APPLICATION OF SANDWICH STRUCTURES TO AUTOMOTIVE RIMS

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1 Introduction

Advanced composite materials are finding an increasing role in car manufacturing because of their favorable specific stiffness. The use of these materials allows to reduce structures' weight without compromising stiffness, this helps developing cars with improved performances. An even more important reason to reduce car weight comes from environmental considerations [1]. Fuel is consumed for two main reasons: moving the mass of the car and overcoming the resistance of the air. At usual urban speed air resistance is relatively small and almost the entire fuel consumption is due to the displacement of the mass of the car. On the other hand the car mass is steadily growing because of safety regulations and the protective equipment they entail, and of the many other systems that make a modern car comfortable but heavy as well. There is a growing consensus about introducing more and more composites, even in structural roles, to reduce weight and therefore save fuel. The reduction of wheel weight would bring even more beneficial effects since the wheels do not only move rigidly with the car but they, obviously, rotate and therefore are responsible for a quota of kinetic energy bigger than that they share with the car mass. The present paper was generated when the authors were studying the possibility of making lighter composite wheels for automotive applications and were investigating various possibilities to increase their stiffness. Nevertheless, the significance of the main results is not limited to composite wheels only.

One of the most important parameters to qualify the behaviour of a wheel is its specific stiffness, i.e. the ratio stiffness/weight. In fact, lighter unsprung weight results in improved vehicle handling, response and control [2], while the wheel stiffness assures a better interaction between the tire and the ground. Nowadays most of the best performing automotive wheels are made of metallic alloys. Concerning composite materials, fiber-reinforced plastics (FRP) are currently used in high performance bike and motorbike wheels. FRP are more expensive than metallic materials and, moreover, their fatigue behaviour is not well known. On one hand these reasons discourage the use of this kind of materials for car rims but, on the other hand, they are characterized by better specific properties and therefore composite materials are a natural candidate to manufacture stiffer and lighter rims. Wheels made of metallic alloys constitute the natural element of comparison for composite wheels which have to result, if possible, stiffer and lighter with a comparable cost. The cost constraint is particularly demanding because composite materials can achieve extraordinary performances, but only if expensive materials are used. However an industrial production of composite wheels cannot rely on materials which can be afforded only by a small fraction of the potential customers.

Another possibility to increase the wheel stiffness, keeping its cost under control, could rely on the use of sandwich structures, possibly coupled with FRP. In the present paper we analyze the possibility of increasing the stiffness of a wheel rim by means of a sandwich structure: in section 2 the main concept of sandwich structures is presented, in section 3 the models and their results are discussed and finally in section 4 some concluding remarks are reported.

2 The sandwich concept

Sandwich structures find an application in many structural fields such as spacecraft, aircraft, train and car structures, wind turbine blades, boat or ship superstructures… Their geometry can vary widely, but their common feature is a lightweight thick core, included between two thin stiff skins. The core material is normally of low strength, but its high thickness provides the sandwich composite with high bending stiffness and with an overall low density. The two outer faces are often made of laminated polymeric based composite materials, sometimes metal sheets are also used and, typically, the core can be an open- or closed-cell structured polymeric foam, balsa wood or a honeycomb type material. Particularly, honeycomb structure cores allow the minimization of the amount of used material to reach minimal weight and minimal material cost. A honeycomb sandwich panel is a structural element with very low density and relatively high out-of-plane compression properties and out-of-plane shear properties. Figure 1 shows a sketch of a typical honeycomb sandwich panel.

As shown in Table 1, stiffness in structures subjected to pure bending load is considerably enhanced by the insertion of a honeycomb core. In a simple plate, by inserting a honeycomb core of thickness t between two skins of $t/2$ each the bending stiffness increases 7 times, with an increase in weight of a few percentage points [3].

Finally it is worth mentioning that currently available technology can rather easily manufacture wheel rims with a sandwich structure and therefore there would be no technological reason preventing their introduction in use. On the other hand, more caution should be used to assess the torsion and fatigue behavior of wheels made including sandwich structures. That is a probably unexplored aspect which is beyond the scope of this paper and will not be taken into consideration in the present work.

3 The wheel: models, virtual tests and discussions

An automotive wheel consists of a rim, that is the outer edge of the structure where the tire is fitted, and a flange, made of a set of spokes connecting the centre of the wheel to the rim itself. The thickness of the rim can be of variable size, but it is usually in the range 3-10 mm whereas the spokes are much thicker, therefore the rim is the most flexible part of the wheel.

In the following, we will refer to a Cartesian system of coordinates, where x is the direction of the hub, y is the vertical axis and z is the horizontal axis along which the wheel would roll. Figure 2 and Figure 3 show the nomenclature and some details of the wheel and the rim respectively, while Figure 4 (taken from the European Tyre and Rim Organization Standards Manual [4]) shows the typical rim section.

A quasi-static test which can provide a measure the overall stiffness of an automotive wheel is what will be called the ‘compression test’ in the remainder, schematically shown in Figure 5. A car wheel is supported by two rigid plates, respectively at the lowest and the uppermost points on its inner edge, that is the one without the flange (Figure 3). The upper plate is moved toward the lower one and in this way a vertical load P is applied to the two contact areas. No other restraints are applied, the friction between the plates and the rim prevents the wheel from rotating and displacing in the horizontal directions x and z. As a result of the compression the rim is deformed and a reduction of vertical diameter is produced. The relevant diameter reduction $\Delta\phi$ is measured and the ratio $P/\Delta\phi$ provides an indication of the wheel stiffness. This change in diameter is measured directly as the displacement of the upper rigid surface, thus including the global deformation of the wheel as well as the local deformation of the rim border occurring at the contact areas. The increase of the horizontal diameter on the inner edge of the wheel is recorded too. Figure 5b shows the deformed shape of a realistic finite element (FE) model of a wheel. It is evident that under the compression test the rim deforms considerably whereas the change of shape of the flange is more limited. The overall stiffness of the wheel can therefore be more efficiently increased by making the rim stiffer. This can be achieved in (at least) two ways:

- By using materials with better mechanical properties, and therefore more expensive ones;
- By using a different structural concept, such as that of sandwich structure.

The second approach is investigated in the present work.

3.1 Detailed finite element models

In order to evaluate the performance of a sandwich structure for the rim, the compression test described above is simulated by using the finite element method (FEM). Three FE models of a realistic wheel were generated by using the software *Abaqus Standard* [5]. The flange is composed of nine spokes and the rim has a geometrical profile of the type shown in Figure 4. The three models differ only for the material taken into account for the rim: in the first case it has a constant thickness *t* made of homogeneous material, in the second and third case it is a sandwich structure made of two outer layers of the same material as previously and having a thickness *t/2* and an intermediate layer made of honeycomb of thickness *t* and *2t* respectively.

In the three cases the discretization is the same. The rim is modeled with quadrilateral shell elements, having four nodes and six degrees of freedom (dofs) per node, with reduced integration. In the case of sandwich type rims they are composite shell, where three layers are given. The flange of spokes is modeled by four-nodes linear tetrahedrons, having three dofs per node. The flange is connected to the rim by kinematical coupling between the corresponding nodes. The lower support plane and the upper punch are made of four-node bilinear quadrilateral rigid elements. The contact of these rigid surfaces with the rim is modelled by the usual surface to surface contact, using the master slave algorithm. The total number of elements is about 200000, and the number of nodes is about 85000, for a total of about 400000 variables in the model.

The comparison between the virtual tests reveals that the overall stiffness increment is much smaller than the one obtained in the case of pure bending. As shown in Table 2, if we consider the reduction of the vertical diameter, the increase of stiffness is from 14% to 45% by doubling or tripling the total thickness. Similar values are obtained by considering the horizontal diameter. In any case we are very far from the stiffening effects presented in Table 1. It is evident that the case under investigation differs significantly for two main aspects from the pure bending cases corresponding to the results shown in Table 1:

- only a portion of the wheel is stiffened with the sandwich;
- the stress state in the wheel is not of pure bending type.

Nonetheless the limited stiffness increase due to the introduction of the sandwich came as an unexpected result worth of further investigation.

3.2 Simplified models

In order to remove all unnecessary complexities and reduce the problem to its simplest constitutive elements, some numerical experiments were performed on simple geometrical configurations (Figure 6). The rim is represented by a cylinder having a diameter of 460 mm, a length of 230 mm and a constant thickness of 3 or 6 mm depending upon the considered case, while the flange of spokes is simply formed by a set of ten beams directly connected to the cylinder and to a central point, as shown in Figure 6. This model is composed of a cylindrical surface discretized with layered shell elements with four nodes and six degrees of freedom per node as previously and by a ‘star’ of beam elements having two nodes and six degrees of freedom per node. Three lines of nodes on the lower part of the cylinder are prevented from vertical displacement, and the corresponding three lines on the upper part are loaded with nodal forces (Figure 6). The total number of variables in this model is about 15000, the number of nodes is about 2500 and the number of elements is about 2400. With this simplified model and by considering a homogeneous and isotropic material for a *t*=3 mm thick rim, four cases were considered: one in which the rim with no spokes was loaded and three characterized by different stiffness of the spokes, very soft, realistic and very stiff. The same examples were studied by considering a sandwich structure for the rim, composed of two outer layers 1.5 mm thick of the same material as in the previous case and an intermediate layer of honeycomb 3 mm thick.

Table 3 and Table 4 summarize the results of this second set of simulations. The FEM calculations provided the change in length of the diameter parallel to the *y* axis (vertical) and that of a diameter parallel to *z* axis (horizontal), both on the edge without the spokes. Also in this configuration the increase in overall stiffness due to the presence of the sandwich structure is strongly reduced with respect to the plate bending case. With a honeycomb core of thickness *t* the overall stiffness increases between 1.6 times (*z* axis) to around 2.5 times (*y* axis) in the case of spokes with a usual stiffness (realistic spokes in Table 3 and 4), and the stiffness increment will in general depend on the spoke stiffness relative to the rim stiffness. Values similar to those obtained for a plate in bending are achieved only with the cylinder without spokes, the stiffness of the rim reinforced with the honeycomb is about 6.5 times the stiffness calculated with a homogeneous rim.

4 Conclusions

A car wheel is made of two main components: the flange and the rim. Due to its limited thickness the rim is more flexible than the flange and therefore its stiffness should be increased to obtain an increase of the overall stiffness of the wheel. Our simulations suggest that the introduction of a honeycomb core in the rim leads to a limited increment in overall stiffness. This is probably due to two main factors:

- the flange is not stiffened by the honeycomb and
- in the test used to evaluate the wheel stiffness, bending is only one of the stress components affecting the wheel.

During its use a wheel is subjected to a wide variety of external forces, whereas the sandwich structure is optimized only with respect to bending.
Moreover currently adopted standards [4] define the geometry of rims precisely, as a consequence strict limits, not taken in account here, are posed to their thickness.
Besides this, simulations have pointed out how influent the flange is in the overall structure stiffness (as seen in Table 3 and 4). This observation leads to the consideration that in further developments of composite wheel design, sandwich structures may be better used to make light and stiff spokes.

Acknowledgement

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Table 1. Stiffness in plates under bending

	Thickness	Stiffness
Simple plate thickness *t*	1	1.00
Sandwich plate thickness *2t*	1/2+1+1/2	7.00
Sandwich plate thickness *3t*	1/2+2+1/2	19.00

Table 2. Stiffness in the wheel model

	Change in diameter		Stiffness ratio based on	
	Δy	Δz	vertical diameter	horizontal diameter
Homogeneous rim	-2.59	1.88	1.00	1.00
Core thickness 3 mm	-2.27	1.68	1.14	1.12
Core thickness 6 mm	-1.78	1.31	1.45	1.43

Table 3. Stiffness in cylinder with spokes considering Δy

	Homegeneous rim: Δy	Sandwich rim: Δy	Relative Stiffness
Without spokes	-7.23	-1.13	6.4
Soft spokes	-6.53	-1.11	5.9
Realistic spokes	-1.35	-0.55	2.5
Rigid spokes	-0.64	-0.27	2.4

Table 4. Stiffness in cylinder with spokes considering Δz

	Homegeneous rim: Δz	Sandwich rim: Δz	Relative Stiffness
Without spokes	6.81	1.04	6.5
Soft spokes	6.08	1.02	6.0
Realistic spokes	0.7	0.44	1.6
Rigid spokes	0.2	0.16	1.3

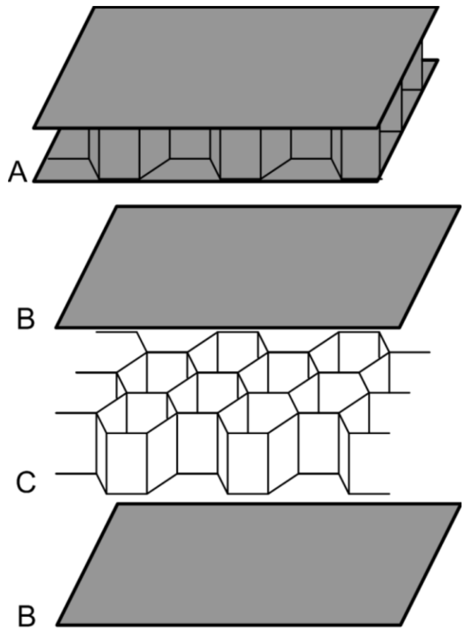

Figure 1. Diagram of a composite sandwich panel showing complete panel ("A"), face plates/sheets ("B"), and honeycomb core ("C") (alternately, foam core). Courtesy of George William Herbert, http://en.wikipedia.org/wiki/File:CompositeSandwich.png

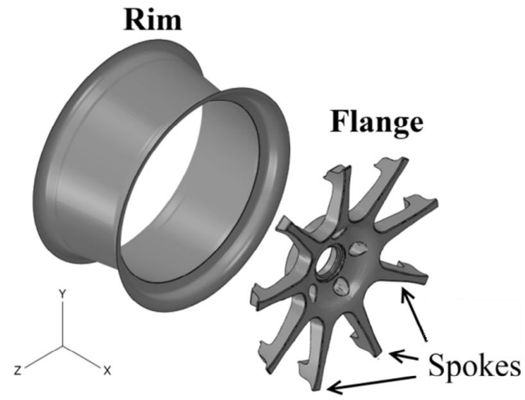

Figure 2. Wheel parts

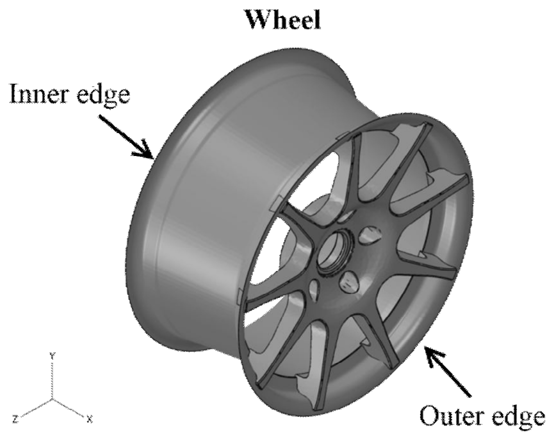

Figure 3. Inner and outer edge of the wheel

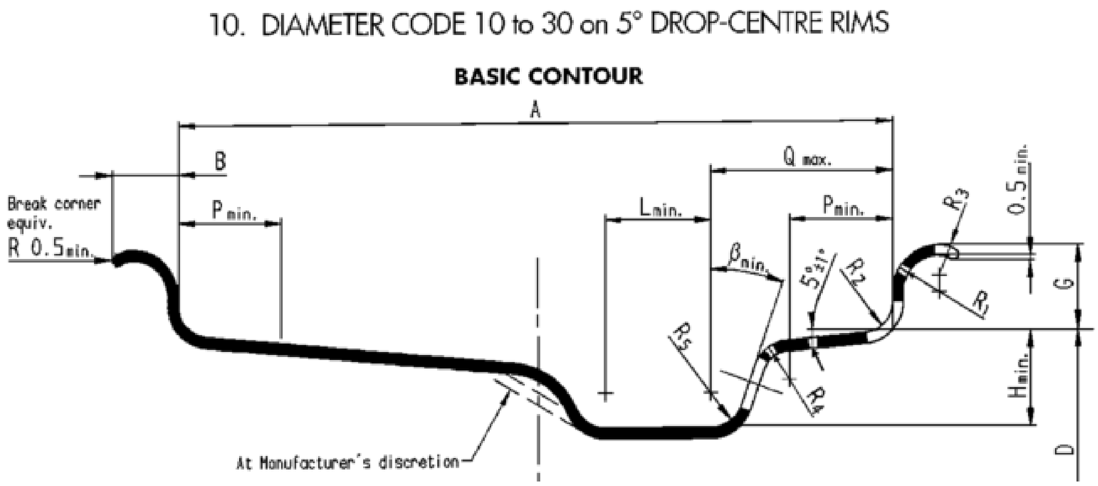

Figure 4. Rim section, taken from ETRTO Standards Manual

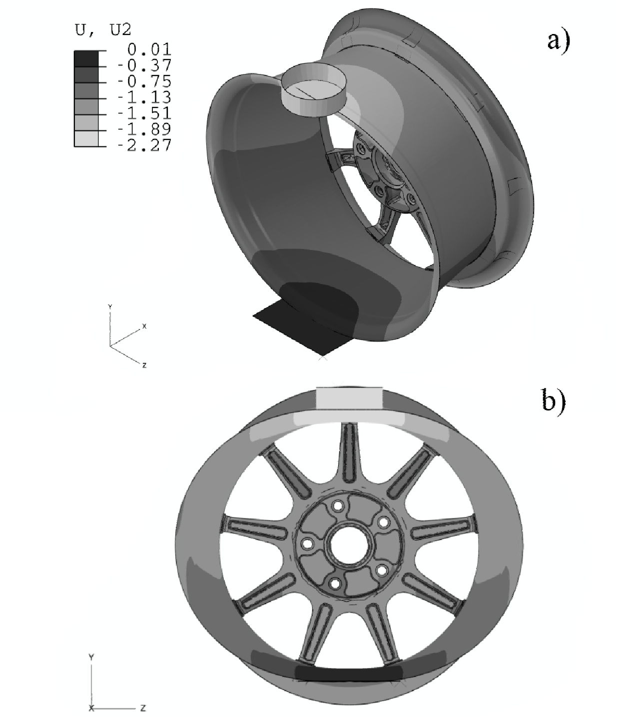

Figure 5. Compression test and FEM model of the wheel, deformed shape of the wheel under compression test.

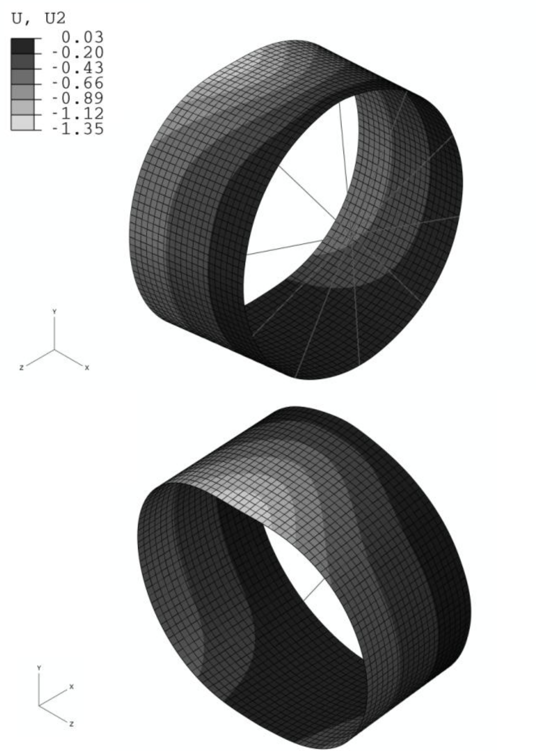

Figure 7. Deformed shape of the cylinder with spokes

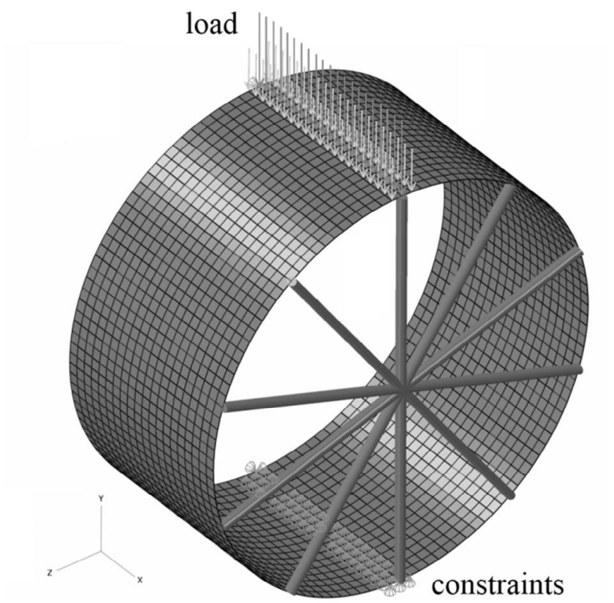

Figure 6. Cylinder with spokes