Carbon Fibre Composite Wheel Design and Prototype for a FSAE Race Car

Brendan M. Peters¹

The University of New South Wales at the Australian Defence Force Academy

Surplus mass in a race car reduces performance and excessive rotating unsprung mass is detrimental to vehicle dynamics. Carbon fibre composites offer increased strength and stiffness in addition to fatigue performance with reduced mass, making these materials suitable to replace metal in road wheels to enhance roadholding and performance of a vehicle. Whilst vehicle and aftermarket suppliers have started to offer composite wheels to market, their design processes and fabrication techniques are closely guarded resulting in this aspect of wheel design remaining immature. A review of available published work in wheel design and composites has been completed to guide this project and ensure correct design and fabrication principles were employed. In this study metal wheels were modelled and simulated with various loads to inform the design of improved Carbon Fibre Reinforced Polymer (CFRP) wheels. The complex dynamic forces experienced by a wheel during use can be approximated with static load cases. This design was then prototyped by fabricating a CFRP wheel for future testing and evaluation. Fabrication techniques require further development to produce the desired part quality; however, the CFRP wheel had significantly less mass than the aluminium wheel and modelling indicates it exhibits greater stiffness and strength which all contributes to improved vehicle performance.

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Nomenclature

Terms:

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
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<tr>
<td>FSAE</td>
<td>Formula SAE</td>
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<tr>
<td>UNSW</td>
<td>University of New South Wales</td>
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<td>CFRP</td>
<td>Carbon Fibre Reinforced Polymer</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
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<tr>
<td>Prepreg</td>
<td>Carbon fibre woven sheet pre-impregnated with semi-cured polymer resin</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
</tr>
<tr>
<td>FoS</td>
<td>Factor of Safety</td>
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Variables:

- $I$ = mass moment of inertia [kg.m$^2$]
- $m$ = mass [kg]
- $r$ = tyre outer radius [mm]
- $h$ = tyre deflection at contact patch [mm]
- $\alpha$ = tyre contact patch swept angle [degrees]
- $d$ = tyre contact patch length [mm]
- $\gamma$ = load application angle on bead seat [degrees]
- $F_x$ = $X$ component of the load force acting on the wheel [N]
- $F_y$ = $Y$ component of the load force acting on the wheel [N]
- $F_z$ = $Z$ component of the load force acting on the wheel [N]
- $g$ = gravitational acceleration [m/s$^2$]

I. Introduction

A. Background

The wheel as a human invention is widely acknowledged by contemporary archaeologists and historians as the most significant discovery of old times and the real genesis of any ancient civilisation (Meghashyam et al., 2013). Modern vehicles utilise wheels in a multitude of variations including bearings, gears, rotary controls and the road wheels themselves, which this report focuses on. Materials used to produce vehicle wheels have evolved with wheel design over the age of automobiles; beginning with wooden spoke designs which were a carryover from the horse-drawn cart and then steel was incorporated to replace the wood elements as greater durability and strength was required. Large flat disks of steel became prominent reflecting rail wheel designs of the period but, as manufacturers began to recognise the effect of wheel mass, wire spokes reminiscent of bicycle wheels gained popularity. As materials technology and metallurgy improved different wheel materials emerged to become more common including magnesium and the aluminium alloys of today’s modern vehicles.

UNSW Canberra participates in the FSAE program which is an engineering design competition for undergraduate and graduate students to develop and construct a single-seat race car (SAE International, 2019). The vehicle, which was fielded by the UNSW Canberra team in 2018, with its aluminium wheels is depicted at figure 1. The goal of the annual competition is to engineer a vehicle with the best overall package of design, construction, performance and cost. An aspect of design and performance for which there is opportunity to improve upon is the vehicle’s wheels by making them stronger, stiffer and lighter than the current aluminium wheels, with a corresponding lower moment of inertia. This is possible using CFRP in their construction which necessitates a redesign of the current wheels.

Mass reduction is particularly critical in the wheel package because it is both rotating and unsprung. Unsprung mass is defined as all mass outboard of the suspended vehicle – sprung mass is that which is supported and
dynamically affected by the vehicle’s suspension system. Any reduction in unsprung mass has a positive effect on the performance of the vehicle as it improves suspension transience; that is the time taken for the suspension to force the tyre back into contact with the ground after it travels over a bump. The more time that a tyre is correctly contacting the ground the better it can grip the surface and thus improve the vehicle’s reaction to driver inputs. Furthermore, when a vehicle accelerates it must accelerate not only the wheel mass in the direction of travel but also accelerate the rotational direction of the wheel (Jarvie, n.d.). The moment of inertia (resistance to rotational acceleration) for a wheel is expressed by the mass multiplied by the square of the rotating radius divided by two:

\[ I = \frac{mr^2}{2} \]  

(1)

Therefore, the moment of inertia can be reduced with a lower wheel mass and/or reducing the distance of said mass from the axis of rotation.

Composites have been increasingly used in the design of lightweight vehicles and race cars due to their excellent strength and stiffness properties with much lower mass than metals. However, conventional design and fabrication methods do not apply to composites because their structures differ markedly from metals and pure polymers. Instead of machining, stamping or moulding parts CFRP composites are formed by stacking fibre plies on a mould and immersing them in a polymer liquid matrix which later cures solid. Additionally, most metals are isotropic whereas CFRP composites can be designed to have anisotropic properties (Lei et al., 2018). This provides great opportunity for race car wheel design to unlock performance increases with reduced mass and increased strength.

An aftermarket industry is blossoming in luxury and high performance wheels and vehicle manufacturers have begun to implement CFRP wheels as OEM fitment; for example, Koenigsegg developed and manufacture their own CFRP wheels in-house and the Australian-based Carbon Revolution supply CFRP wheels for the 2018 Ford Mustang GT350R (Walther, 2016). Such companies do not detail the design and fabrication methods of their wheels purely because they have invested heavily in them and there is no business case in making such information freely available to competitors. Also the literature available on CFRP wheel design and manufacture was still emerging at the time of this study; there was reported examples of composite wheel prototypes yet the methods for fabrication and detailed studies of CFRP wheels had yet to become widespread (Lei et al., 2018), which has left gaps in the open-source knowledge.

B. Aim

The aim of this project was to design and prototype a CFRP wheel for the UNSW Canberra FSAE race car. The team currently runs commercially available aluminium wheels which perform adequately, yet an opportunity existed to improve vehicle performance and competitiveness through a reduction in wheel mass without sacrificing strength and stiffness. This could be achieved using CFRP as the wheel material and the intent was to demonstrate that a reduced mass CFRP wheel would have greater strength and stiffness properties that the current aluminium wheel. To achieve this aim, baseline characteristics of the current aluminium wheel were established utilising FEA software which was then used to design a new CFRP model. This wheel would be prototyped to establish appropriate fabrication techniques and inspected/tested to confirm FEA results. The desired outcome of this project was the blueprint and fabrication process complete with moulds with which to fabricate further CFRP wheels for the UNSW Canberra FSAE team to conduct future testing and verification with a view to use in competition.

C. Scope

The scope of this project was defined primarily by wheel compatibility with the 2019 UNSW Canberra FSAE race car and must also comply with FSAE competition rules. It was not the intent to make changes to the UNSW Canberra FSAE vehicle such as specifying alternate tyres or wheel sizes that were not currently used. Valuable data and tuning had been collected from the current setup and this project only sought to improve upon the current wheels whilst maintaining compatibility with the currently used tyres and hub/brake/wheel carrier assemblies. As such, only the wheel and its potential for reduced mass and moment of inertia, along with the material properties, were studied in this report. All design changes in this project were limited to the vehicle wheels to ensure that the new design was able to fit the current Hoosier slick tyres. CFRP was the material from which the prototype wheel was designed for and fabricated from utilising UNSW Canberra resources and facilities.
II. Finite Element Analysis

A. Wheel Design

Wheels used on FSAE vehicles must comply with the rules of the competition as stipulated by SAE International. The current version of rules at the time of this project was the 2019 rules which provided substantial freedom of wheel design. The primary requirement was set in regulation T.1.7.1 which stated that “wheels must be 203.2mm (8.0 inches) or more in diameter” with a secondary regulation T.1.8.1b stating that “dry tires may be any size” (SAE International, 2018). The current wheels were 10 inches in diameter, thus compliant with the rules, and as outlined in the scope the redesigned CFRP wheels will retain current width (8 inch) dimensions. Important aspects of the wheel and common nomenclature are depicted in figure 2 to better understand wheel design theory. Firstly, wheels have two parts: the cylindrical rim on which the tyre is mounted and the centre which is mounted inside the rim and attaches to the hub face of the vehicle. Of note is that the rim is made of two separate pieces (inner and outer barrels) on the current aluminium wheels which makes it a 3-piece wheel. The wheel centre includes stud holes for the wheel to be affixed to the hub and there are two methods of centring the wheel; hub-centric uses the hub itself to pilot the correctly sized machined area of the wheel centre whereas stud-centric uses the wheels studs only to centre the wheels (Gilles, 2012). Lastly, wheel offset is the difference between the rim centreline and the wheel mounting surface, which can be either positive or negative depending on if the distance is outboard or inboard. The greater the positive offset, the greater space available for braking systems and the track width of the vehicle increases.

Utilising CFRP as the wheel material significantly affects the design process and wheel features. To make best use of the material properties and reduce fabrication time and effort, sharp edge features need to be avoided and small curvature radii should be enlarged (Walther, 2016). It would not be feasible or practical to simply replicate the current aluminium wheel design illustrated in figure 2 with CFRP, despite the expected mass savings. Additionally, Walther (2016) goes on to state that an aluminium or like-metal centre mounting area bonded within the wheel centre is required for abrasion resistance. This area would be regularly pressed against the metal hub surface and experience crush and friction loading against the heavy bolt preload and CFRP is likely to suffer premature wear in these areas (Xiaoyin et al., 2016). Despite such limitations, the benefit is up to 50% reduction in unsprung rotating mass (Sloan, 2018) (Carbon Revolution Pty Ltd., 2012). CFRP is also more susceptible to damage and degradation of surface finish in the presence of elevated temperatures. This is a factor in race cars and high-performance vehicles which decelerate regularly from high speeds and generate very high brake temperatures which radiates and conducts into the wheel. To mitigate this, manufacturers can employ a thermal barrier coating on the inner wheel barrels and rear surfaces of the centre (Carbon Revolution Pty Ltd., 2015). However, as the driving aspects of FSAE competitions are generally over short distances with limited speeds and infrequent brake application this treatment is deemed unnecessary for this project.

In order to apply lightweight design principals in wheel design, the actual service stresses and allowable stress of the materials must be known. Standard tests developed by SAE specify measurement methods and tooling/facilities required to understand the stresses but it is acknowledged that limitations exist in the capability to simulate complex dynamic loading conditions on a wheel experienced during service (Grubisic and Fischer, 1983). With load cases approximated and a safety factor allowed for, FEA and multi-objective topology optimisation is commonly used in wheel design (Xiaoyin et al., 2016) and this is especially applicable to the area of maximum design space availability: the wheel centre. It was observed that a five-spoke design was optimal to withstand stress applied in existing load cases utilising topology optimisation (Das, 2014).

B. Loading on Wheels

A reduction in both unsprung and rotating mass is beneficial for vehicle performance, but it is the unsprung mass alone that most affects roadholding characteristics. A lower unsprung mass requires a lower vertical force amplitude to return the wheel to the road surface after a bump, which can thus be performed in less time (Guiggiani, 2014). Many methodologies exist for examining loads a wheel is subjected to in service and the forces can also be measured directly. Such forces are typically non-linear and dynamic in nature and therefore complex to model and reproduce in the lab environment. One method is to convert the dynamic events to equivalent static loads (Dattakumar and Ganeshan, 2017). Here analysis was completed to record displacements and stress distributions of a dynamic event, a modal transient analysis was performed in conjunction with determining the modal participation factor and effective modal mass, feedback was assessed on the active nodes, and finally equivalent static loads were scaled to match the dynamic event.
A simpler method of determining loads is to use data gathered during service of the vehicle and identify the peak forces experienced during various manoeuvres (Dhakar and Ranjan, 2016). In this method, maximum force events were determined in each global \( x \), \( y \) and \( z \) direction. This was braking for the longitudinal \( x \) direction, cornering for the lateral \( y \) direction and striking a bump for the normal \( z \) direction. An additional force exerted upon the wheel continuously is that from inflation pressure of the tyre. Thus, four separate loads were identified and the values of each can be determined from the mass of the vehicle combined with driver and g-forces experienced during each event.

Except for the case of inflation pressure load, it is the tyre that transmits loads into the wheel, so it is therefore the bead seats where these loads are applied. During longitudinal loading there is a shear traction load on both bead seats and during lateral loading there is a normal-to-surface load on the single bead seat which faces the outside of the corner being negotiated. Normal bump loading differs because the load is not transferred through the whole bead seat but only a portion of it adjacent to the contact patch of the tyre – the remainder of the tyre bead contributes negligible or zero force outside of this arc (Stearns et al., 2005). This is illustrated in figure 3 where the edges of the measured contact patch are projected in to the centre of the wheel to form angle \( \alpha \). Distance \( h \) is the tyre deflection at the contact patch and is a function of tyre radius and \( \alpha \) as follows:

\[
h = r \left[ 1 - \cos \left( \frac{\alpha}{2} \right) \right]
\]

(2)

It is assumed that the application area of the load is 80% of the bead seat arc swept by angle \( \alpha \) (Walther, 2016) due to length of contact patch \( d \) being measured at 95mm and \( r \) of 228.6mm. Utilising the law of cosines equation, 0.8\( \alpha \) results in angle \( \gamma \) being:

\[
\gamma = 0.8 \alpha = 0.8 \cos^{-1} \left( \frac{2r^2 + d^2 - r^2}{2r^2} \right) = 0.8 \cos^{-1} \left( \frac{2(0.2286)^2 + 0.95^2 - (0.2286)^2}{2(0.2286)^2} \right) = 19.2^\circ
\]

(3)

Inflation pressure affects the structural stiffness of the tyre but does not directly support the rim (Guiggiani, 2014). This load is applied as a normal-to-surface force across all internal-to-the-tyre areas of the rim surface; however, because its magnitude is small relative to the other loads discussed, inflation pressure has little to no stress effect on a vehicle rim (Stearns et al., 2005). Alternatively, an extreme case of inflation pressure is during the tyre seating process whereby the tyre is overinflated for a short duration in order to seat the tyre bead correctly onto the rim.

Table 1: Static Load Equivalents of Dynamic Wheel Forces

<table>
<thead>
<tr>
<th>Load</th>
<th>Schematic</th>
<th>Magnitude</th>
<th>ABAQUS Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seating Pressure</td>
<td><img src="image1.png" alt="Seating Pressure" /></td>
<td>1.4psi = 0.09653N/mm²</td>
<td>0.09653MPa Uniform Pressure</td>
</tr>
<tr>
<td>Running Pressure</td>
<td><img src="image2.png" alt="Running Pressure" /></td>
<td>30psi = 0.20686N/mm²</td>
<td>0.20686MPa Uniform Pressure</td>
</tr>
<tr>
<td>Normal Force ( (F_n) )</td>
<td><img src="image3.png" alt="Normal Force" /></td>
<td>vehicle mass ( \times g ) ( \times ) bump ( \times ) FoS ( \div ) applicable wheels (4 for ( F_n )) = 2432.88N</td>
<td>2432.88N/853mm² = 2.851MPa Uniform Pressure</td>
</tr>
<tr>
<td>Cornering Force ( (F_c) )</td>
<td><img src="image4.png" alt="Cornering Force" /></td>
<td>vehicle mass ( \times g ) ( \times ) cornering ( \times ) bump ( \times ) FoS ( \div ) applicable wheels (outside 2 for ( F_c )) = 4865.76N</td>
<td>4865.76N/14000mm² = 0.34755MPa Uniform Pressure</td>
</tr>
<tr>
<td>Braking Force ( (F_b) )</td>
<td><img src="image5.png" alt="Braking Force" /></td>
<td>vehicle mass ( \times g ) ( \times ) braking ( \times ) bump ( \times ) FoS ( \div ) applicable wheels (front 2 for ( F_b )) = 4865.76N</td>
<td>4865.76N x 126.302mm = 61455Nmm Moment about axis</td>
</tr>
</tbody>
</table>

Table 1 sets out each load and the calculations performed to derive a force in each. A FoS of 2 was used throughout in the interests of conservatism and vehicle mass including driver was measured to be 310kg. Bump
G is the g-force equivalent multiplier from striking a bump at speed and is a constant value assessed to be 1.6 according to Dattakumar and Ganeshan (2017). Cornering G is the maximum g-force equivalent multiplier experienced in the Fy direction during cornering at speed and is a constant value assessed to be 1 from data gathered during UNSW Canberra vehicle testing; likewise, for braking G experienced in theFx direction.

Clearly these forces do not occur in isolation; for example, running pressure is always present as is Fz. Therefore, it was necessary to combine these forces into load cases for the maximum possible static load equivalents to respective dynamic events. There were four load cases to be simulated in this project:

1. Tyre Seating Load Case = seating pressure force.
3. Cornering Load Case = running pressure force + normal force + cornering force.

C. Current Wheel FEA

A lack of design science had been used for wheels initially and for much of the automobile’s existence it was aesthetics often prioritised over rational design (Liu et al., 2011). Only after manufacture and machining could a wheel’s structural strength and fatigue performance, along with other properties, be assessed. This was inefficient and wasteful when a prototype did not perform satisfactorily. FEA improves wheel design accuracy and efficiency by enabling designers and engineers to apply virtual loads to virtual models that can be rapidly developed and modified on a computer to produce more ideal designs in less time without costly alteration to tooling and equipment (Chauhan et al., 2015). Chauhan et al. (2015) also state that static analysis using FEA can closely mimic dynamic wheel loading.

One of the licenced FEA resources available for use at UNSW Canberra is Abaqus, a product of Dassault Systèmes Simulia Corp. Abaqus is a powerful FEA simulation software package which can be used for any geometry and typical engineering properties of materials (Wang et al., 2011). Abaqus simulations of wheel/tyre compressive and tensile stresses correlate closely with lab tests (Billal K et al., 2013), giving designers and engineers confidence in the results.

An integral aspect of FEA is the ‘mesh’ which is the process of dividing a part or structure into many small elements for analysis of how each element interacts with neighbouring elements upon the application of force. The stress and strain expected in each element can be calculated by the FEA software and specific areas of the part or structure are easily identified as potential failure points or otherwise. Utilising a 10mm tetrahedral mesh it was identified that danger areas of wheels are the rim, the junction between the centre and rim, and areas around the stud holes (Wang et al., 2011). With a finer mesh more accurate results can be expected but the trade-off is increased computing power required to complete the calculations. In choosing mesh size one must balance available computing power against part complexity and required accuracy of results. Utilising a 2mm mesh, the wheel optimisation study by Lei et al. (2018) had 73102 elements yet another study reduced the computation power requirement by taking advantage of the repeating geometry of a wheel: it was divided into ten 36˚ slices with a 5mm mesh (Das, 2014). The wheel was a five spoke design with symmetrical spokes, so the results were mirrored about the spoke and repeated around the wheel to complete the analysis.

As for the output of FEA, the model is displayed with areas of high and/or low stress highlighted or tabulated and strains can be visualised through the ability to create video of the simulated load being applied and the subsequent deformations produced. Wheel stress plots typically show that the majority of load is carried on the outer surfaces of the material (Jarvie, n.d.) which implies that the model can be simplified to a shell instead of a solid. Von-misses stress is most commonly used as the output due to the complexity of wheel geometry (Wang et al., 2011).

![Figure 4. FEA boundary condition](image_url)

The UNSW Canberra FSAE team currently runs Keizer 10 inch rims with 6 inch inners and 2 inch outers. The centres are 7075 Aluminium designed and fabricated by the UNSW Canberra FSAE team. The Keizer rims are CNC spun 6061-T6 aluminium (K2W Precision Inc, 2017) fastened together with the use of a Keizer rubber seal, and to the centre with 12 steel fasteners. This was modelled in Abaqus with precise geometry as a three-dimensional shell assembly, pictured in figures 2 and 4, and meshed with 99470 elements using a 2.5mm seed. Material specifications for the two types of aluminium were drawn from text (Callister, 2010), the assembly was built with tie constraints to mimic the action of fasteners and the aforementioned load cases were applied at the relevant bead seat areas. A boundary condition was also applied to the surfaces of the wheel centre which contact the hub and stud bolts as shown in figure 4.
D. Design of CFRP Wheel

Freedom of design for the new wheel was limited by design constraints including competition rules relating to wheels and the requirement for compatibility with current hardware. The decision was made to ensure the new wheel attaches to the vehicle in the same manner with the same tyre to eliminate the need for changes to the vehicle or setup. No changes to wheel offset or size were considered to ensure consistency in the data body of knowledge. An additional spatial constraint was also relevant as pictured in figure 5 which shows minimal clearance between the outer edge of the brake calliper and the inner wheel. Further constraints included the principle of design for manufacture; this wheel was to be fabricated in-house utilising UNSW Canberra resources which meant that complex moulds and processing techniques were not possible. As such, it was deemed most appropriate to pursue a two-piece wheel design with the same 12-bolt fastening pattern as the current wheel to continue use of the Keizer rubber seal. However, a two-piece wheel would mate CFRP surfaces directly to the metal hub on the wheel carrier and this was identified as a potential point of abrasion and damage due to the frequent removal and replacement of wheels on the vehicle. Therefore, an aluminium piece with large bonding area for strength was designed to be bonded to the rear of the outer CFRP rim to act as the mating interface between wheel and hub.

A spoked design was desirable for volume reduction and aesthetics and a four-spoke design was most appropriate due to the four-bolt pattern of the wheel studs. The final design iteration is represented as an Abaqus model in figure 6a and the aluminium interface is shown at figure 6b. The outer rim profile differs from the current wheel, as shown in figure 7, with a more pronounced radius curve to eliminate the potential of a stress concentrator in the sharp bend and improve drapability of the prepreg over the mould.

E. CFRP Wheel FEA and Comparison with Aluminium Wheel

The CFRP wheel design was modelled in Abaqus with the aluminium interface represented as a three-dimensional homogenous aluminium shell part and the inner and outer rims modelled as two-dimensional swept shell profiles, as shown at figure 6c. The material properties for the CFRP layers was taken from 2x2 twill weave prepreg stock available at UNSW Canberra identical to that used in a prior study (Dhaliwal and Newaz, 2016). Within the shell profiles, the composite layup was modelled as 15 layers of 0.2mm thick prepreg with a 0°/45°/-45°/90° orientation as indicated in figure 8. This was assembled and loaded in Abaqus in the same manner as the aluminium wheel and the resultant mesh was 50240 elements with a 2.5mm seed. With the simulations of both types of wheel subjected to all four load cases run, the results
could be compared. The stress scales in MPa were normalised for both wheels to that of the maximum stress element of the CFRP wheel which can be seen in figures 9, 10, 11 and 12.

In each load case the maximum stress was higher in the aluminium wheel than the CFRP wheel and stress is better distributed in the CFRP wheel as opposed to concentrated in particular areas in the aluminium wheel. This analysis confirmed the theory of increased strength and stiffness in the CFRP wheel with equivalent section thickness and validated the design geometry and features. Additionally, the shear and peel strength of Loctite Aero 9309NA for the bonded area is greater than any element peak stress expected (Henkel Corporation Aerospace, 2013).

Figure 9. Tyre seating load case FEA visualisation with aluminium wheel (left) and CFRP wheel (right)

Figure 10. Normal load case FEA visualisation with aluminium wheel (left) and CFRP wheel (right)

Figure 11. Cornering load case FEA visualisation with aluminium wheel (left) and CFRP wheel (right)
III. Prototype Fabrication

A. Moulds and Hub

In order to fabricate CFRP parts with the desired finish, strength and profile, the use of prepreg CFRP cured in an autoclave was required. This necessitated moulds to be made prior and aluminium billets were machined to the correct geometry and profile, plans for which was also completed in Abaqus. Aluminium was chosen as the mould material due to its strength and durability compared to foam or wood, and its favourable thermal properties during the cure cycle. UNSW Canberra Technical Support Group (TSG) fabricated the two moulds along with the aluminium hub interface utilising a CNC machine to accurately reproduce the respective three-dimensional models. The machined moulds, pictured in figures 13 and 14, then required polishing as any surface imperfection would be formed into the surface of the CFRP part. Figure 14 illustrates the difference between the polished and unpolished moulds. Finally, as shown in figure 15, before use each mould required thorough cleaning with Methyl Ethyl Ketone (MEK) in readiness for the application of mould release agent – Frekote 44-NC in this instance.

B. Wet Layup

During the planned fabrication period there was uncertainty regarding availability of the autoclave, so a wet layup of the outer rim was completed which also provided an opportunity to test the outer mould suitability. Fifteen layers of woven carbon fibre fabric were laid in the $0^\circ/45^\circ/-45^\circ/90^\circ$ orientation with two-part epoxy resin wetted into each. This was subsequently vacuum bagged to apply one atmosphere of pressure to the entire surface during cure.

Once cured, the resulting part was very difficult to separate from the mould which prompted a minor modification of notches being cut into the edges of the mould to assist with insertion of wedging tools for future use. However, the wet layup was otherwise successful with minimal surface defects and the desired profile thickness achieved. Subsequent machining was conducted to remove excess material from the beat seats and prepare the aluminium interface bonding surface. The aluminium interface was then bonded to the outer rim with Loctite Aero 9309NA and an image of this part mocked up with the prepreg inner rim can be seen at figure 16.
C. Prepreg Layups

The modified outer mould was again used for the first prepreg run and 350mm x 350mm sheets of prepreg were cut with orientation identified in preparation for layup as seen in figure 17. Heating each layer with hot air improved drapability to minimise wrinkling; however, it was not entirely avoidable. The part was then vacuum bagged and figure 18 shows it placed inside the autoclave prior to curing. The autoclave was programmed to ramp the temperature up by 2°C/min to 120°C where it would be held for 60 minutes at six bar of pressure in accordance with the recommended prepreg cure rate (Gurit, n.d.). Curing temperature was monitored by a lag thermocouple positioned on the prepreg and recorded in the chart of figure 19. The heating elements were then switched off and the part allowed to cool at the same rate as the vessel. Figure 20 depicts the CFRP outer rim with the cure cycle complete and the part cooled sufficiently to remove vacuum bagging and handle.

The CFRP prepreg part was even more difficult to remove from the mould than the wet layup part and damage resulted to both the mould and part during separation. Resin had bonded with the aluminium surface of the mould which gave rise to a poor surface finish of the CFRP outer rim. Despite this, the profile thickness and integrity of the part was satisfactory based on visual inspection. From this experience it was apparent the same issues would occur with the inner rim mould so two modifications were made; firstly the mould was cut into three sections and fastened together with screw plates as shown in figure 21 to enable easy removal of the centre wedge piece and subsequent removal of the outer pieces, and secondly an additional layer of polytetrafluoroethylene (PTFE) lubricant was sprayed onto the mould surface prior to layup. Furthermore, draping single sheets over the inner mould would encourage significant wrinkling due to its large cylindrical shape so each layer was applied using 12 shaped cut-outs of prepreg as shown in figure 22. With approximately 5mm overlap of each new prepreg shape on the last, the number of layers was reduced from 15 to 13 to maintain the 3mm profile thickness desired. With layup complete, the CFRP inner rim was vacuum bagged and cured in the same manner as that of the outer rim.

During the cure of the CFRP inner rim the autoclave operator noticed that vacuum was lost, indicating a failure of bag sealing. On removal of the part from the autoclave there was a noticeable section of the bag which had pulled away from the baseplate, confirming the loss of vacuum. With the bagging material removed the CFRP inner rim was pictured at figure 23. The loss of vacuum resulted in a cured part that had not compacted tightly against the mould and the prepreg layers were not completely bonded to each other. The awkward shape of the inner mould contributed to difficulty in vacuum bagging and an alternate approach would be required for future runs of this part. Despite this, removal of the part from the mould was straightforward without any damage to the mould or CFRP, validating the modifications made to the inner mould and PTFE lubricant as a mould release agent. The completed CFRP wheel had a mass of 1.575kg which was significantly lighter than the 2.454kg aluminium wheel.
IV. Future Work

A. Topology Optimisation

An opportunity exists to optimise the outer rim shape together with the centre using topology optimisation software. This was initiated with Abaqus until the lack of correct software licence prevented continuation of effort in this area. A proof-of-concept exercise was then conducted in SolidWorks, also a product of Dassault Systèmes Simulia Corp. The wheel axis along with the bead seats and tyre-facing surface of both rim profiles were fixed in three-dimensional space relative to each other which created the remaining unfixed design areas for optimisation. The model was conducted with a 90° arc of the wheel profile to reduce computational demand and a hole was cut in the expected spoke region on the outer rim to encourage spoke geometry to form. With the load cases and boundary condition from FEA applied, areas in which material could be removed were visualised. Figure 24 shows that profile thickness of the inner rim could be reduced by approximately 50% which correlates with the low stress exhibited in this region from FEA. There is potential to further increase the mass savings and strength/stiffness of this prototype wheel through a topology optimisation design study and it is recommended that this be included in future development of the CFRP wheel with a complete, finely meshed model.

B. Test and Evaluation

Fabrication of the CFRP wheel is unfinished due to unanticipated delay accessing the autoclave and a lack of CFRP machining capability at UNSW Canberra. Additional fabrication runs of both the outer and inner rim are required to implement the lessons learnt from prior construction; most significantly, the use of PTFE lubricant to aid mould release of the outer CFRP rim and an improved vacuum bag used during cure of the inner CFRP rim. Once these parts are fabricated with no additional defects final machining shall occur to create the desired bead seat profile and bolt/spoke holes.

When assembled the CFRP wheel will be inspected for flaws and checked for porosity. Thickness of the sections will be checked for correctness and uniformity and fitment of a tyre shall be conducted to confirm it can function as intended - hold air and is able to be balanced. Finally, the wheel shall be tested for deflection at the bead seat to confirm strength and stiffness using the universal test machine at UNSW Canberra. Both the current aluminium wheel and the new CFRP wheel should be tested in this manner to compare empirical data and confirm the CFRP structure performs as expected from FEA.

V. Conclusions

This project has achieved the aim of designing and prototyping a CFRP wheel for the UNSW Canberra FSAE race car. There remains refinement of the layup and cure of the CFRP rim parts to produce high-quality parts without flaws or defects, and final machining is then required to produce the finished product. Due to the experience gained in completing a wet layup and subsequent prepreg layups the inner mould was successfully modified, and mould release was improved. FEA of the aluminium and CFRP wheel designs confirmed stress distribution is improved with lower magnitudes in the CFRP wheel. Load cases were developed to inform design of the CFRP wheel and dynamic force events can be approximated with static loads for the purposes of simulation in Abaqus. The work completed on this wheel can be leveraged to reproduce further wheels of the same, or improved with topology optimisation, design for reduced unsprung rotating mass resulting in a better performing vehicle.

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References


