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

Bjelanović, Adriana[1*], Pavlić, Vedran[2], Rajčić, Vlatka[3]

[1] *Faculty of Civil Engineering; Rijeka, Croatia, adriana.bjelanovic@gradri.hr*
[2] *Student of Faculty of Civil Engineering; Rijeka, Croatia, vedran.pavlic@gmail.hr*
[3] *Faculty of Civil Engineering; Zagreb, Croatia, vrajcic@grad.hr*

ABSTRACT: This paper represents a part of diploma work[2] in the scope of glued laminated girders of special geometry. It also shows results of previous research[1, 3] engaged in the field of timber (material and structural design) and FEM. The main subjects of our 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. Wood is an anisotropic material whose tensile strength perpendicular on grains is far below the rest of its material properties. Therefore, we must deal very seriously with the safety of the curvature zone of girder, where these stresses appear. EC5 makes some simplifications that are acceptable enough in engineering practice. We tried to compare the results obtained using different codes and FEA.

KEY WORDS: glulam pitched cambered main girders, curvature, structural safety and practical design, comparison of European codes, analysis of parametrically prepared FE models

1. INTRODUCTION

From the aspect of architecture, pitched cambered glulam beams of great intrados curvature are aesthetically very attractive and desirable shapes of main girders. On the other hand, from structural and technological view, the complex geometry of those girders is a potential limit to their economic application. A big intrados curvature in the ridge zone, non linear distribution of stresses along the cross section's width, and both a complex state of stresses caused by girders' geometry and anisotropy of wood as a material make it necessary to handle carefully the calculation of those girders. As for their mechanical resistance and stability, the study of tensile strength perpendicular to grains intensified by curvature is of enormous significance. The bearing capacity of wood in regard to tension perpendicular to grains is exceptionally low and varies significantly from its other mechanical properties. It is therefore hard to optimize the dimensions of those girders according to this criterion as its other characteristic cross-sections are not enough used. 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. 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. We compared the results with those of the calculation according to pre-norms, DIN ENV 1995:2000-1-1. The proofs for mechanical strength and stability of the characteristic section x-x relevant for the stability control differ in the norm and pre-norm. 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. The expressions for dimensioning (norms) by a series of coefficients transform the non linear stress distribution with respect to the height of the cross-section into a linear one, and a complex stress state transforms into bending stresses. FE analysis done in COSMOS/M package reflects a real state of stresses and deformations.

Therefore, we wanted to investigate whether, and to which extent are the practical proofs of mechanical strength and stability on the side of safety. The paper addresses just a small part of research deals with investigations in the field of limits of suitable geometry on certain spans.

2. DESCRIPTION OF METHODS INCLUDED IN RESEARCH

The constants in the calculation are as follows:

1. Mechanical properties (strength, stiffness and density modules) of comparable classes of laminated wood with high bearing capacity and of 1st serviceability class – BS 28H (DIN ENV 1052:2000) made from structural timber S13, and GL 28H (EN 1995:2004) made from structural timber C30 class.
2. The 5,0m distance of main girders and characteristic load of 1,25kN/m^2 as a short - term action. The total value of the constant action has been estimated to be 0,7kN/m^2.
3. 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):

1. 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, α and β, their divergence, γ, L girder span, chord length on the C_{in} 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, h_a 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.
2. The Excel programme package has been used for limiting the input parameters values (α,β,γ,L,C_{in}, h_a, 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».
3. 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).

2. PARAMETRIC DESIGN PROCEDURE OBTAINED IN ACCORDANCE WITH EC5 CODES

The calculation's procedure diagram shows the ways in which the girder's calculation and the analysis of design's rationality along with the construction of related girders were conducted. The paper presents the required stages to dimension accurately and rationally the girder (pitched camber and/or curved girder of high intrados curvature). The girders are simple static schemes (freely leaning beams), and the curvature is in the limits of $2 \leq R / h_{ap} < 10$, tj. $0,1 \leq h_{ap} / R < 0,5$. The design of these girders is technologically far more complex as the axis in the ridge zone is designed by inserting the short radius curve. The number of phases and the mode of gluing the plates affect the static height and the bearing capacity in the ridge zone (full or reduced cross-section of pitched cambered girders). However, the height in the ridge exceeds 3,0m of the production hindrances (the limit value is here restricted to 2,5m). The curved area's volume limitation is 2/3 from the total girder volume. The biggest transversal slope of these girders limits to the value ≤ 25°. There is also an additional limitation related to the value difference $\alpha - \beta \leq 10°$ for the pitched cambered girders, the cross-section height of whom changes due to varied slope angles of extrados (α) and intrados (β). Such a condition results from the fact that the plates are, generally laid parallel with one of the girder's generatrices. Therefore, the effect of oblique slashed edge appears on the opposite generatrix. The unsuitable effect that oblique weakening has on the values of components of complex stress state gets modified by limiting the generatrices' slope difference.

In the practice, the shapes of laminated pitched cambered girders of curved intrados can be constructed so that their static cross-section height in the ridge zone gets reduced (fitted apex), whereas the constant remains (concentric curvature). In the zone where the girder's axes the straight line's height of girder's cross-section can be either changeable or constant. Due to the reduction of static height in the ridge zone they are treated as curved girders.

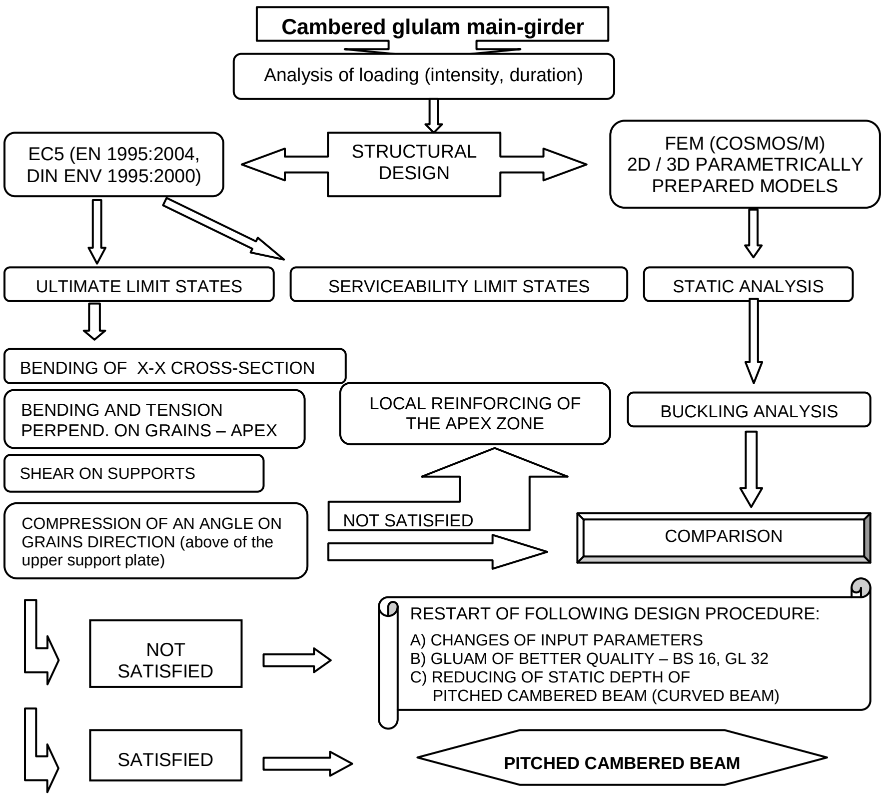
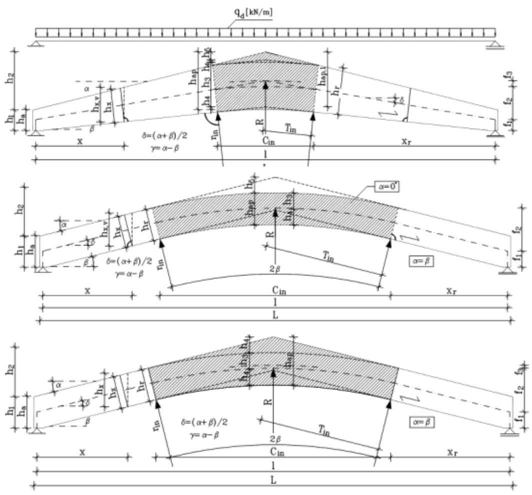


Fig. 1 *Flow-chart of design procedure and parametric analysis*



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

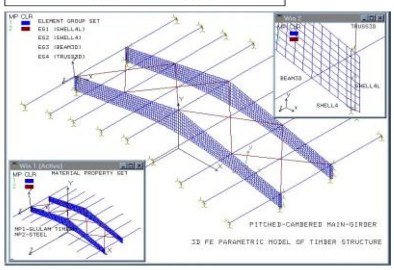
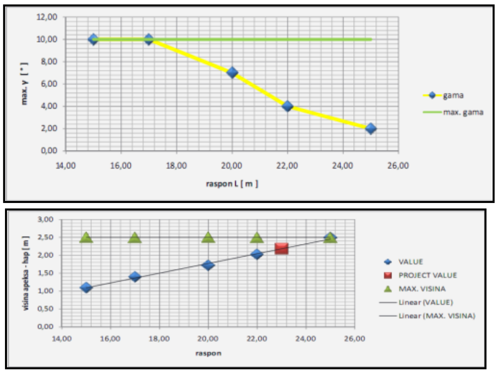
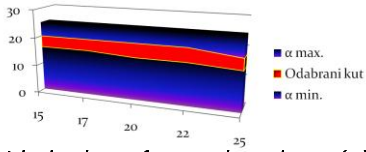


Fig. 2 *Pitched cambered beams and curved beams (cambered beams with non-glued apex – reduced static depth of cross-section) on left. 3D parametrically prepared FE models – SHELL4L (girder), BEAM 3D (purline),TRUSS 3D (bracing diagonals) and PLATE FE (just for upper support plates) on right.*





Limitation of extrados slope (α) –right on rational spans: L = 15 – 25 m (top right)

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

Height limitation in the apex, $H_{ap,max} = 2,5m$ (bottom left)

***Fig. 3** Input parameters, values of limitations and obtained results*

The comparison of the design according to ENV and EN does not show major differences in the utilisation and safety. The difference in the value of partial coefficients for material (γ_M = 1,25 according to EN or γ_M = 1,3 according to DIN ENV is negligible). As far as the calculations are concerned, the only difference relates to the treatment of the characteristic cross-section x–x on the girder's flat part, where the difference in the cross-section utilisation (bending and stability), in the notched extrados is 30% – 36%, and the calculation according to EN 1995-1-1:2004 (eq. 1, 2) is on the safety side in relation to DIN ENV 1995-1-1:2000 (eq. 3,4). The difference in the utilization of cross-section x– x on the lower flat intrados is little and amounts some 15%. The comparison with FEA shows that the impact of longitudinal force (visible in FE models) for the girders with a usual bearing combination (unmovable and movable) is negligible. Therefore, the simplifications applied in the norms are practice related and acceptable from the engineering point of view, in laboratory research and the theory of anisotropic plates. The cross-section positions x – x with the highest stress from bending, comparing FEA and EC5 are not the same.

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

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

$$\sigma_{m,d,\gamma} = (1 - 4\,tg^2\gamma) \cdot \frac{M_{x-x,d}}{W_{x-x}} \leq k_{m,\gamma} \cdot f_{m,d} \quad (3)$$

$$k_{m,\gamma} = \frac{1}{\frac{f_{m,d}}{f_{c,90,d}} \cdot sin^2\gamma + cos^2\gamma} \quad (4)$$

4. CONCLUSION

For the above described cambered beams the vital bearing capacity proof for tension perpendicular to grains in the apex, especially when there are greater slopes. 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.

5. REFERENCES

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