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Technical Report

Structural design of a composite bicycle fork

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ABSTRACT

Despite the wide literature on the mechanical behaviour of carbon/epoxy composites, it is rare to find practical methodological approaches in finite element design of structural components made by laminate layup. Through the case study of a special bicycle fork needed in a Student Team prototype, this paper proposes a simplified methodology as starting point for educational and manufacturing purposes. In order to compare two manufacturing solutions in terms of stiffness, strength and failure mode, a numerical model was implemented. Since the project requirements imposed to avoid standard destructive testing, the model validation was based on *a posteriori* linear stiffness comparison with the manufactured component. The slight discrepancies between experimental and numerical results were discussed in order to check their origin and to assess the reliability of the model. The overall methodology, even if complain with only a part of the safety standard requirements, shows to be reliable enough and can be the basis for further extension and refinement.

1. Introduction

The growing demand of lightweight structural components in transportation and sport industries has determined the success of carbon fibre composites. In particular, the production cost of carbon/epoxy products has lowered in the last decades in a virtuous circle with the market expansion. The market diffusion of carbon fibre composites in sport equipments and in particular for cycling is still leading the cost lowering process [1–3], but sometimes with drawbacks on quality and safety. As the recent introduction of standard testing requirements for such products has provided a guideline for manufacturers, the development of methodologies for pre-production analysis through numerical models is the key for a better approach to design and for cost reduction of pre-series testing. However, despite the wide academic literature about the mechanical behaviour of carbon/epoxy composites, it is rare to find practical methodological approaches in design and finite element analysis (FEA) of composite structural components.

In the present paper a case study is discussed: the need for a non-standard size front fork in a Student Team prototype has given the chance to design, build and test a component made by composite material. Two special requirements with respect to the available commercial forks were leading to the need for a specific design and manufacturing:

- to fit a small 20" wheel of 471 mm at the rolling diameter;
- to fit the traction hub for a front-wheel-drive, with a dropouts width of 135 mm instead of the usual 100 mm in commercial front forks.

In addition, the entire process was constrained by the need for non-destructive testing on the manufactured prototype in order to use the same component in a racing event, due to both time and budget limitations.

While there is a consolidated industrial experience in the production of such components, no trace of a shared methodological approach for their design was found in literature by the authors. At least, some specific aspects of structural composite design or manufacturing are discussed in literature. In [4] a pioneer approach to FEA of bicycle monocoque frame made by composite is presented. In [5] an experimental analysis on fatigue and impact behaviour of a composite fork points out the importance of a quality check on manufacturing anomalies. Looking at other bicycle components, in [6] both theoretical and experimental approaches are used to estimate the deformation and 1st-ply failure load of an asymmetric laminate composite handlebar, while crank design methodologies are proposed in [7,8]. A Pareto multi-objective optimization is applied to design a special composite seat post for cycle-ball bicycles in [9]. From this point of view, the FEA proposed hereafter could be helpful in establishing the behaviour of the ideal component and in setting the acceptance threshold through non-destructive mechanical testing. In [10] the optimal fibre direction

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and stacking sequence for a carbon/epoxy bicycle frame is found through FEA under different loading conditions.

Moving away from the bicycle related topics, some useful information about FEA of composite parts can be found in [11], where the problem of numerical artefact local stresses is discussed, while a selection of papers can provide data for fatigue assessment [12–15]. An advanced design selection methodology for composite structures is proposed in [16] and applied to a case study in [17] by taking into account a wide number of design and manufacturing parameters with respect to the need and to the design-to-race schedule of the present work.

A design, analysis and validation procedure is presented hereafter in order to provide a practical fast methodological approach for similar design-to-race conditions, with application in educational engineering projects and with possible extension to industrial preliminary prototype design.

2. Materials and methods

The main technical requirements for road/track cycling front forks can be summarized as follow:

- adequate stiffness;
- structural resistance in static, impact and fatigue conditions;
- aerodynamic shape.

Together with the frame stiffness, the first property defines comfort and handling of the whole bike and can be designed to different targets depending on the market focus. The second requirement is the only one being imposed by specific standards such as EN 14781 [18] and subjected to mandatory safety testing for market purposes. If the aerodynamics of the fork plays a dominant role in the target product class, the shape and the cross sectional geometry of its crown and blades cannot be considered as variables for the structural design process. Given a specific aero-shape, the variables for the design engineer are local thickness and fibre orientation for each ply. This is the condition of the present case study: as in recumbent track racing the aerodynamics plays a crucial role, the CAD geometry design was driven by an iterative process focused at the best performance in computational fluid dynamics (CFD) analysis of the fork, with the only imposed constraint of 13 mm minimum width for the fork blades given by a first approach estimation of the required lateral stiffness. The CAD model is shown in Fig. 1.

2.1. Finite elements modeling

Starting from the CFD-optimized CAD geometry, a FE model was created with the commercial code HyperMesh®. The fork was discretized with about 450.000 2nd order elements and 580.000 nodes. The aluminium machined dropouts at the fork end (Fig. 2c), were modelled through TETRA10 solid elements, while the composite structure of crown (Fig. 3a), head-tube and blades was meshed with TRIA6 shell elements.

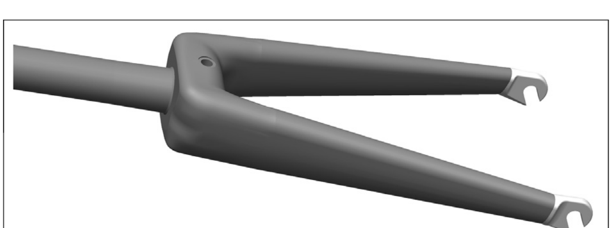

Fig. 1. CAD model of the fork.

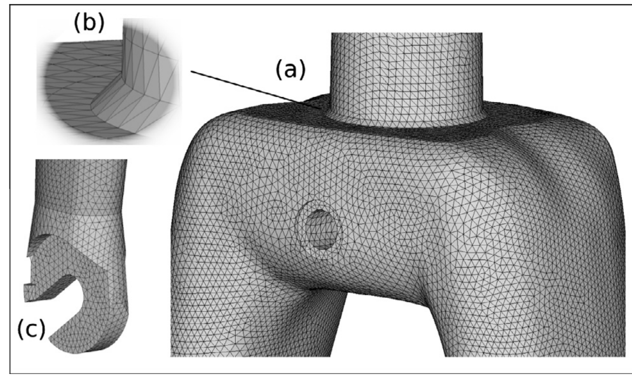

Fig. 2. FE model: fork crown (a), chamfer detail (b), dropout (c).

The extremely small local curvature radii of less than 0.5 mm at the boundary between the head-tube and the fork crown was neglected. However, in order to avoid numerical artefacts in stress concentration [11], a $0.5 \times 45^{\circ}$ chamfer was modelled as detailed in Fig. 2b.

In order to evaluate the possibility of a simplified manufacturing process two design solutions were modelled and analysed:

A – with the head-tube passing through the whole fork crown as in Fig. 3a;
B – without head-tube prosecution inside the fork crown as in Fig. 3b.

The solution A is intended to model the traditional manufacturing process, with separated volumes in head-tube and blades and with a compact solid crown. The second design approach would allow to realize the fork by using a structural foam core inside the unique continuous encased volume. In particular, the comparison was performed to quantify the structural contribution of the head-tube prosecution into the crown in order to evaluate if it could be compensated by the crown thickness.

2.1.1. Material properties

The orthotropic materials properties (MAT8) for twill and unidirectional plies were created in order to be assigned to shell elements. A linear isotropic model (MAT1) was assigned to the dropout solid elements. Table 1 shows the material properties. The values for the composite were taken from a worldwide supplier technical sheets and referring to 120 °C curable epoxy and T700S fibre [19] as the same prepreg and conditions were available for the manufacturing process. For the design solution A, a Rohacell® structural foam was modelled through TETRA10 solid elements inside the fork.

2.1.2. Laminate layup

Eight quasi-isotropic $0^{\circ}/\pm 45^{\circ}/90^{\circ}$ laminate packages were created by using the HyperLaminate® interface in order to have different thickness (ranging from 1.56 mm up to 6.00 mm). Any package included a 45° twill ply as first and last ones for the final product aesthetic.

Four different models of the fork were simulated by iteratively increasing the thickness in the crown zone (from 2 mm up to 6 mm) until reaching a structural acceptable design with the standard manufacturing solution B. Then, the simulation was repeated with the design solution A.

The ply thickness and direction represent the most important approximation of the model as it neglects the manufacturing process anomalies such as porosity, waviness or ply drops [5]. From this perspective, the FE model represents an ideal fork and could