NUMERICAL AND EXPERIMENTAL INVESTIGATION ON WOODEN PROFILES WITH FIBER CONFINEMENT

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Abstract
A procedure to manufacture wooden profiles, in which thick solid panels of compressed wood are transformed to open or closed prismatic cross sections, has been developed and patented. This manufacturing principle may be applied to a wide variety of sections: all open and closed prismatic cross-sections may be produced in a continuous manufacturing process The resulting profile encompasses efficient use of the material and optimal structural performance. An outer reinforcement of Fibre Reinforced Plastics has been proposed, to improve even more its mechanical properties. Numerical and analytical models have been developed to analyse the behaviour of fibre reinforced wood tubes. An extensive parametrical analysis has been accomplished. In this paper, the results from both models are compared, and their relative performance according to the different geometrical features assessed.

1 Introduction
Though usually regarded as the oldest structural material used by mankind, many technological changes have modified the way wood is used in construction. The growth of the population, inequality between industrialized and developing countries as well as the release of carbon dioxide in the atmosphere, which is supposed to contribute to a global climatic change and to the greenhouse effect, provide guidelines for socio-economical decisions. It looks plausible that the future design objectives will be more and more determined by the need of a sustainable economical development in a global world, where resources such as raw materials and fossil energy are limited. This future scenario will influence the way timber is used in construction, as well. Therefore, an efficient and optimum use of renewable materials, such as wood, will become increasingly important.

As pointed out previously [1], the forest is not considered as producer of material but of cross sections. But it is indeed, not only one of the greatest but also one of the cheapest producers of material in the world. As explained in [1], several disadvantages have prevented the use of wood for technical applications, namely:

- its low strength spectrum when compared to other structural materials,
- its anisotropy (the directional dependence of the mechanical properties), and
- its low biological resistance (in particular, of some softwoods frequently used for structural applications).

Figure 1. Wooden formed tube.

From those thoughts, a procedure of manufacturing wooden profiles has been developed and patented [1]. The resulting profile encompasses efficient use of the material and optimal structural performance. Wood is compressed in its transverse direction up to 50% of its original size by folding its microstructure. This is a reversible process and the principle of this innovative process, where thick solid panels of compressed wood are transformed to open or closed prismatic cross sections (Figure 1). This manufacturing principle may be applied to a wide variety of sections: all open and closed prismatic cross-sections may be produced in a continuous manufacturing process.

An additional fibre reinforced plastic (FRP) glued to the outer surface of the profile might be required to strengthen the wood [1]. Thin walled profiles are prone as well to develop longitudinal cracks due to shear and tensile stresses perpendicular to the grain. Load adapted FRP reinforcement can avoid brittle type failures of the profiles. Both materials benefit: wood profits from the outstanding mechanical and physical characteristics of FRP, while FRP does it from the mechanical characteristics and the low price of wood as well as its environmental friendliness. Wood profiles are well suited for the use in lightweight structures, the classical field of FRP composites. The use as a permanent winding core can help to reduce manufacturing costs. The wooden core will eliminate local buckling effects and strengthen the FRP profile in axial direction.

The presented research work deals with the developed analytical and numerical models for wooden tubes confined with glass-fibre-epoxy composite subjected to simple axial compression loading. The paper will briefly describe both models, the developed parametrical analysis and its corresponding results.

2 Developed models and experimental campaign

2.1 Analytical model

An analytical model to obtain the failure stress of fibre reinforced wood tubes has been developed [2]. Herein, a brief explanation of the developed analytical model is given. Further explanations may be found in [2] or [3]. The model is based on the Classical Laminate Theory (CLT), used in combination with Tsai-Wu failure criteria for both wood and fibre reinforcement.

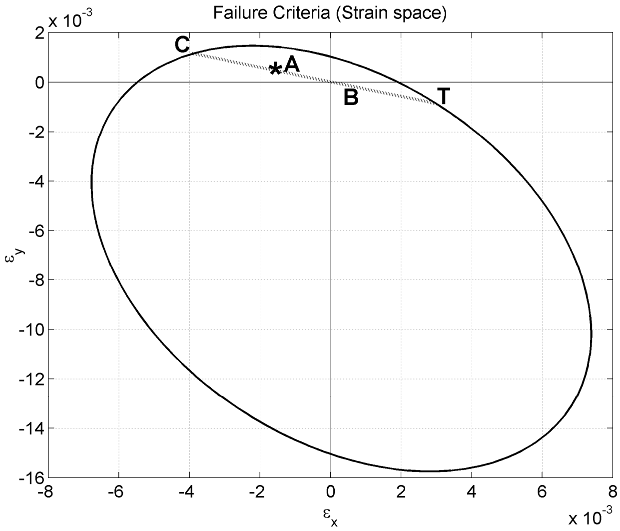


Figure 2. Graphical application of the analytical model

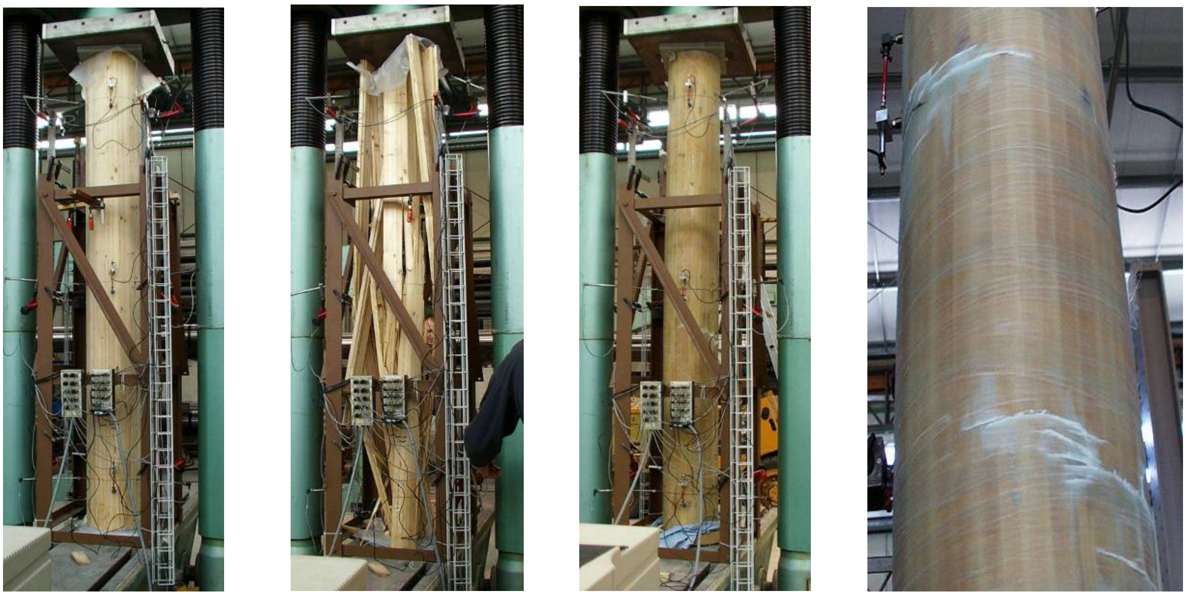
Figure 2 depicts the proposed algorithm in a graphical way. In the strain space, the Tsai-Wu failure criterion of the layers of a composite material is plotted. A known strain state may be easily plotted, since both coordinates are known, as point **A**. It is assumed that for this strain state, the corresponding stress state is known as well. If no residual stresses are assumed, consequently the initial unloaded strain state of the laminate corresponded to zero strains (origin point, **B**). Since the present laminate is room temperature cured, it seems reasonable for this particular application. If a linear behaviour of the material is assumed, it is represented by a line connecting points **B** (no load applied) and **A** (given stress state).

If proportional loading and elastic response is assumed till material failure, the response line, **AB**, may be extended until its intersection with the failure criteria envelope, point **C**. This would correspond to the failure strain state of the laminate when First Ply Failure is assumed. Since the failure strain state is known, and proportional loading is assumed, the corresponding failure stress state may be obtained.

The above described deals only with the material resistance of the wood-fibre composite. Additionally, buckling formulae have been used, namely ring and chessboard local buckling modes and global buckling. Employed formulations are those proposed from Michaeli *et al.* [4].

2.2 Numerical model

The commercial software package ANSYS [18] was used for the numerical model. The structural tubes were modelled via the solid element SOLID46, which is a layered version of the 8-node structural solid designed for layered thick shells or solids. The element is defined by layer thicknesses, layer material direction angles, and orthotropic material properties. In the case of the reinforced tube, twelve layers were used: ten of them correspond to the wood material, two to the FRP reinforcement (one for each ply of the composite). Both wood and composite reinforcement are considered orthotropic in the plane of the element. For both materials linear-elastic behaviour was defined.



(a) (b) (c) (d)

Figure 3. Failure modes of unreinforced and composite reinforced tubes: (a) REF before testing, (b) splitting of REF, (c) local buckling of tube CR85 and (d) detail of CR85 – crushing of wood and glass fibres.

In order to account for imperfections, an initial deformed geometry was assumed. As described in [3], instead of applying a force (whose magnitude must be properly calibrated and validated), an initial deformation was applied. The buckling modes of the unreinforced tube are employed as the initial deformed pattern: both first global (Euler) and local buckling modes. They are conveniently scaled so that their maximum deformation corresponds to 1/2000 of the tube length. These buckling modes provide the seed so the numerical model (which would be geometrically perfect if they were not applied) behaves in a more realistic way. Additionally, the same model is able to reproduce both local and global buckling modes and, consequently, the subsequent parametrical analysis is greatly simplified.

The Tsai-Wu failure criterion was used to assess the possibility of failure of the materials and to predict the failure load of the tubes. Failure load is reached when the corresponding "strength ratio" is greater than unity. In the commercial packages, sich as ANSYS, failure criteria are regarded as design criteria: they do not modify the structural behaviour. They are evaluated after the analysis has been completed, in the post-processing phase. As a main consequence, the results do not provide the exact point of failure, but an approximate point. The resulting Strength Ratio may be used to obtain a more accurate approach to the failure load.

2.3 Experimental campaign

Figure 3(a) shows the specimen geometry and an unreinforced tube in the test machine. The tests were conducted under axial compression loading according to the German Standard DIN EN 408. The columns had different end support conditions. The base was set on a non-rotating steel support, while the upper plate was pinned.

Several tubes, unreinforced reference specimens (REF) and composite reinforced tubes (CR) with a slenderness ratio of 28 were tested. The relatively thin walled tubes (tW = 18 mm) with a length of 2.5 m have a self-weight of about 30 kg, plus 3.9 kg composite reinforcement. The thickness tF of the composite layer was 1 mm. The glass-fibre yarns wound around the tube were oriented in an angle of ±45° (CR45) and ±85° (CR85) to the column axis. The weight per area of the glass-fibres was about 900 g/m2.

The unreinforced tube exhibited brittle failure (see Figure 3) at a load level of 685 kN - equals to a compression stress of 47.3 N/mm2. The test results of the reinforced columns demonstrate that load-carrying capacity and ductility were enhanced by means of composite reinforcement. In average the reinforced tubes reached a maximum load of 1000 kN - equals to a compression stress of 65.2 N/mm2. The highest loads were achieved for the columns with 85° glass-fibre orientation (CR85). The ductility of the CR85 tubes was determined to 1.08, while the CR45 tubes behave more ductile reaching a ductility of 1.35. When compared to the reference, the load-carrying capacity of the reinforced columns increased by factors of 1.46 and 1.22, respectively. In regard to the stiffness the presence of reinforcement is negligible.

Due to Poisson's effect, the diameter of the tubes increases under axial compression. This expansion results into tensile stresses in the tangential direction. In contrast to the reference, no brittle failure was observed for the reinforced columns. In both cases, CR45 and CR85, failure was due to the exceeded compression strength of wood resulting into a local buckling failure mode.

The tests were used to validate the previously described analytical and numerical models. The validation process is described in more detail in [3].

3 Parametrical analysis

A parametrical analysis is in progress. Up to the moment, 2 176 different analyses have been done. The following geometrical properties are being analysed, to assess their influence on the tubes' behaviour:

- wood thickness (*tW*): 10-15-20 mm;
- fibre reinforcement thickness (*tF*): 1-2 mm
- angle in relation to the wood fibre direction of the cross-ply fibre reinforcement (*oF*): 0, 15, 30, 45, 60, 75, 90;
- length of the tube (*h*):1 000-10 000 mm, every 250 mm;
- external diameter of the tube: 100, 200, 300 mm.

The parametrical analysis is carried out by means of an automated procedure, which allows saving a considerable amount of time. The model with the appropriate geometrical parameters is automatically launched and analysed, and when concluded, it automatically processes the failure load. Only a few files in txt format, which account the complete results for each layer are kept, so the memory of the computer does not get overloaded, and the process is able to continue without memory flows.

3.1 Results comparison for both models

A comparison between the failure loads according to both previously presented models (analytical –Sect. 2.1- and numerical –Sect. 2.2-) is presented. In Figure 4, a global

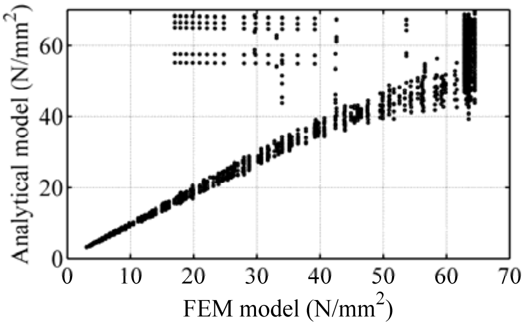


Figure 4. Analytical failure stress vs. numerical failure stress.

comparison between both models is plotted, where it may be seen that, exception made of some outliers (to be analysed in detail in the future), both models quite agree.

3.1.1 Model performance in relation to the height of the tube

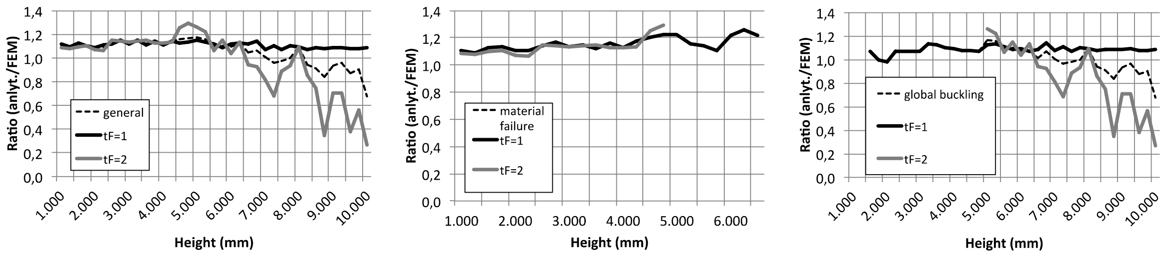
Figure 5 plots the ratio between the failure loads of the analytical and numerical models, for two thicknesses of the fibre reinforcement, 1mm (tF=1) and 2 mm (tF=2). The analytical model slightly over predicts the failure load for all the analysed height range (Fig 5a). However, the analytical model performs worse when the fibre reinforcement increases, and clearly under predicts the resulting failure load.

In those cases dominated by the material failure (Fig 5b), the analytical model [2] performs quite similar up to a height of 4 metres, with a mean error close to 10%. When global buckling occurs (slender tubes), the buckling formula [4] predicts the buckling load quite well for the 1 mm fibre reinforcement, but under predicts in the case of the 2 mm.

Fig. 6 depicts the same results, but in this case, series related to the wood thickness are considered. As previously, it may be seen in Fig 6a how the analytical proposal predicts in quite a constant manner up to a height of about 6 metres, and from then on under predicts the numerical results. That divergence in the results is mostly due to the buckling formula when applied to a wood thickness of 10mm (Fig. 6c). The analytical model performs quite well for the 20mm wood thickness: it slightly over predicts the failure load, but its mean error is usually lower around 10% (Figs 6b and 6c).

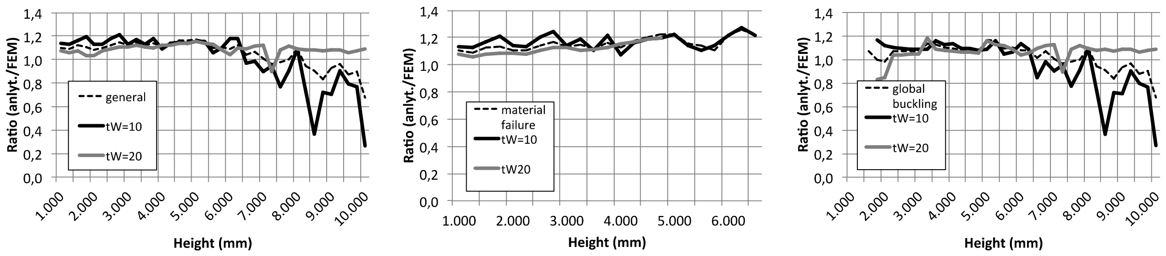
3.1.2 Model performance in relation to the orientation of the fibre reinforcement

Fig. 7 plots the ratio between both models' failure loads in relation to the fibre orientation (being 0º when placed in the direction of the wood grain). A two layered cross-ply is considered in this part of the study. The mean ratio between both models is quite similar for all the considered fibre orientations.



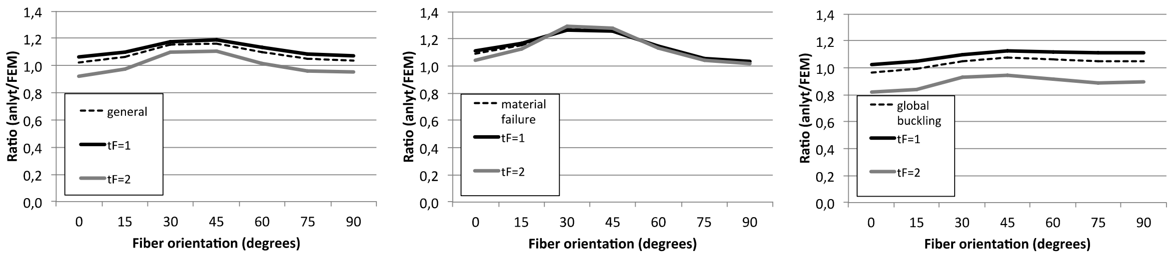
(a) (b) (c)

Figure 5. Ratio between the failure load of the analytical and numerical models in relation to the tube height. Fibre thickness series. All considered cases (a); material failure (b) and global buckling dominated (c).



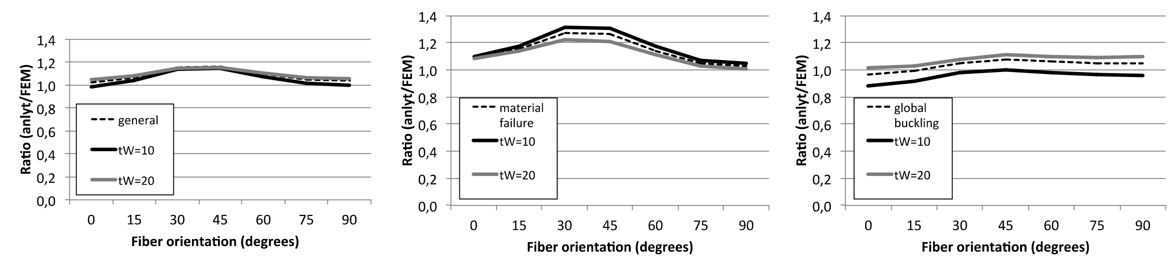
(a) (b) (c)

Figure 6. Ratio between the failure load of the analytical and numerical models in relation to the tube height. Wood thickness series. All considered cases (a); material failure (b) and global buckling dominated (c).



(a) (b) (c)

Figure 7. Ratio between the failure load of the analytical and numerical models in relation to the fibre orientation. Fibre thickness series. All considered cases (a); material failure (b) and global buckling dominated (c).



(a) (b) (c)

Figure 8. Ratio between the failure load of the analytical and numerical models in relation to the fibre orientation. Wood thickness series. All considered cases (a); material failure (b) and global buckling dominated (c).

As shown, the performance of the analytical model for the material failure [2] is not the same for all the orientations. The analytical model over predicts the strength of fibre angles from 30º to 60º (Fig 7b). This trend is the same for both analysed fibre thicknesses. The global buckling formula [4] performs quite similar for all the orientations (Fig 7c). However, it under predicts the failure load for thicker fibre reinforcements, and performs quite well for thin reinforcements.

Quite similar conclusions may be drawn when the wood thickness is considered (Fig 8). The material failure formula [2] over predicts the same angle range (Fig 8a), and performs quite similar for both studied wood thicknesses. For the global buckling dominated cases, the analytical model behaves in a similar way for all the analysed orientation angles (Fig 8b).

4. Conclusions and future work

Numerical and analytical models have been applied for the failure load analysis of fibre reinforced wood tubes. An extensive parametrical analysis has been accomplished. In this paper, the results from both models have been compared, and their relative performance according to the different geometrical features assessed:

- The material failure model developed in [2] predicts the failure loads given by the numerical model in quite a constant trend. There is a slight over prediction, but the mean error is usually around 10%. It is not sensible to the thickness of both wood and fibre layers. A slight effect of the fibre orientation is seen for those fibre reinforcement angles close to 45º.
- The global buckling formula proposed in [4] performs poorly for slender tubes with moderate thick fibre reinforcements or thin wood layers. However, it shows no influence of the fibre reinforcement in the quality of its predictions.

The herein presented parametrical analysis is an on-going study, which has not been yet concluded. Additionally, future work should include analytical procedures that take confinement into account, in order to assess its suitability for this kind of structures and materials.

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