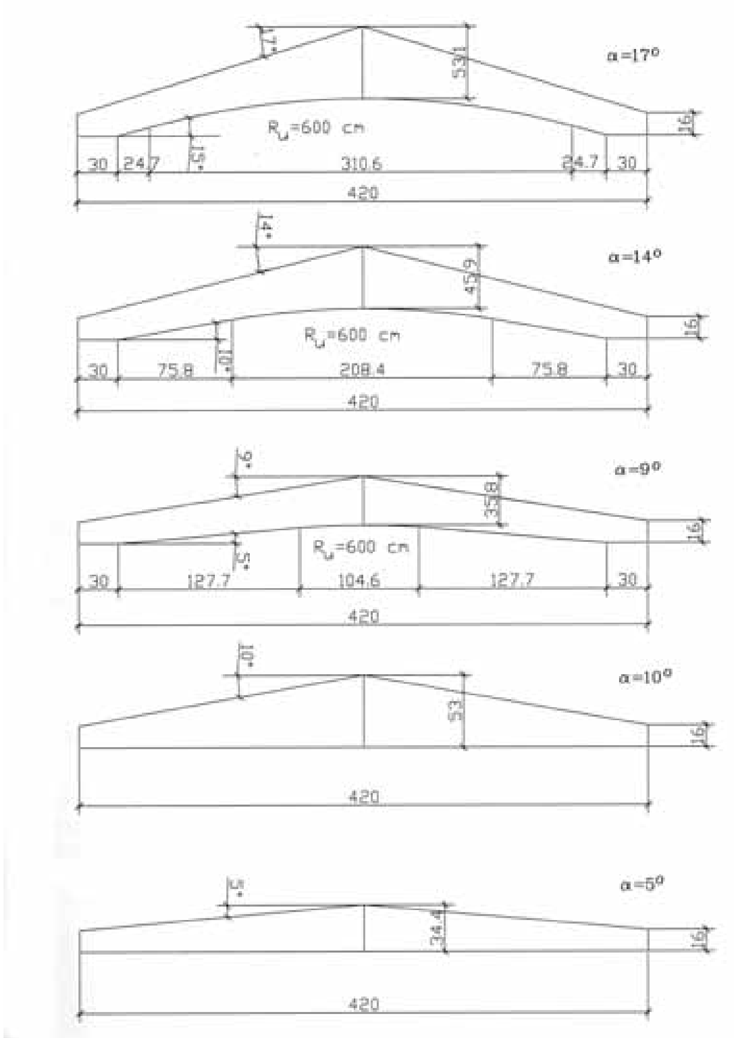
Theoretical explanation of the tensile stresses perp. to grain

- Bending moments in curved members cause radial stresses perpendicular to grain. Assuming, for simplification, a linear stress distribution, it can be easily shown that resulting tensile and compresive forces F_t i F_c, lead to the force U in radial direction. If the moment increases the radius of curvature, the radial stresses are in tension.



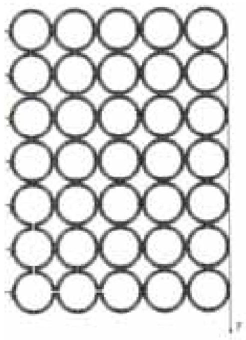
I. Analysis of five types of glulam girders with and without FRP reinforcing plates

- Inside the scientific project "Analysis of reliability of the timber structures" led by Prof. Žagar, candidate M. Haiman (both from the Faculty of Civil Engineering, University if Zagreb) made the Ph.D work about reliability of glulam beams with or without reinforcement with FRP plates.



I. Analysis of the “rolling shear” of the timber grains in contact with FRP plate

- For that purpose, five samples for every type of glulam girders were tested. Ultimate and design value of rolling shear strength were determined. Next Figures show the test setup, mode of sample collapse and theoretical deformation of the tracheae of the timber under tensile force on the FRP plate.



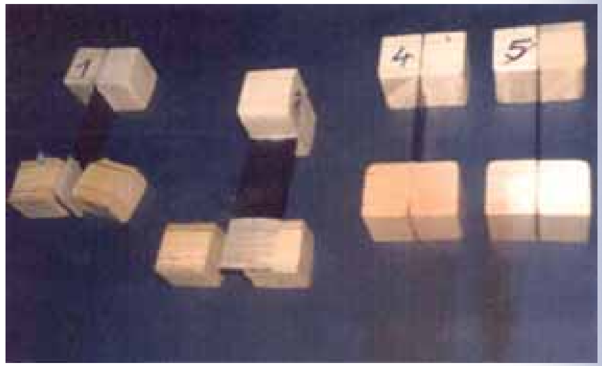
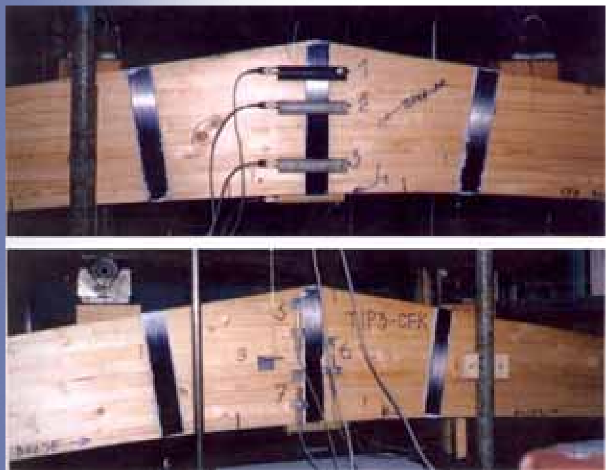


Figure: Test of the samples – “rolling shear”

I. Lab tests of the glulam girders

- As it could be seen, five types of glulam beams with special shapes are tested on the bending according to four point test.

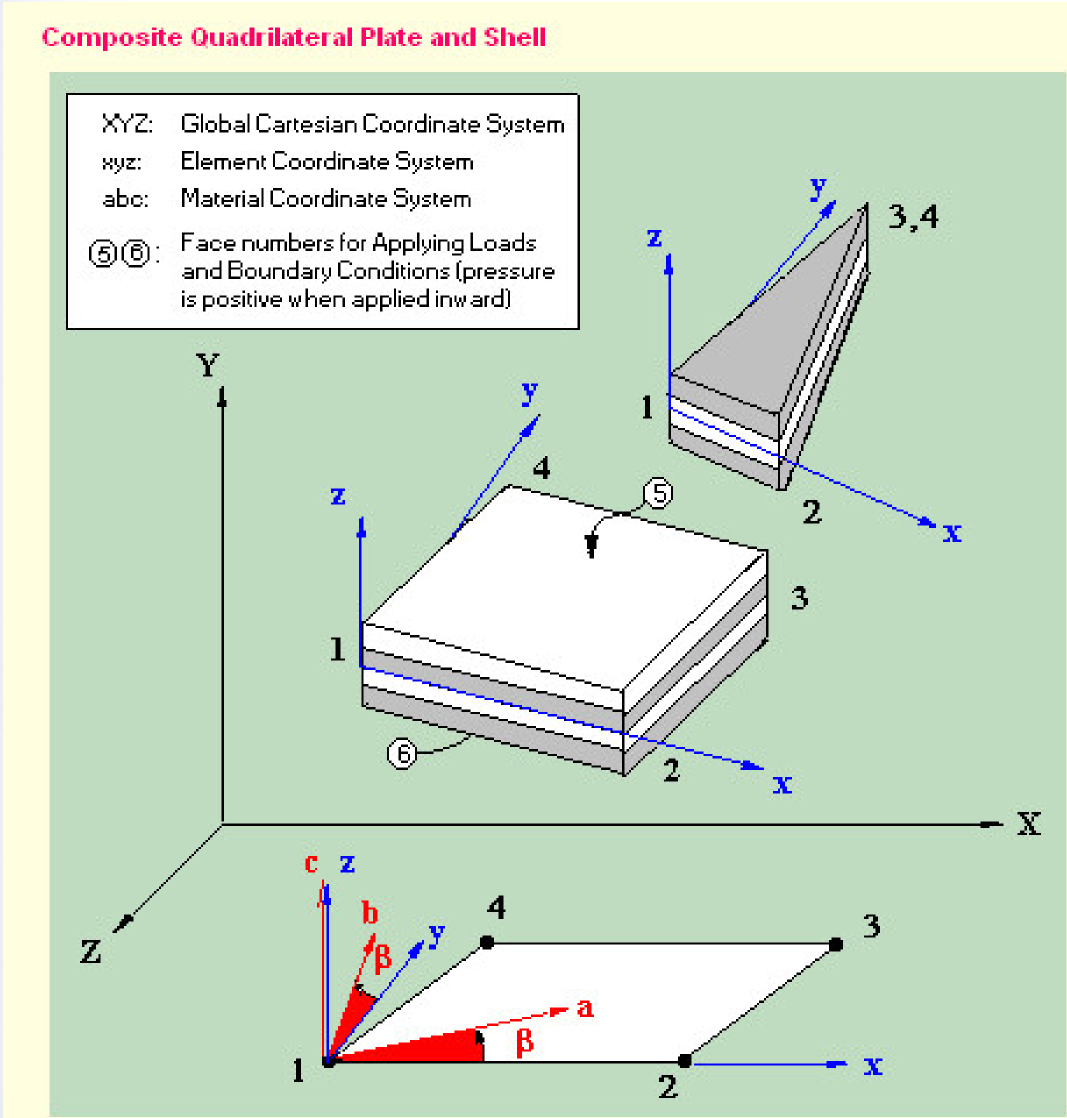


Position of the FRP plates: plates were in the apex of the glulam girders but also they were glued 40 cm from the midspan on both sides(left); Collapse of the glulam beam without FRP plate due to stress perpendicular to grain (right)

I. Numerical analysis of the tested glulam girders

- All dimensions of the numerical analysed girders followed the geometry of lab tested girders.
- For numerical modeling finite element SHELL4L was used because it has possibility to define orthotropic characteristics. To increase the accuracy of analysis, QUAD4 option was choosen and list of results in the local coordinate system. It is especially important because the results of stresses σx and σy are shown parallel to down edge and perpendicular to down edge.

I. Shell4L / QAUD FE



I. Accurate modeling glulam beams

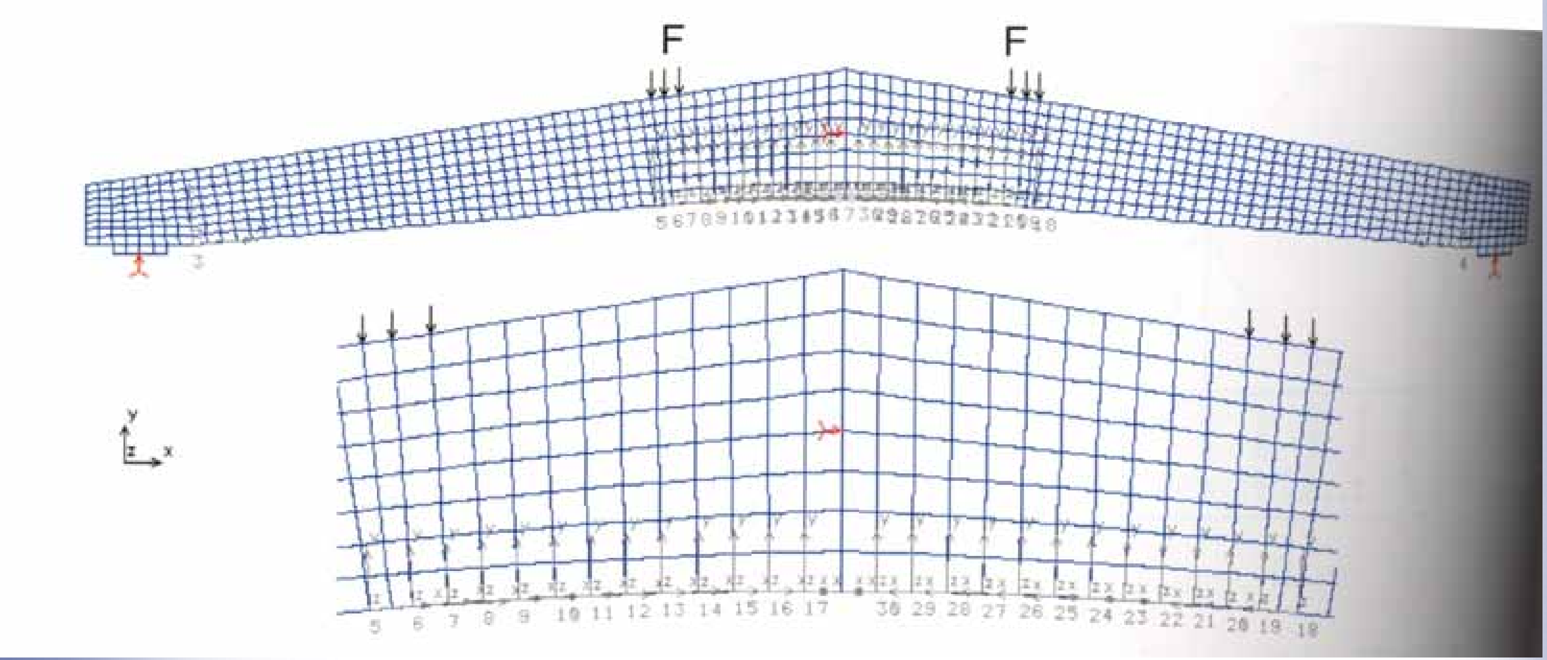


Figure: Shows detailed modeling of the material paralel to down edge using numerous local coordinate systems characteristics. The difference between corect model and incorect, very rough model could be very big looking in percent (up to the 100%). When the model is corect , tensile stresses perpendicular to grain decrease and it is very near to the value of the meassured stress.

I. Distribution of stresses perpendicular to grain

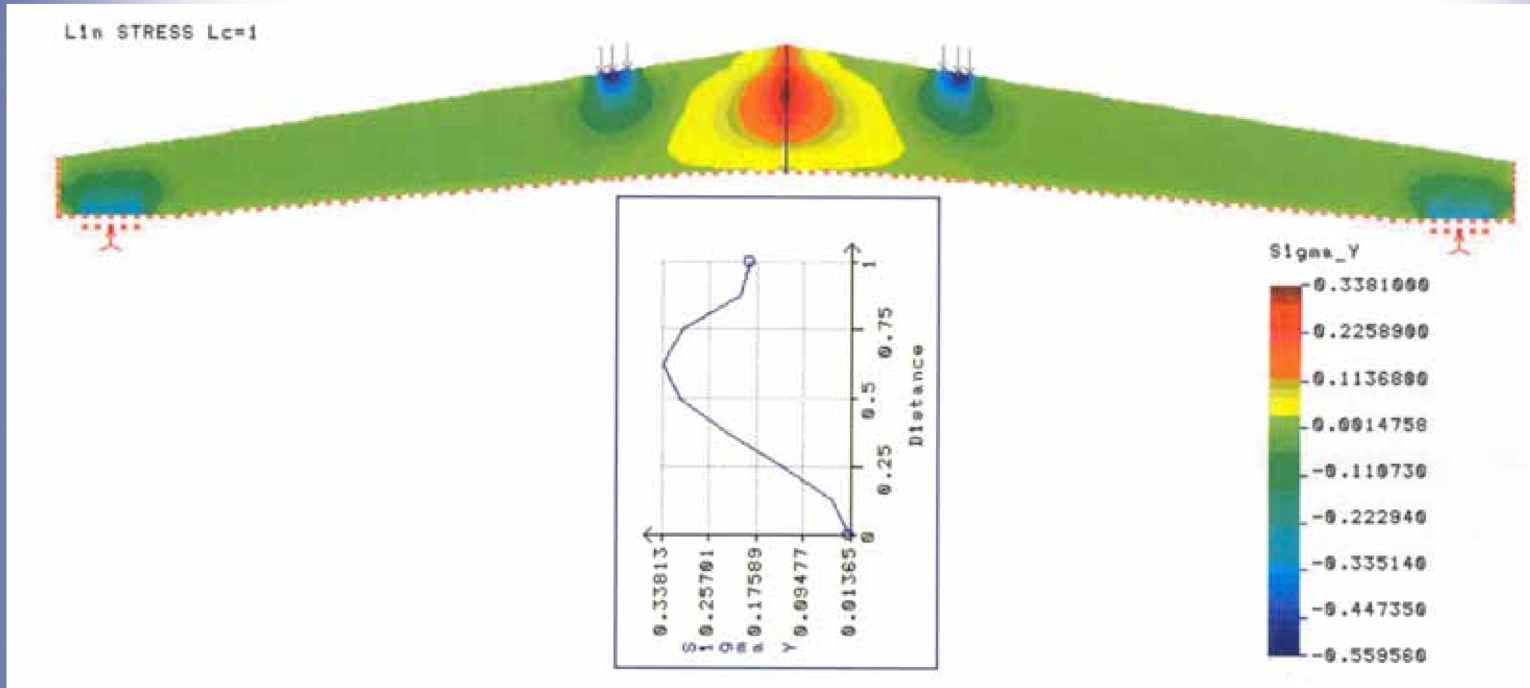


Figure: Distribution of the stresses perpendicular to grain – in apex cross section – TYPE 3

I. Distribution of stresses perpendicular to grain

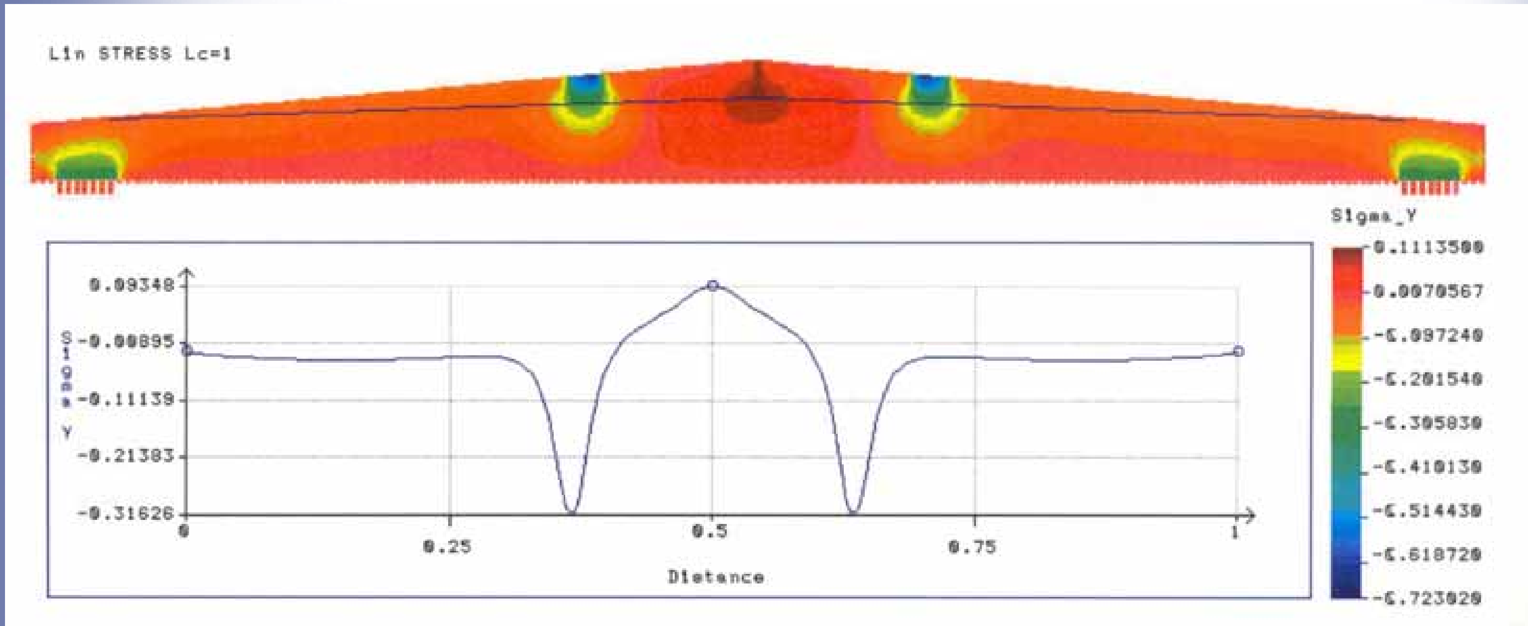


Figure: Distribution of the stresses perpendicular to grain in tapered beam, longitudinaly - TYPE 1

I. Conclusions (1) :

1. Meassurments of the deformations ε_x and ε_y in all five types of glulam beams shows good correspodence with the results of numerical analysis done by COSMOS/M program package. This gives the opportunity for reliable real modeling of glulam girders using such packages.

I. Conclusions (2) :

3. Good correspodence o numerical and testing results of the deformation εx was in range ± 10%. For the perpendicular deformations εy range was bigger (±20%).

4. According to P-δ diagrams it could be seen that the glulam girders with bigger volume and all girders with FRP plates reinforcement are ductile after force 2/3 Fu.

I. Conclusions (3) :

5. In four types of glulam beams, putting the FRP plates in lower tensile zone longitudinaly gives much more reliable beam. On the other hand, glueing the FRP plates sided to glulam girder is much less effective than it was expected before testing.

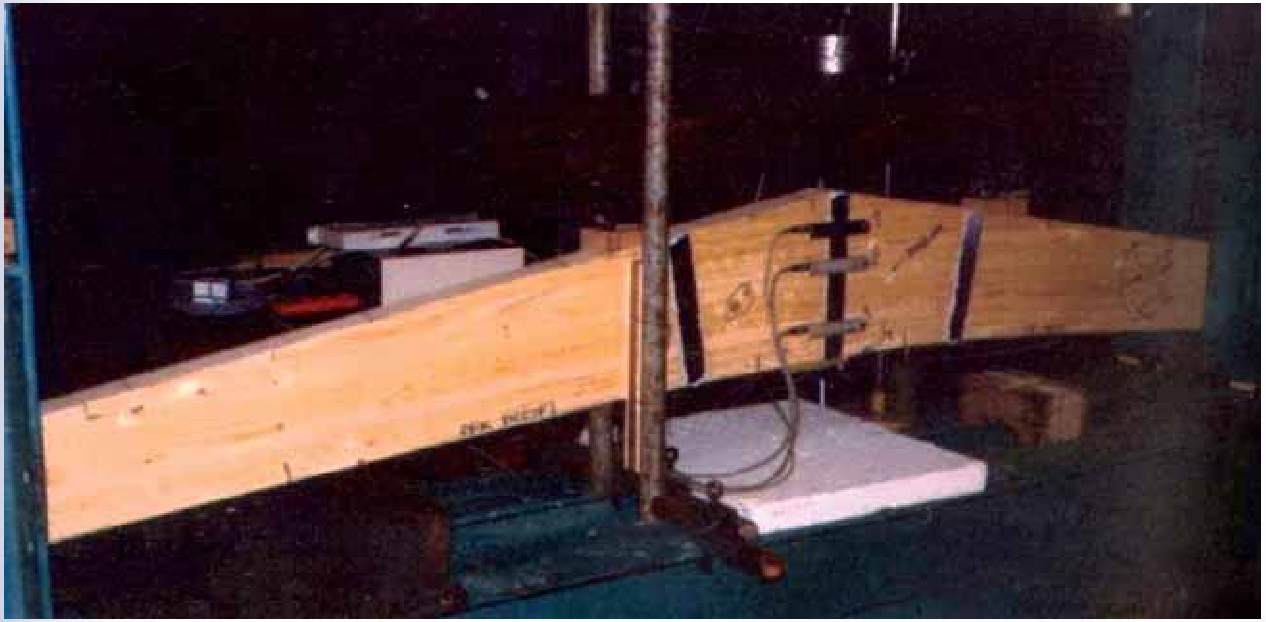
6. In the glulam beams with width of 10, 12, most 14 cm, tensile stress perpendicular to grain could be partly effectively taken over by FRP plates.

I. Conclusions (4) :

7. Very usefull researh of the perpendicular „rolling shear" capacity showed almost identical strength as $f_{t,90,k}$. By the space model analysis it is shown that depth influence of the FRP plates is about 20 mm which is not enough for the glulam beams of mid and larger span.

I. Conclusions (5) :

9. Putting the FRP plates longitudinaly in the bottom of tensile zone across the whole span is very good solution which increase the lavel of reliability significantly, especially when it covers defects in wood.



II. ANALYSIS OF SLOPE EFFECT AND GEOMETRY OF GLULAM PITCHED CAMBERED BEAMS – ADVISES FOR THEIR DESIGN AND PRACTICAL APPLICATION

- a part of diploma work of student Vedran Pavlic under the mentorship of assist. Prof. A. Bjelanovic (Faculty of Civil Engineering University of Rijeka)
- the main subjects of interest are glulam pitched-cambered beams the form of whom is aesthetically very impressive
- however, an unsuitable form, e.g. inappropriate slope, due to the span and radius of curvature of the apex zone, could incite very serious problems in practice and jeopardize a safety of the whole structure

II. ANALYSIS OF SLOPE EFFECT AND GEOMETRY OF GLULAM PITCHED CAMBERED BEAMS – ADVISES FOR THEIR DESIGN AND PRACTICAL APPLICATION

- EC5 makes some simplifications that are acceptable enough in engineering practice.
- the results are obtained using different codes and FEA are compared.

$$\sigma_{m,d,\gamma} = \frac{M_{x-x,d}}{W_{x-x}} \leq k_{m,\gamma} \cdot f_{m,d}$$

$$k_{m,\gamma} = \frac{1}{\sqrt{1 + \left(\frac{f_{m,d}}{1{,}5\, f_{v,d}} \cdot tg\gamma\right)^2 + \left(\frac{f_{m,d}}{f_{c,90,d}} \cdot tg^2\gamma\right)^2}}$$

$$\sigma_{m,d,\gamma} = (1 - 4\, tg^2\gamma) \cdot \frac{M_{x-x,d}}{W_{x-x}} \leq k_{m,\gamma} \cdot f_{m,d}$$

$$k_{m,\gamma} = \frac{1}{\frac{f_{m,d}}{f_{c,90,d}} \cdot \sin^2\gamma + \cos^2\gamma}$$

II. ANALYSIS OF SLOPE EFFECT AND GEOMETRY OF GLULAM PITCHED CAMBERED BEAMS – ADVISES FOR THEIR DESIGN AND PRACTICAL APPLICATION

- Anisotropy of material and nonlinear distribution of stresses => it is therefore hard to optimize the dimensions of those girders according to this criterion as its other characteristic cross-sections.

- Such a problem can be avoided in different ways: local strengthening of the curved area, the construction of ridge girders of reduced static height (rounded ridge) or the construction of girders in couples instead of uneconomic increase of the single girder's height.

II. ANALYSIS OF SLOPE EFFECT AND GEOMETRY OF GLULAM PITCHED CAMBERED BEAMS – ADVISES FOR THEIR DESIGN AND PRACTICAL APPLICATION

- Much better solutions relate to the geometry’s rationalization (the slope of the flat girder’s part of the axis, the raise of the curved area radius and the variation of the static height – full or reduced, modifying or constant girder’s height as well) in relation to the span
- The paper advocates such an approach, and the results lead to the summary of guidelines for a practical usage. As the basis for an investigation new European norms were taken, EN 1995:2004-1-1.

II. Description of methods included in research :

The FE 2D and 3D girders' models are parametrically prepared as well, undergoing the static analysis and global stability analysis (buckling) in order to look at the impact of simplification which leads to the introduction of norms into the calculation

II. Description of methods included in research :

Symmetric load of main girders (the wind impact omitted – asymmetric impact).
The application of programme packages and the approach to the calculation (parametrically conducted analyses):

Programme package MATCHAD 13 for the proofs of mechanical strength and girders' stability. The girders are modelled parametrically (seven input parameters are: intrados and extrados slope angles, a and b, their divergence, g, L girder span, chord length on the Cin intrados dependent on the radius and central curvature angle, affecting the volume of the curved zone, then cross-section dimensions – the height on the girder's bearing, ha and the width, b). The alteration of stresses and the estimation of the cross - section 's bearing capacity (satisfying or not) result from varying the input parameters.

II. Description of methods included in research :

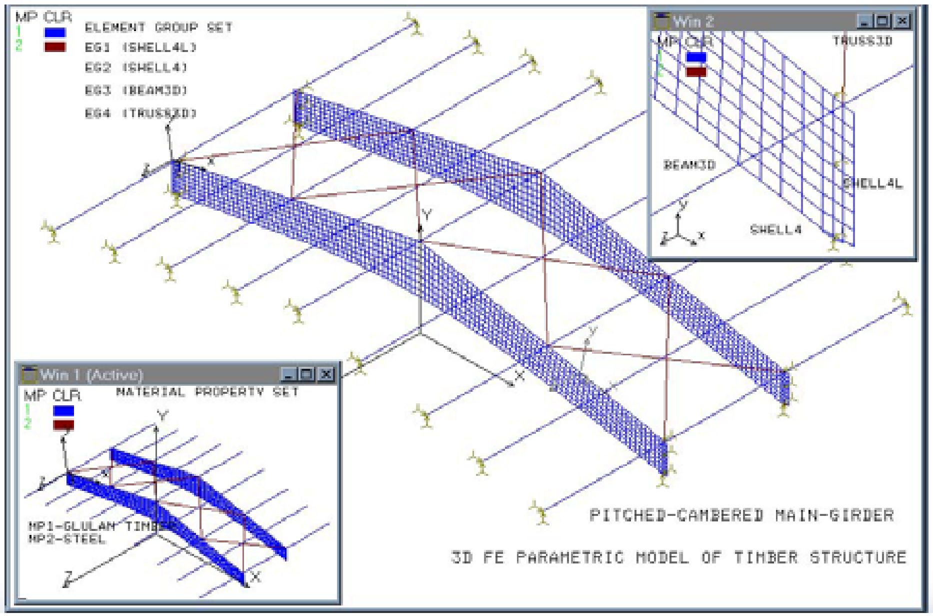
Symmetric load of main girders (the wind impact omitted – asymmetric impact).
The application of programme packages and the approach to the calculation (parametrically conducted analyses):

The Excel programme package has been used for limiting the input parameters values (α, β, γ, L, C_{in}, ha, b) so as to evaluate the girder’s rationality. The assessment of rationality (dependence of mechanical strength and girder’s stability on geometry). With regard to limitations of the study scope (samples’ number, simplified analysis only for symmetric actions, etc.), rationality assessment for the glulam girders of highly curved intrados can be considered as a design «guideline».

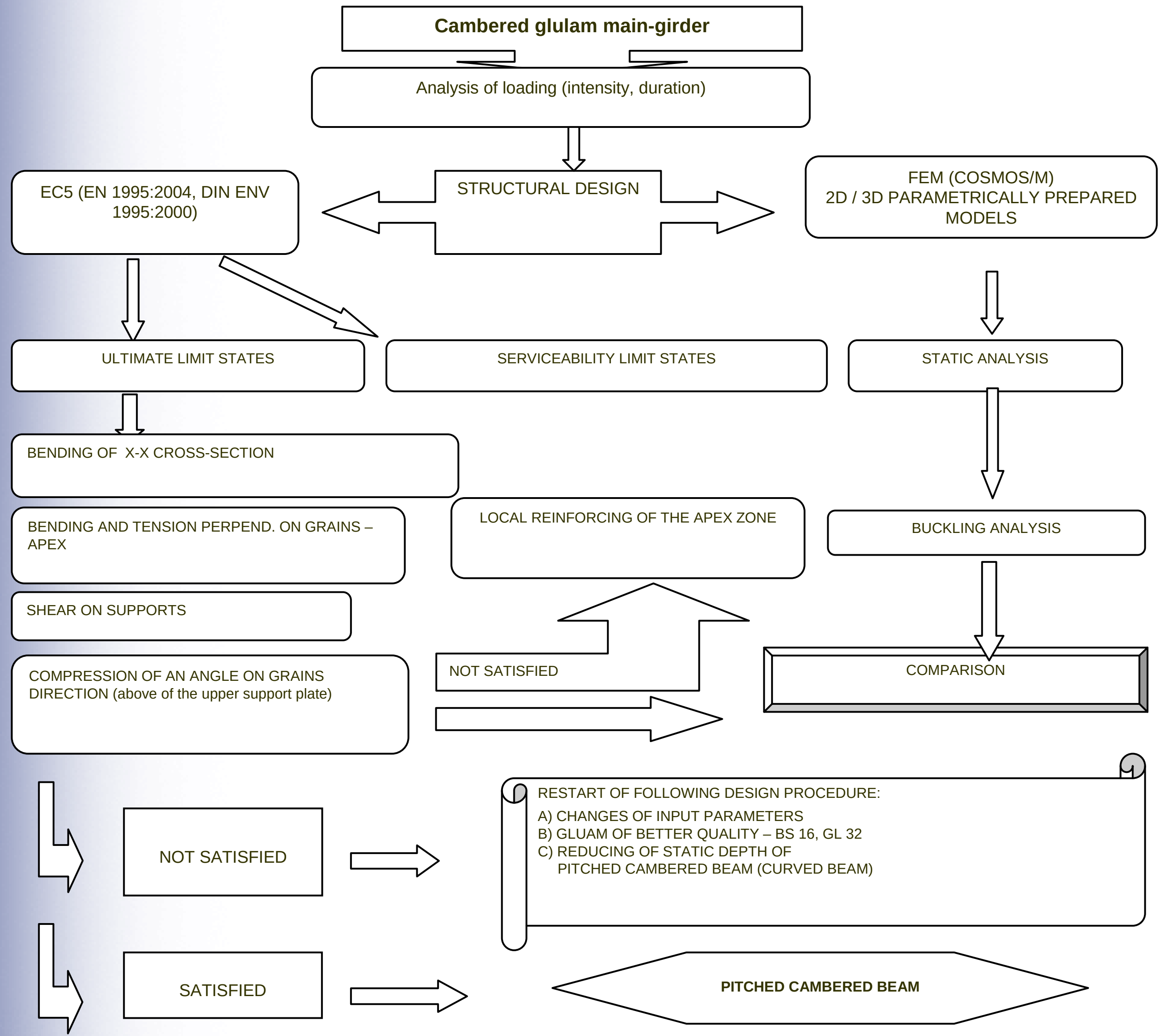
II. Description of methods included in research :

Symmetric load The application of programme packages and the approach to the calculation (parametrically conducted analyses):

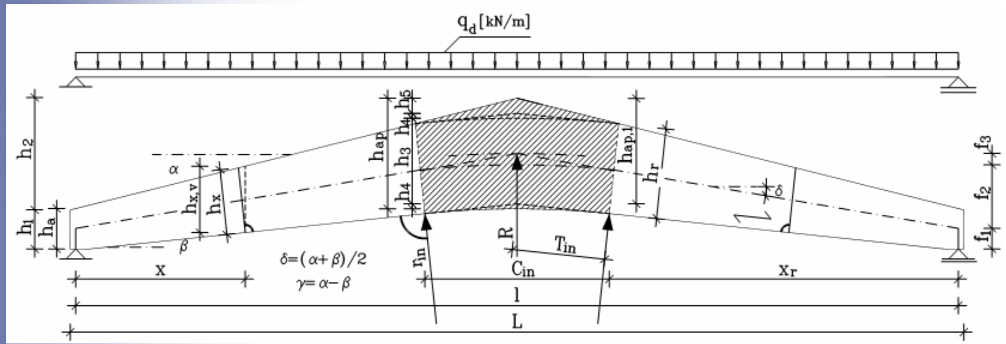
The COSMOS/M programme package has been used for MKE analysis of parametrically modelled girders (the same input parameters) undergoing the same analysis and repetitive calculations. The package is used to introduce the possibility of comparing results with those obtained by the calculations and application of expressions for dimensioning (EN, ENV).

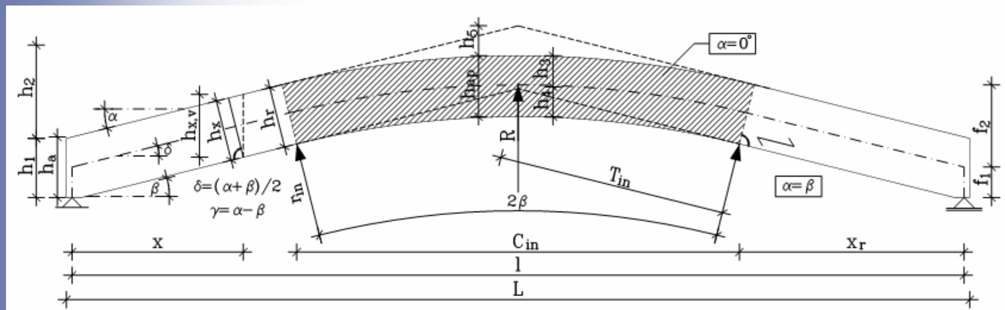


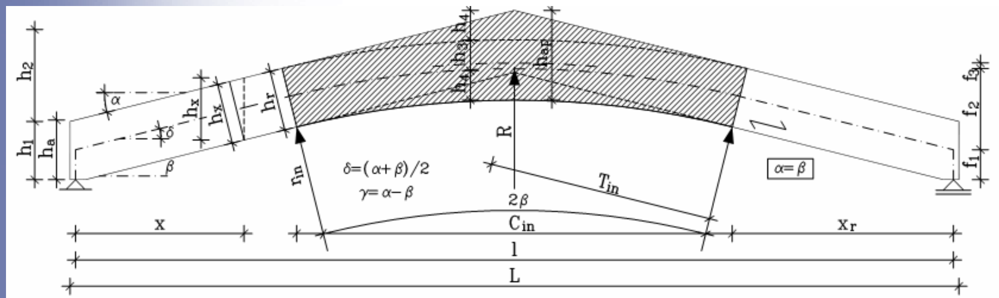
II. Flow-chart of design procedure and parametric analysis :

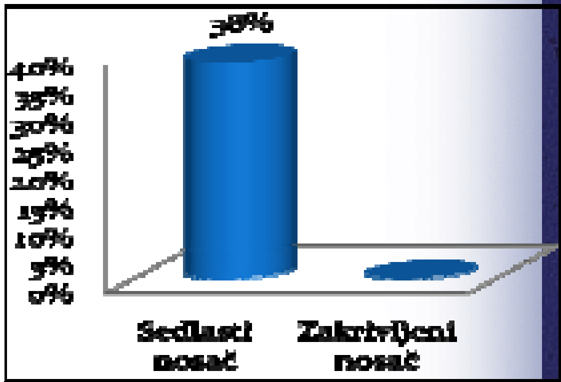


II. Tensile stress perpendicular to grains - comparison



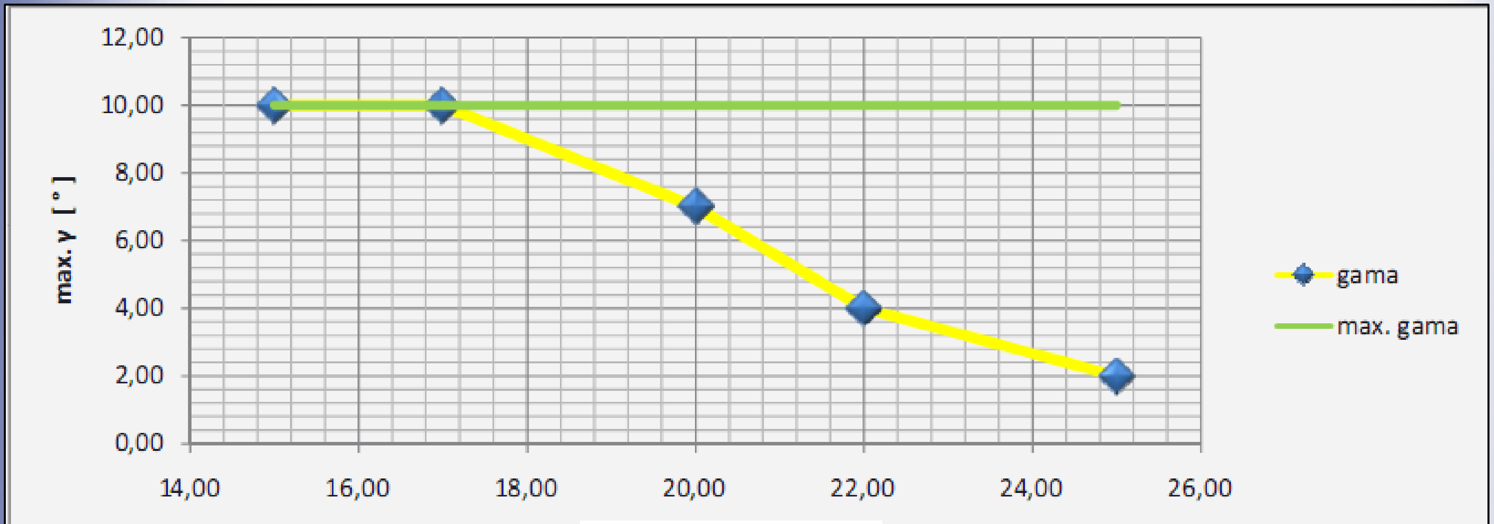






*Tensile stresses perpendicular on grains in apex – **pitched cambered beam** (left) and **curved beam** (right)*

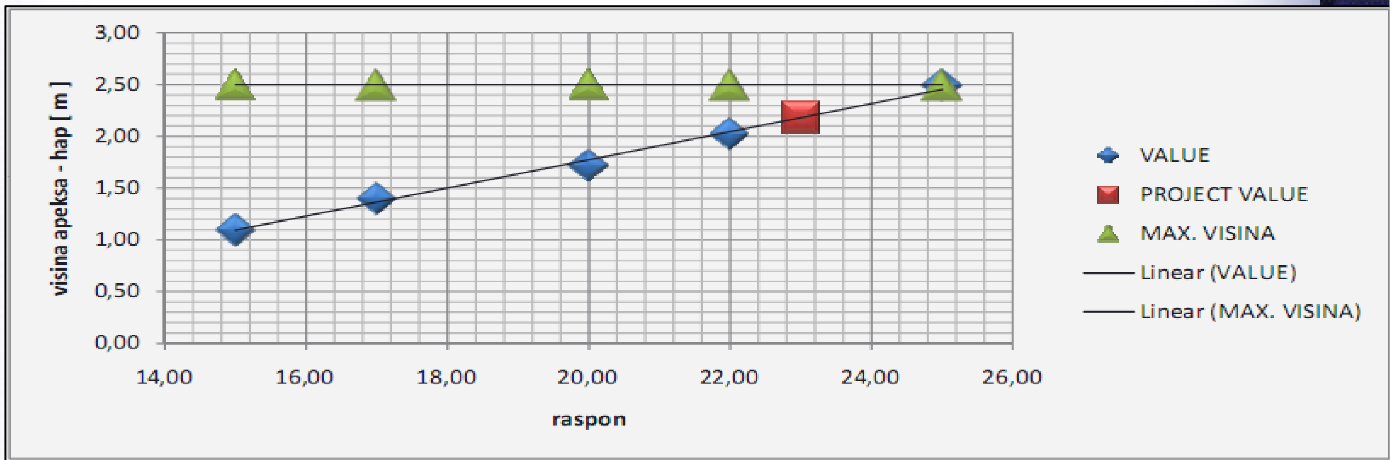
II. Limitations in geometry



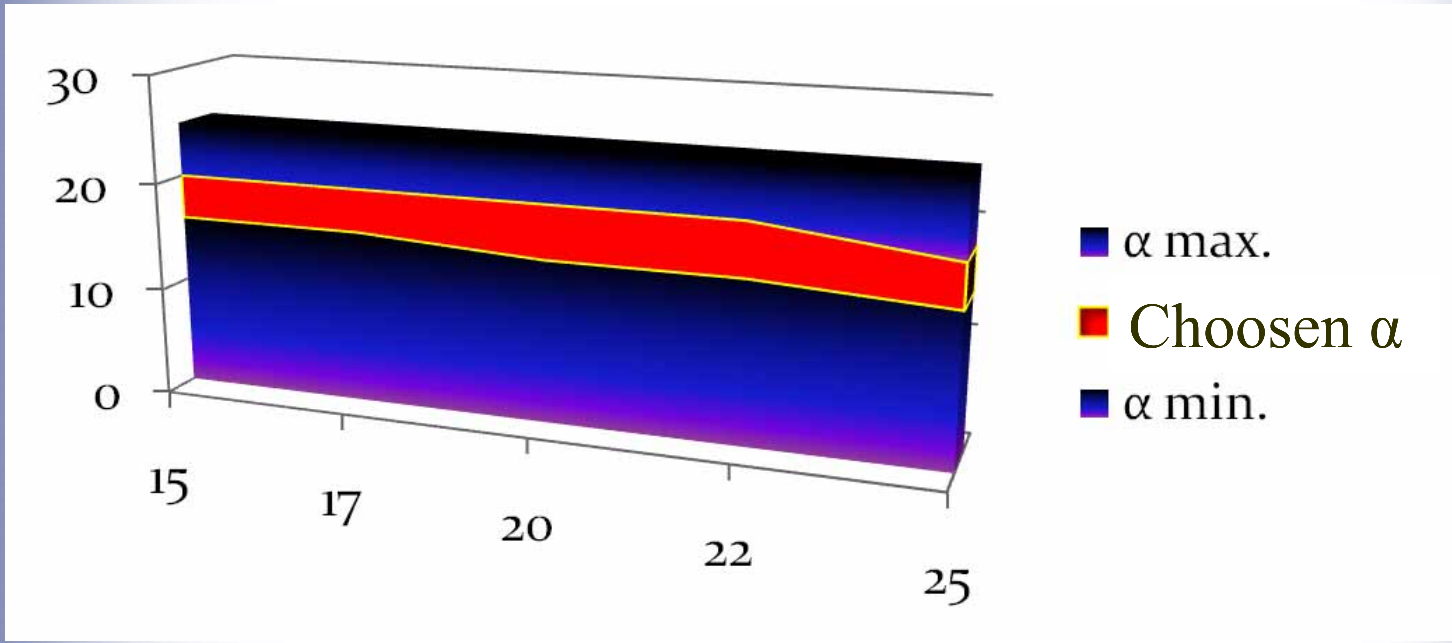
Span (m)

Limitation of the girders' generatrices slope difference, $\gamma \leq 10°$ *where* $\gamma = \alpha - \beta$ *(upper slide)*

Height limitation in the apex, $h_{ap,max}$ *= 2,5m (bottom right)*



II. Limitations in geometry



Span(m)

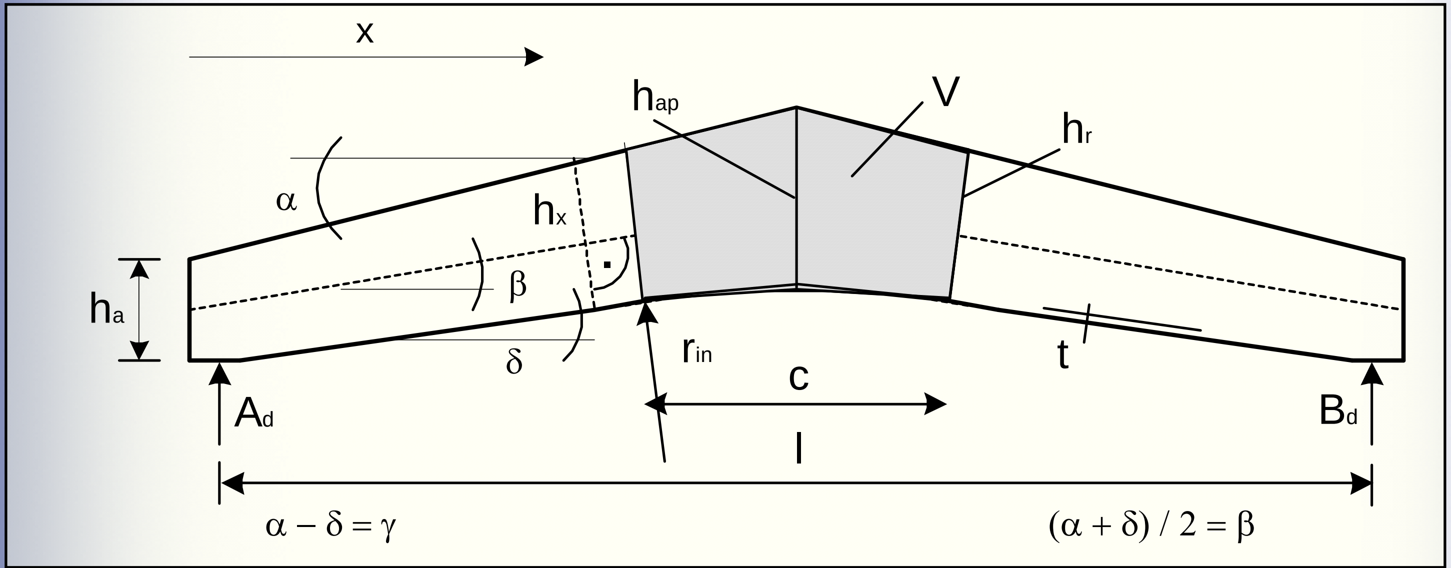
Limitation of extrados slope (a) –rational spans:
L = 15 – 25 m

II. Conclusion

For the above described cambered beams the vital bearing capacity is proofed for tension perpendicular to grains in the apex, especially when there are greater slopes by EC5 and FEA.

By connecting the stress lengths perpendicular to grains obtained from EC5 and FEM we get to the difference in the distribution and values of the results, which is confirmed by the connection with the slope. Both design methods include conforming to the stress increase trend, but not with the stress magnitude. The design of pitched cambered girders is not rational on the L > 25m spans. The better solutions present the curved girders (L < 30m) or the full replacement of static system.

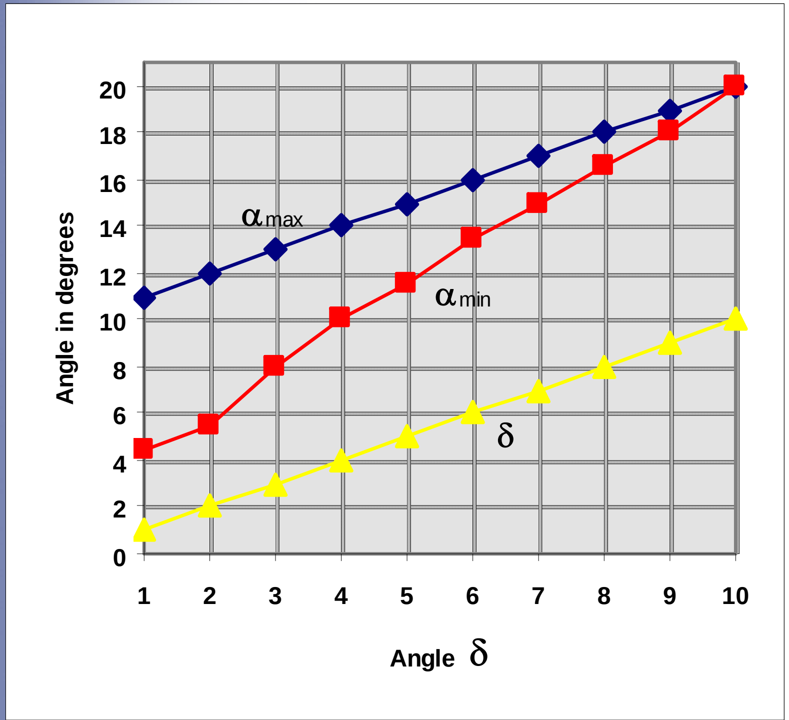
III. PARAMETRIC ANALYSIS OF SLOPE EFFECT AND GEOMETRY OF GLULAM PITCHED CAMBERED BEAMS



Variables for parametric modelling

Three different spans are analyzed:
10, 15, 20, 25 and 30 meters.

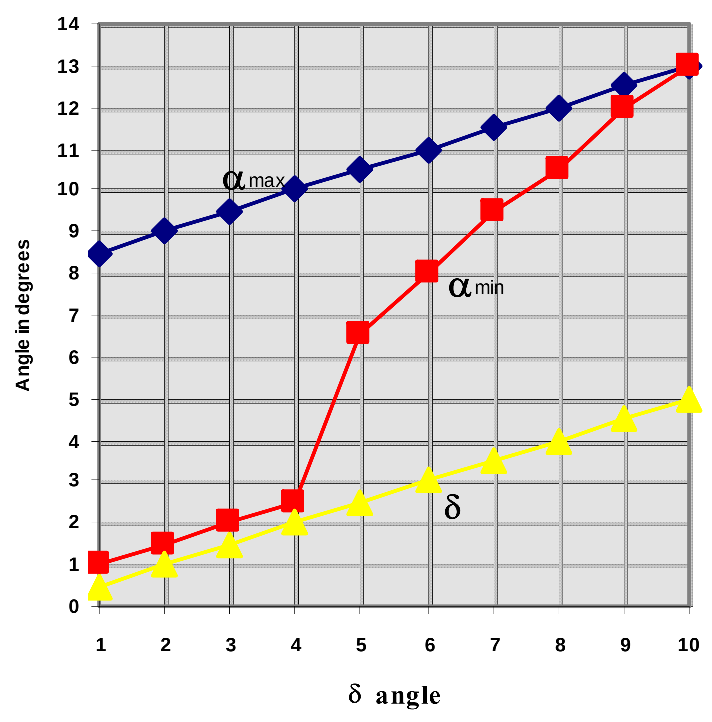
III. PARAMETRIC ANALYSIS OF SLOPE EFFECT AND GEOMETRY OF GLULAM PITCHED CAMBERED BEAMS



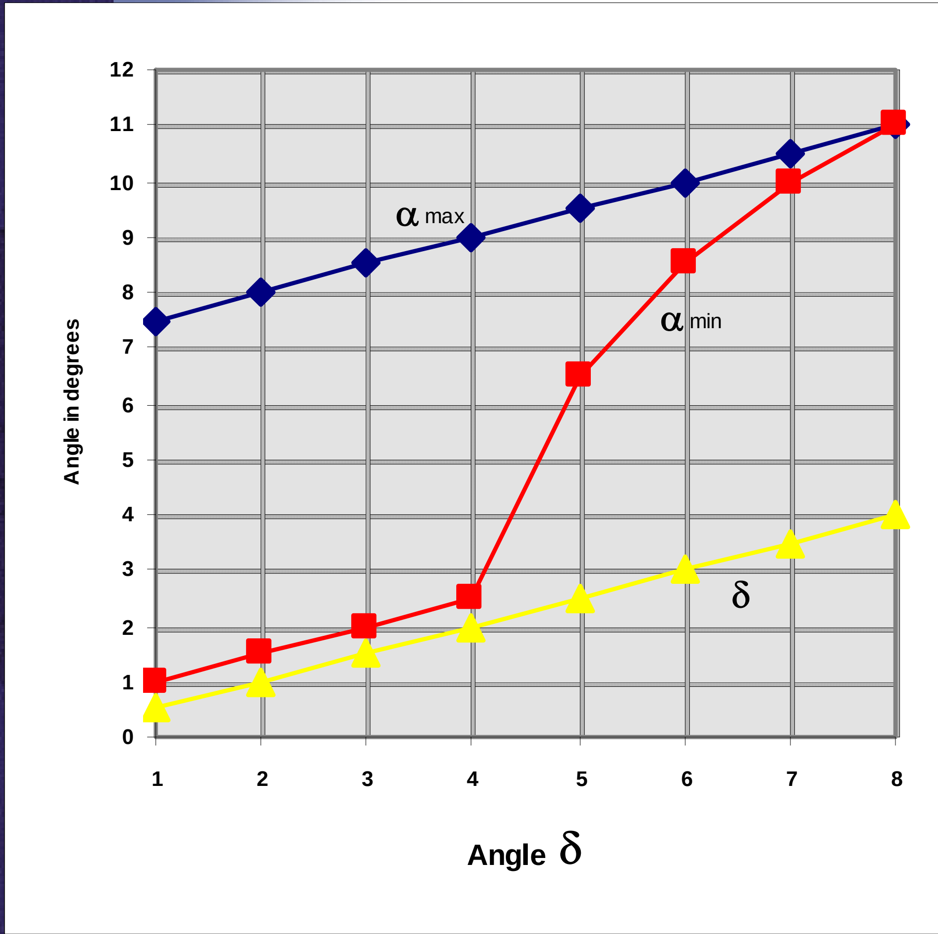
a) Span: 10 meters

In this table all date is for h_a=300 mm and curvature length (C) is 3 meters. Increasing ha up to 400 mm and curvature length (C) to 4 meters, angles rose up to: **α**max =22°**,** **α**min =21,5° and **δ**=12°

b) Span: 25 meters



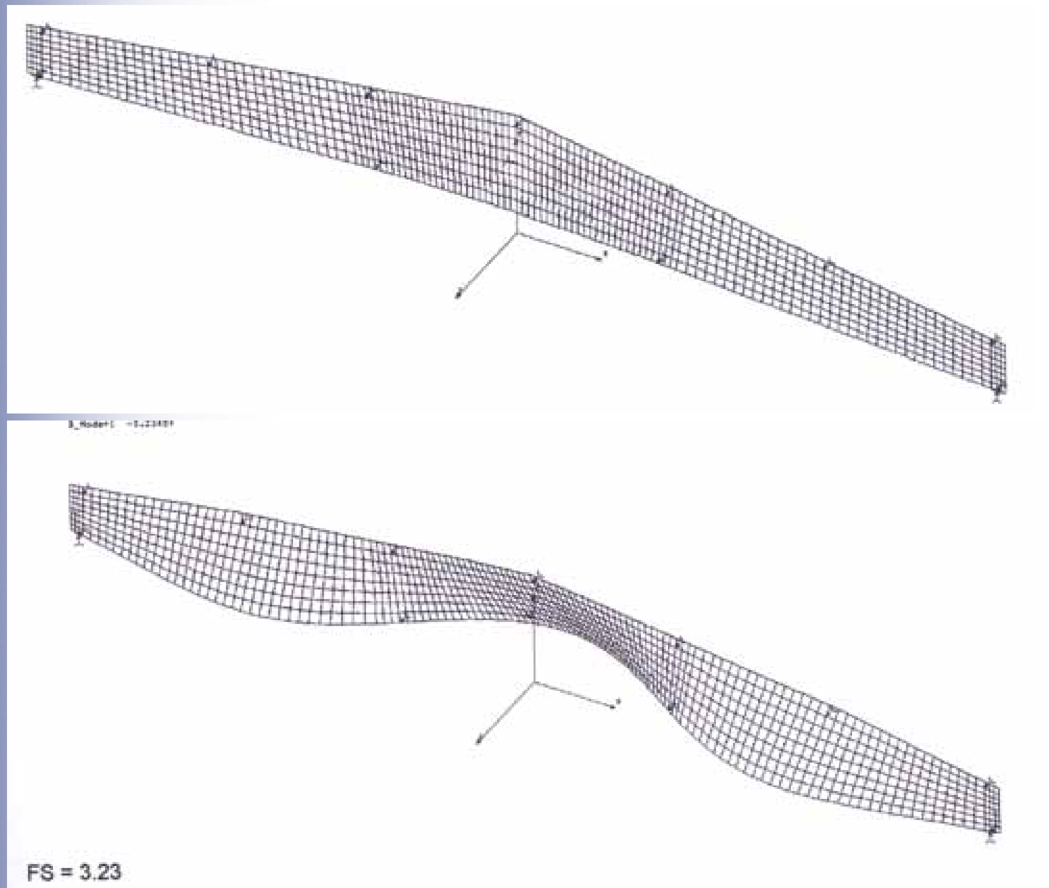
α_{max}	α_{min}	δ	$\gamma_{min} = \alpha_{min} - \delta$	$\gamma_{max} = \alpha_{max} - \delta$	r_{in}	h_{ap}
8,5 °	1°	0,5 °	0,5 °	8 °	515,70 m	1,33 m
9 °	1,5 °	1 °	0,5 °	8 °	257,80 m	1,35 m
9,5°	2°	1,5°	0,5 °	8 °	171,90 m	1,37 m
10 °	2,5 °	2 °	0,5 °	8 °	128,90 m	1,39 m
10,5 °	6,5 °	2,5 °	4 °	8 °	103,20 m	2,18 m
11 °	8 °	3 °	5 °	8 °	86,00 m	2,42 m
11,5 °	9,5 °	3,5 °	6 °	8 °	73,70 m	2,67 m
12 °	10,5 °	4°	6,5 °	8 °	64,50 m	2,80 m
12,5 °	12 °	4,5 °	7,5 °	8 °	57,40 m	3,05 m
13 °	13°	5 °	8°	8 °	51,60 m	3,19 m



				$\gamma_{max} = \alpha_{max} - \delta$	r_{in}	h_{ap}
				7 °	573,00 m	1,70 m
				7 °	286,50 m	1,73 m
				7 °	191,00 m	1,75 m
				7 °	143,30 m	1,77 m
				7 °	114,60 m	2,71 m
10 °	8, °5	3 °	5,5 °	7 °	95,50 m	3,13 m
10,5 °	1 °0	3, °5	6,5 °	7 °	81,90 m	3,43 m
11 °	1 °1	4 °	7 °	7 °	71,70 m	3,59 m

c) Span: 30 meters

RESULTS OF FEM ANALYSIS



Bucking of girder

III. Conclusions

- Biggest problem concerning glulam pitched cambered beams are tensile stresses perpendicular to grain.

- For spans between 10 to 20 meters tensile stresses are not crucial for design. As the span increases (20 -30 meters) these stresses are becoming more problematic and therefore crucial for design. It must be noted that stresses parallel to grain are very low, effectively meaning that beam in not fully utilized.

- Very small changes in angles results in big height increase. Beams with spans larger than 25 meters (25-30) have additional stability problems due to bucking in tensile zone. This analysis suggest that glulam pitched cambered beams are most efficient for span range 10-20 (maximal 25 meters).

Questions to disscuss:

- Size effect of the girder of special shapes => effect the results very much?
- What was the sizes of the girders tested while working on EC5?
- Cost benifit of using reinforcement with (FRP, aramid glass fibre or similar)?

Thank you for your attention !!!