# SELECTION OF TEST METHODS TO EXAMINE THE FRACTURE MECHANICS OF CARBON FIBRE COMPOSITE FLYWHEELS

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## Abstract

*Flywheels are devices that can store energy in the form of kinetic energy whilst allowing for high charge and discharge rates and providing a high efficiency. This makes them extremely suitable for applications in hybrid vehicles within the automotive industry. Yet before application in this industry can take place, the potential for failure and the associated failure mechanics of composite flywheels must be sufficiently well understood to control the risk to passengers. This paper outlines a study that aims to induce failure in CFRP flywheels such that the consequences of failure can be assessed and the implications for flywheel containment can be better understood. Following a review of flywheel failures and a consideration of the stresses in one particular composite flywheel rim, a number of defect scenarios are presented and a test programme is presented based upon these considerations.*

## 1. Introduction

Since composite materials have emerged, flywheels have become an increasingly feasible and efficient method for energy storage [1] as they offer a much higher energy storage density than other materials such as metals. Additionally their energy storage capabilities do not degrade with every discharge cycle and they have a low impact on the environment when compared to other energy storage devices such as batteries. Their high power density makes flywheels very suitable for applications in the automotive industry where frequent charge and discharge cycles at high power ratings are expected [2, 3].

For the successful application of composite flywheels in the automotive industry it must be assured that their use within the vehicle poses an acceptably low risk. Although a CFRP filament wound rim structure is inherently resistant to transverse failures (fracture in the radial direction), a number of flywheel failures have been reported in the literature. For example, a ‘Flywheel Safety and Containment Program’ supported by the Defence Advanced Research Projects Agency (DARPA) resulted in a number burst failures of composite flywheel rotors [4-6]. However, there is little detailed information about these failures and the associated fracture mechanisms in the literature. In another study at Oak Ridge National Laboratory in the USA some further details of the consequences of a flywheel burst were described in terms of the damage caused to the containment vessel. A detailed evaluation of this rotor failure is provided in [7]. Perhaps the most critical failure reported in the literature was an intentional burst failure of a flywheel rotor in Europe in 1995 that had fatal consequences for one of the test operators. In that case a flywheel was loaded unrealistically by installing soft iron on its inside causing high compressive stresses at the interface between the rims. Upon flywheel failure the resulting axial load overcame the vacuum seal in the rig so that the containment lid was forced open and rotor material was ejected at high speeds [4, 8].

A major aim of the present project is to develop a better understanding of the potential failure mechanisms in CFRP flywheels. A project entitled FLYSAFE - 'Flywheel-hybrid safety engineering' has brought together a consortium of all three of the UK's leading developers of flywheel-hybrid systems, together with two universities to research the fundamental mechanisms of composite flywheel failure, thus enhancing understanding and the development of standards, and accelerating market acceptance. The project lead partner is Ricardo and the further two industrial partners are Williams-Hybrid Power and Flybrid. The academic partners are Imperial College London and the University of Brighton. The project is supported financially by the industrial partners and the UK Technology Strategy Board.

Within this project a number of intact as well as 'made-to-fail' flywheels provided by the industrial partners will be tested at the University of Brighton using a test-rig that is currently being developed by the project lead partner, Ricardo. Modelling and analysis in addition to coupon testing to determine the fracture resistance for the various fracture modes is being carried out at Imperial College London. Details of this experimental programme and initial results are described within this paper.

## 2. Analysis of flywheel Stress Profiles

### *2.1. Generic stress profiles*

The stresses within a flywheel mostly stem from the centrifugal force caused by the rotation of the flywheel and interference stresses in between flywheel rims. Thermal residual stresses, moisture effects within the composite section of the flywheel and strain restrictions may add to these but only tend to have a relatively small influence [9-11]. The general stress profile observed in a flywheel with an inner steel hub and an outer hoop wound rim made from a CFPR composite is shown in Figure 1a and Figure 1b. These stress profiles have been computed by an FE analysis using the Abaqus 6.12 package where two separate analyses were carried out for the same flywheel; one modelling the full 3D flywheel, one carrying out a simplified 3D analysis.

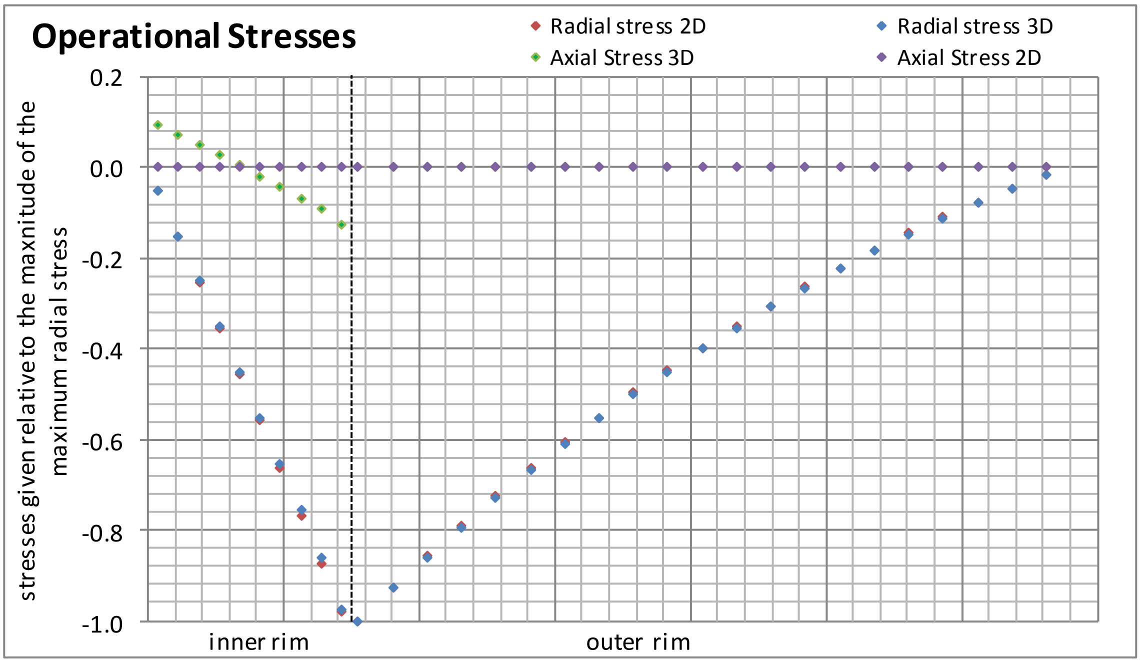

**Figure 1a.** Radial and axial stress profiles for both a 3D and a simplified 2D flywheel.

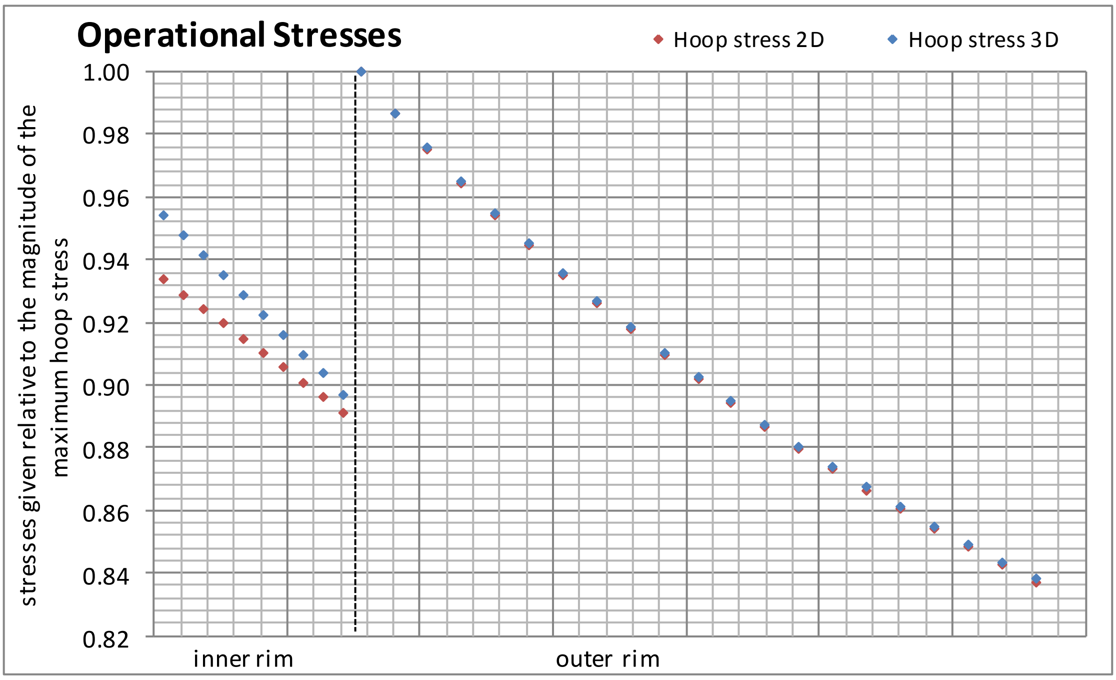

**Figure 1b.** Hoop stress profiles for both a 3D and a simplified 2D flywheel.

For CFRP flywheel rims which have been wound at a very low angle so that the fibres are essentially aligned purely along the hoop direction, the main stress acting is the hoop stress along the fibre direction. For this example, the hoop stress tends to be about 30 times higher than the magnitude of radial stress. Within each rim the hoop stress will peak at its inner radius.

### 2.2. *Modelling of the flywheel*

Both a full three-dimensional and a simplified two-dimensional model of the Flybrid flywheel have been generated using Abaqus. The analysis was based on the Flybrid flywheel design shown in Figure 2. Here two separate parts were used for the steel-hub and the composite-rim and meshes of similar density were used for both, resulting in a 26500 – element mesh for the steel hub and a 60900 – element mesh for the composite rim. A cylindrical coordinate system and a quad mesh such as shown in Figure 3 and Figure 4 were used. The interference stresses in between both rims and the stresses caused by the rotation of the flywheel at the operating speed of 60,000rpm were added in two separate steps.

**Figure 2.** Flybrid Flywheel

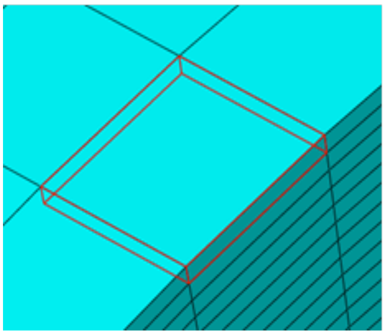

**Figure 3.** FE mesh

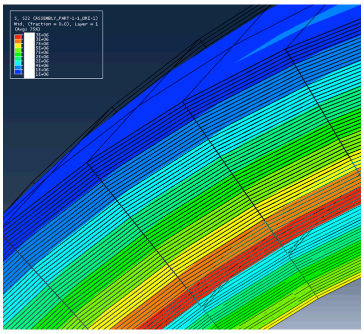

**Figure 4.** FE mesh

## 3. Fracture Modes

A crack along a plane within a material can grow in three different modes which are mode I where the crack is opened by tensional forces along the crack plane, mode II where the crack propagates due to shear forces acting along the crack plane and mode III where the crack is propagates due to torsional forces acting along the crack plane.

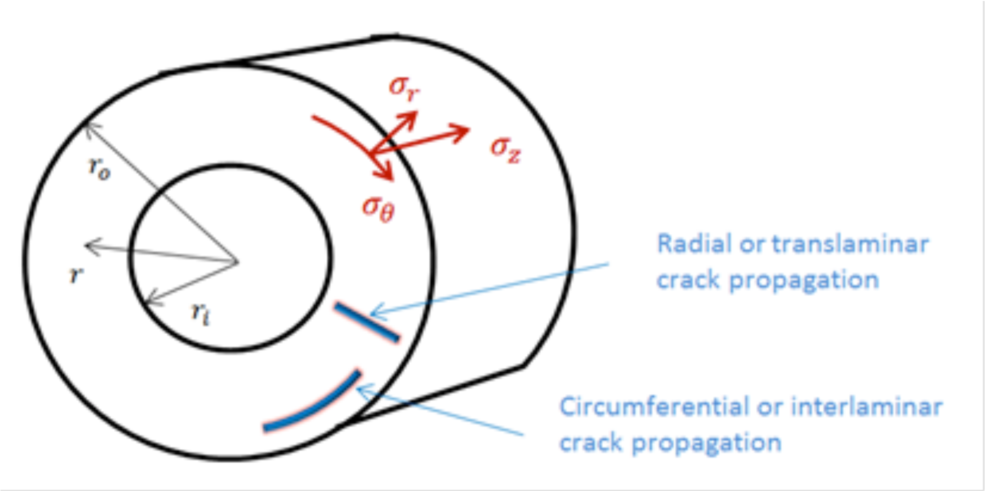

**Figure 5.** Stresses and ways of crack propagation within a flywheel

Figure 5 shows the stress co-ordinates and the direction of a number of crack propagation paths in a flywheel rim. Firstly, interlaminar crack growth can occur along the circumferential direction (between the hoop wound fibres). Secondly, translaminar crack propagation can occur along the radial direction (requires breaking fibres). The interlaminar cracks are driven by mode I through the radial stress component $\sigma_{r,}$ (if tensile) and by mode II through the axial stress component $\sigma_z$ as well as the shear stress caused upon acceleration and deceleration of the flywheel. Even though the stresses triggering the growth of such cracks are relatively small, circumferential cracks form most readily as wound CPFR rims have a very low resistance to interlaminar crack propagation. In the case of crack propagation in the radial direction, carbon fibres need to be broken and thus the resistance is much greater to this direction of fracture. However, the mode I opening of radial cracks is driven by the high magnitude stress $\sigma_\theta$ so thus the opening of radial cracks may be possible if a sufficiently sharp notch is present. Studies have shown that the critical notch tip radius for translaminar crack propagation is around 200μm [12].

As the flywheel designs considered have a purely compressive radial stress profiles the main modes of crack propagation to consider will be mode II propagation of interlaminar cracks and mode I opening of translaminar cracks. Whilst circumferential crack propagation will cause the flywheel to split into rings the opening of radial cracks could result in the flywheel bursting into larger segments that could then be ejected at high speed and would then need to be captured by the containment system. More complex fracture mechanisms may also arise in the flywheels and will be investigated as the study progresses.

## 4. Defect options for spin testing

In the FLYSAFE project, each industrial partner will fabricate flywheels for spin testing in the specially developed rig. This rig has been designed and built by Ricardo and is to be installed at the University of Brighton. Following the literature review into previously reported composite flywheel failures and after discussions with the industrial partners and the manufacturer where the filament winding of the CFRP rims is undertaken, the decision was taken to consider three different categories of defects in the project. These are: (i) a critical defect that will have a significant impact on the flywheel and is highly likely to cause failure but which is highly unlikely to occur in operation; (ii) a defect that could potentially be caused during the manufacture of the flywheel (but is still unlikely to occur in a commercial flywheel due to quality control) and (iii) an in-service defect that could potentially occur in a commercial flywheel in operation.

Critical defect scenarios considered included radial fibre cutting during (or post) manufacture of the composite rim as well as a combination of hole-drilling and sharpening. These approaches would remove the circumferential strength provided by the section of fibres cut which will increase the circumferential stress in the remaining section of the flywheel and give rise to stress concentrations. These defects are also likely to give rise to both interlaminar and translaminar crack propagation. The hole-drilling and sharpening method is considered most likely to give rise to translaminar crack propagation but mode II interlaminar crack propagation is also a possibility.

Manufacturing defect scenarios considered included an embedded material introduced unexpectedly during the winding process as well as an incorrect cure cycle being used. Another defect that could occur in manufacturing is a winding defect that can occur if the fibre tension throughout the winding process is not monitored correctly. Here the stresses caused by a varying winding tension can result in fibre-buckling that may then give rise to delamination sites and local stress concentrations as the flywheel is spun up.

Potential in-service defect scenarios considered included impact loading, to which the flywheel could be subjected during assembly or transport, and the occurrence of a loss-of-vacuum event in operation.

In the first series of spin tests, critical defects are to be introduced to give a high probability of flywheel failure. Initial preliminary tests by Flybrid showed that the composite rims were resistant to burst type failures when circular holes were drilled to the rims of varying diameters and depths, close to the CFRP/steel hub interface. In a more severe version of this defect scenario, a circular hole is to be drilled through the entire axial length and then the defect is to be sharpened prior to spin testing. Modifications to this procedure may be required as the research progresses. The other two project partners have designed modified versions of their commercial flywheels with narrower composite sections designed to fail at designated speeds in the spin test. The defects used in subsequent spin tests will be selected based upon the results of the first phase of the testing.
Table 1 shows the tests planned throughout the first series of spin testing, following which a further two series of spin testing will be carried out.

**Table 1.** Planned tests for the 1st flywheel spin test series in chronological order

| *Test No.* | *Flywheel* | *Defect* |
|---|---|---|
| 1 | Flybrid – 1st test series | Hole drilling and sharpening |
| 2 | Williams – 1st test series | Designed to fail |
| 3 | Ricardo – 1st test series | Designed to fail |

## 5. Fracture toughness testing

To predict how cracks will propagate within the flywheels the fracture toughness for the various proposed failure modes will need to be determined experimentally. As defined previously the most relevant crack propagation modes will be translaminar mode I and interlaminar mode II. As the flywheel rims are filament wound, coupon test samples are required to be cut from a manufactured flywheel rim. Initial samples have been prepared by water jet-cutting. It was decided that the most suitable coupons for the required tests could be obtained by cutting a ninety-degree section out of an intact rim such as shown in Figure 7 for the Flybrid flywheel design. Figure 6 shows two such resulting coupons.

**Figure 7.** Flybrid flywheel

**Figure 6.** Two coupon specimens

### *5.1. Translaminar mode I*

Fracture toughness tests (including those for arc shaped specimens) exist for metals [13]. For composite materials a standard using the extended compact tension specimen [14] exists [15] yet this test is designed to be performed on flat specimens and therefore is not directly applicable to the material coupons available. An alternative option is to use a three-point-bend test to determine the translaminar fracture toughness [16, 17] but this test has not yet been standardized for composite materials and is also normally applied to flat rather than arc shaped specimens. A first set of tests will be carried out using the method for arc shaped specimen defined in the ASTM E399 standard. Here a crack tip radius of 100µm will be used to ensure that the notch tip radius lies below the critical value.

### *5.2. Interlaminar mode II*

For interlaminar mode II toughness testing a number of toughness tests exists [18-20]. The main challenge here is to insert a sufficiently sharp initial crack into the material. In most test studies the initial defect is achieved by placing a thin insert of less than 13µm thickness into the sample as it is manufactured which gives a crack sharp enough to lie below the critical notch-tip radius [21]. As the coupon samples available for this study have already been manufactured the crack will need to be inserted manually by means of razor-tapping. Experimental work on how easily sufficient crack sharpness can be achieved by that method is currently being carried out.

## 6. Conclusion and outline of future work

Filament wound CFRP rims possess a high degree of resistance to burst failures in operation however, inducing such failures in designed-to-fail components is an important step towards demonstrating the adequacy of the containment and the overall safety case. Three types of defect scenario have been identified in this research and the initial tests are focusing on the first of these, the insertion of critical defects or the use of designed-to fail components. Stress analysis of the flywheel designs and measurement of the required fracture mechanics parameters for the composite materials is ongoing using arc shaped fracture specimens.

## 7. Acknowledgements

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