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Full Length Article

Conceptual design and numerical validation of a composite monocoque solar passenger vehicle chassis

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ABSTRACT

The concept of the composite monocoque chassis has been implemented in many vehicle designs; however, there is limited open literature defining the process of simulating a composite monocoque chassis. The purpose of this research is to develop a composite monocoque chassis by analysing its structural integrity through an iterative finite element analysis process with the intention of developing a lightweight solar-powered vehicle. Factors that influence this methodology include; the definition of the vehicle loading conditions, failure criteria, and important design parameters, chief among which is the torsional stiffness. The primary design criterion considered is the torsional stiffness which is determined from the application requirements and data available in the literature. The design methodology then follows an iterative process where various geometry and lay-up changes are considered. Under the same loading conditions, with the aim of increasing the torsional stiffness to achieve the required parameter. The ultimate strength of the material was also considered throughout the simulation process however, in most cases, the model failed to meet the torsional stiffness parameter before the material failure or delamination. Secondly, an analysis of the mounting points was conducted to ensure that the chassis is able to withstand the concentrated loads at the suspension mounts. This analysis is concerned with the principal stresses which gives insight into the most suitable orientation of the lay-up. The methodology presented in this paper stands to be supportive in designing a fully composite monocoque chassis for lightweight race vehicle applications.

1. Introduction

A monocoque chassis is a single piece structure with the body acting as a load-bearing member. It supports the suspension system, steering system, drive system, and other components. Effective chassis performance depends on maintaining rigidity in bending and torsion, providing efficient load absorption and reducing the overall weight of the chassis [1]. The objective of the present work is to develop a method for analyzing a composite monocoque chassis under operating conditions and to determine a structurally sound monocoque chassis through finite element analysis. The primary aim is thus to determine the feasibility of a fully composite monocoque chassis of a four-wheeled, lightweight, efficient solar-powered passenger vehicle. Complexities involved in this specific type of analysis include determining composite lay-up orientation, smart geometries for structural enhancement, and general motor vehicle safety requirements. Traditionally, due to their monocoque design, composite materials, are the materials of choice for the manufacture of solar vehicles [2]. Regarding chassis design, rigidity resistance and low weight, for handling performance, are the most important design parameters [3]. Since the vehicle is intended for solar power applications, it must be able to accommodate an appropriate solar panel array. The chassis design specifications, such as geometry constraints, were developed from the 2017 World Solar Challenge cruiser class rules and regulations [4]. The suspension mounting locations must be considered when designing a chassis. Designing a perfect suspension system for the application after the chassis has been designed could cause design complications. Consideration of the suspension systems helps depict the chassis geometry and space requirements at the wheel shrouds and mounting points [5]. A double wishbone system was selected for the front suspension due to its high handling performance and compact design [6,7]. This design has also been used extensively in other solar car designs. A trailing arm system was selected for the rear suspension due to its uncomplicated design and how well it fits into the

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aerodynamic fairing [6]. Solar team *Nuon* has experienced remarkable success with *Nuna 8*'s double wishbone front suspension and trailing arm rear suspension, winning the 2015 World Solar Challenge challenger class [8].

A monocoque offers low weight and high rigidity properties [2], which is favorable for solar car chassis design, however can be considerably more complex to manufacture. In a monocoque chassis the stress generated by the vehicle during motion is distributed throughout the structure, alleviating localized stresses [3]. The monocoque thus exhibits increased torsional stiffness and an ability to resist twisting compared to other chassis types [9]. The torsional stiffness parameter is of utmost importance regarding chassis design as it enables the front and rear suspension systems to act correctly with respect to each other. This largely affects the vehicle's handling ability, in particular, its ability to corner [10]. If a vehicle has insufficient torsional stiffness, it would twist when loaded accordingly, lifting one end of the vehicle and causing one wheel to lose traction [10].

The most common materials used in the production of a monocoque chassis are composites [11], in particular carbon fiber reinforced polymers (CFRP) and Kevlar, because they exhibit high stiffness and strength to weight ratio properties and can be formed to virtually any geometry [12]. However, there are some disadvantages, such as intricate design procedures, high cost and complex manufacturing processes [13]. CFRP monocoques offer among the highest stiffness to weight ratios, when compared to any material and chassis type combination [2]. This is the primary reason why carbon fiber composites are extensively used in solar car chassis design [14].

Existing monocoque solar vehicle chassis designs were investigated to gain an understanding of the shape and geometry features of effective designs. This knowledge was used to develop the preliminary chassis geometry, detailed in Section 7. Solar Team Eindhoven implemented a full CFRP monocoque in their 2015 World Solar Challenge vehicle, *Stella* Lux [15]. The chassis consisted of a dual-hulled, catamaran-like shroud with a tunnel underneath the chassis center, reducing the frontal area and improving the aerodynamics. Kogakuin University finished in second place at the 2015 World Solar Challenge with their solar-powered car, *OWL*. *OWL* which was constructed as a full monocoque using Teijin CFRP prepreg, resulting in the chassis weighing as little as 55 kg [16]. Consistent with *Stella Lux*, *OWL* has a large tunnel in the middle beneath the chassis to reduce its frontal area. The vehicle manufactured by University of New South *Wales*, called *Sunswift*, also exhibits this tunnel to reduce the frontal area [14].

2. Materials

Woven carbon fiber composite reinforcement materials are the materials of choice for solar vehicle monocoque chassis design [17]. They easily form complex shapes, are robust, have greater resistance to damage, and reduce lay-up time [18]. The woven structure of the alternating fiber directions are composed by warp and weft fibers which means that the structure exhibits mechanical properties in multiple directions, making it more suitable in solar vehicle chassis design. Depending on the type of weave, the woven structures exhibit diverse mechanical properties. The most common types of weave are plain, twill and satin. In the plain weave, each warp fiber passes alternatively under and over each weft fiber; this is the most stable weave to prevent strand slippage and distortion, but the high level of fiber crimp imparts relatively low mechanical properties compared to other weave styles. The long fiber sections in a satin weave result in better energy absorption and low fiber crimp, but reduced stability and increased likelyhood of fiber distortion. In a twill weave, one or more warp fibers alternatively weave over and under two or more weft fibers. A 2 × 2 or 4 × 4 twill offers the best compromise between the various conflicting factors that govern the choice of weave. In industry, the weave most commonly used is the 2 × 2 twill [18].

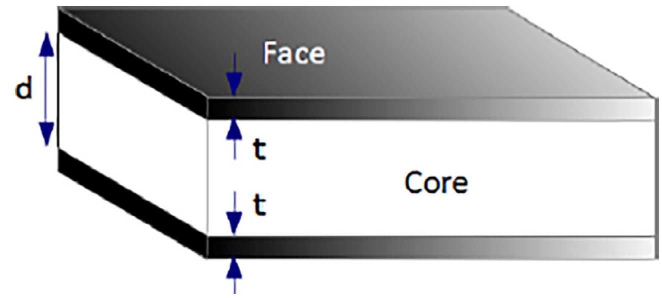

Fig. 1. Typical sandwich structure [19].

A woven fiber and a matrix material are generally combined with another material to form what is known as a sandwich structure – see Fig. 1 [19], which offers similar structural properties to an I-beam, but with overhangs and webs extended in all directions [20]. This additional material is called the core of the sandwich structure and is purposed to increase the rigidity of the structure since it acts similarly to an I-beam's web, which is favorable for chassis design. The core material is normally a low strength material, but its higher thickness, *d*, provides the structure with increased bending stiffness and overall low density. The core increases the moment of inertia and section modulus of the structure, resulting in better resistance to buckling and bending loads [21]. The face or skin material surrounds the core on its upper and lower sides and acts as the overhangs of the I-beam. When loaded in bending, one of the skin materials experiences tension and the other compression, and the core is loaded in shear, which offers rigidity and strength to the entire structure. The thickness of the face material, *t*, is small in comparison to the thickness of the core. Common core materials used in monocoque chassis construction include polyurethane foams and aluminum and Nomex honeycombs [2].

Composite sandwich structures have emerged as one of the most promising material options for many weight reduction applications, which is key in solar vehicle design. It yields improved fatigue performance, superior energy absorption, corrosion resistance, and weight reduction when compared to the individual materials used to construct the sandwich [21].

3. Failure criteria

Failure occurs when a structure can no longer perform its intended function and gives rise to the need for failure criteria to be defined when simulating a design. Composite failure criteria can be divided into two main groups, namely failure criteria not associated with failure modes and failure criteria associated with failure modes [22]. The first uses analytical expressions to describe the failure surface as a function of the material's mechanical properties, which are determined by fitting an expression to a standardized curve attained through experimental methods. Proposed by Tsai and Wu [23], the Tensor Polynomial Criterion is the general polynomial failure criterion used for composite materials and is expressed as:

$$F_i \cdot \sigma_i + F_{ij} \cdot \sigma_i \cdot \sigma_j + F_{ijk} \cdot \sigma_i \cdot \sigma_j \cdot \sigma_k \leqslant 1 \quad (1)$$

where *i, j, k* = 1, 2, 3, 4, 5, 6 for a three-dimensional case. The lamina strengths in the principal directions are given by the parameters *F* and lamina stresses in the principal direction are denoted as σ.