STRESS ANALYSIS OF A FILAMENT WOUND COMPOSITE FLYWHEEL DISK

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Keywords: composite flywheel disk, filament winding, mosaic pattern

1 Introduction

Composite materials are characterised by high strength-to-density and stiffness-to-density ratios. The blending of composite materials’ directional properties with the design optimisation provides greater opportunities to improve the performance of composite structures in comparison to their metallic counterparts. Moreover, the simplified fabrication techniques of composite structures with greater accuracy using latest computer-controlled automatic filament winding machines has broadened the range of applications of composite materials in different areas. A filament wound composite flywheel disk with optimal fibre trajectories [1-2] is an example of increasing number of optimal composite structures. A flywheel or spinning disk is a device designed to store energy in the form of kinetic energy and then release the energy when required. Flywheels can be made of either metals or composite materials. However, a composite flywheel is the most effective one with higher energy storage capacity per unit mass. It offers high power and energy densities without reduction in capacity under repetitive charge-discharge cycles [3]. Optimal composite flywheels can attain much higher rotational speed than metallic ones, and thus enhance the performance and service life in various applications. Moreover, low density of composite materials used in flywheel does not affect the kinetic energy storage capacity of the rotor because increased rotational speed compensates for lower mass.

Promising flywheel technology covers a variety of applications in different fields. Flywheels provide the substantial improvement of performance and service life in different applications such as, spacecraft, aircraft power systems, uninterruptible power supplies and planetary outposts and rovers [4-5]. Flywheels are used also in alternating engines, compressors, press and strike machinery. Composite flywheels offer increased energy density storage capability that is better than batteries which have slow loading and unloading cycle due to chemical process as well as short life [6]. In general, a structure’s mass can be reduced by 20-30% through the replacement of metal alloys by composite materials [2]. One of the major applications of composite flywheels is energy storage for satellites. A flywheel stores the energy generated by photovoltaic cells during passing half of the orbit with greater reliability and lower weight [7]. A flywheel also facilitates the recovery of the kinetic energy of a vehicle lost as heat during braking. It can store and release this kinetic energy in automotive vehicles in fractions of a second [8]. Flywheels can play an important role in preventing blackouts and also in regulating the functioning of not well-meshed networks in electricity distribution [9].

The concept of uniform stress filament-wound spinning composite flywheel disk composed of structural filaments of uniform cross-sections was presented by Kyser [1]. The fibres arranged as of a fine-mesh circular net forming curved load-carrying paths that spiral outward from the centre of the disk and maintain constant tension through the cancellation of decreasing fibre tension toward the centre due to radially directed loading and increasing fibre tension towards the centre because of inertia forces due to rotation. Bokov et al. [10] examined the optimum design of a flywheel in the form of a membrane shell of revolution formed by winding or placing of orthotropic reinforced strips and explored reinforcing paths for ensuring maximum bearing capacity while assessing the energy storage capacity of these shells. Seleznev and Portnov [11] demonstrated the chord winding process of composite-tape disk and showed that the variation of elastic properties along the radius must be taken into account in the stress analysis. An approximate method of the calculation of both mass and volume energy capacity of a chord flywheel was presented by Portnov and Kustova [12] and an analysis was also carried out to reveal the most effective combination of materials. Valiullin et al. [13] demonstrated the use of finite element method to calculate the stress-strain state of a composite flywheel having varying thickness and consisting of a ring with
fibres orientated in the circumferential direction and a peripheral shell made by winding along the lines of constant deviation from geodesic lines. Structural assessment of two circumferentially wound composite flywheel rotor assemblies was performed by Abdul-Aziz et al. [4] using finite element method. Dems and Turant [14] analysed optimally designed composite flywheels to maximize the accumulated kinetic energy of the flywheel. Vasiliev and Morozov [2] discussed the filament-wound composite spinning disk of uniform strength based on the monotropic model of unidirectional filaments as an example of optimal composite structures. In this design, the filaments are arranged in a circular net forming curved load-carrying paths as shown in Fig. 1 [2]. As can be seen, the resulting structure of each of the filament wound layers is composed of two plies with +φ and − φ orientation of the fibres which are interlaced in the process of continuous helical filament winding. As a result, the structure of the layer has the distinctive mosaic pattern. The effect of filament winding mosaic pattern on the strength of thin-walled composite cylindrical shells has been investigated by Morozov et al. [15-16]. The sensitivity of filament winding pattern on the compressive stability of filament-wound composite cylinders has been demonstrated by Jensen and Pai [17]. The effect of mosaic pattern on the filament-wound composite pressure vessels has been demonstrated by Mian and Rahman [18]. As has been shown, the evaluation of mechanical response of the filament-wound composite structures is considerably influenced by the incorporation of the mosaic pattern units in the analyses. However, thickness variation of filament wound structures has not been considered in these studies to explore the effect on stress state. Although composite flywheels hold great promises, a number of challenges need to be overcome for the better service and long-term performance which require the implementation of advanced design and analysis approach. Different studies have been performed to date dealing with composite flywheels to achieve the maximum performance under certain conditions. Most researches on flywheels aim to maximize the energy storage capability while keeping the mass of flywheels at minimum possible level. However, these studies are limited to certain considerations that can not fully encompass the actual configuration of composite structures. For instance, in-built mosaic pattern (MP) of the filament-wound composite spinning disk is one special feature that is generally overlooked in conventional modelling and stress analysis of such structures.

Filament wound composite structures are usually modelled and analysed as laminated shells using analytical or/and finite element solutions with the exploitation of mechanics of composite laminates that takes into consideration the number of plies, stacking sequence and fibre orientation [2, 15-16]. Hence, the conventional approach ignores filament-wound mosaic pattern configuration and thereby, the influence of this pattern on the stress distributions and effectively on the strength characteristics of the filament wound composite flywheel remain unexplored.

The present work investigates the effect of mosaic pattern on the stress state developed in the filament wound spinning composite disk. Modelling and analysis of the filament wound spinning disk have been performed in ANSYS considering two different mosaic pattern configurations around the circumference of the disk. Actual thickness variation has also been taken into consideration for the finite element model development of the filament wound disk. Results of the stress analyses have been compared with those obtained by conventional finite element modelling of laminated shells. The analysis is aimed to demonstrate the effect of mosaic pattern created during filament winding process on the assessment of mechanical response of the filament-wound spinning composite flywheel disk with varying stiffness properties.

2 Filament winding pattern architecture

The filament wound composite disk shown in Fig. 1 consists of an even number of antisymmetric ±φ angle-plies [2, 15]. The helical filament winding process results in interlaced plies in the disk. So the resulting angle-ply layer has a particular type of repeating filament winding pattern around the circumference and along the radius (Fig. 1). This pattern consists of ‘curved triangular’ shaped two-ply units with alternating ±φ and ±φ fibre orientation (see Fig. 2) repeating in a chess-board fashion [15-16]. So the filament wound layer of the disk is comprised of multiple number of mosaic units of varying size depending on the filament winding parameters [15]. The spinning composite disk shown in Fig. 1 is manufactured following the inverse fabrication process as the shape and reinforcement of the final product are given [19]. Hence, a shell of revolution is fabricated by filament winding onto an inflated elastic mandrel at the first stage. After finishing the winding of desired winding pattern, the wound shell is compressed in the axial direction between two plates while the pressure in the mandrel is continuously reduced. Consequently, the shell is transformed into a flat disk and then resin in the composite material is cured after the
transformation is complete. Therefore, the finished filament wound composite disk has an annular band of smooth continuously turning fibre paths tangent both to the outer and inner periphery [1-2].

Using the monotropic material model, i.e., neglecting the transverse \(\sigma_2\) and shear \(\tau_{12}\) stresses in the unidirectional ply, equation for the fibre orientation angle in the spinning composite disk of a radius \(R\) and having a central opening of a radius \(r_o\) is specified as follows [2].

\[
\sin \phi = \frac{R}{r} \sqrt{1 - \frac{\lambda}{2} \left(1 - \frac{r^2}{R^2}\right)}
\]  

(1)

where

\[
\lambda = \frac{2}{1 + \left(\frac{r_o}{R}\right)^2}
\]  

(2)

The thickness of the disk is specified by

\[
h(r) = \frac{kw_0\delta}{2\pi r \cos \phi}
\]  

(3)

where \(k\) is the number of fibrous tapes passing through the circumference \(r = \text{constant}\) and \(w_0\) and \(\delta\) are the tape width and thickness, respectively. The disk thickness varies depending on the values of radial location \(r\) and fibre orientation angle \(\phi\) as can be seen from Eq. (3).

### 3 Analysis techniques for filament wound structures

Filament wound composite structures are usually modelled as laminated shells composed of either homogeneous orthotropic or antisymmetric balanced \(\pm \phi\) angle-ply layers. The first approach assumes that the filament-wound shells are usually composed of a large number of \(\pm \phi\) angle-ply layers. Each \(\pm \phi\) angle-ply layer is treated as orthotropic and homogeneous. The second approach deals with the angle-ply layer as an antisymmetric balanced laminate consisting of \(+\phi\) and \(-\phi\) unidirectional plies. The angle-ply layer in this case consists of two plies with the same thickness and fibre orientation angles \(+\phi\) and \(-\phi\). Although a conventional finite element analysis (FEA) technique based on two aforementioned approaches provides greater flexibility over analytical solutions, the actual texture of the filament wound composite structures and mosaic pattern effects are not considered in widely used stress analyses employing commercially available FEA packages. The influence of mosaic pattern (MP) on the stress state developed in the filament wound composite rotating disk has been demonstrated in the present work by incorporating different mosaic pattern configurations in the modelling of the filament wound disk having varying thickness.

### 4 Finite element modelling of a filament wound flywheel disk

Results of the two dimensional plane stress finite element analysis of a filament wound composite spinning disk with various number of mosaic units around circumference are presented in the present paper. Both the development of finite element models and stress analysis of the filament wound composite spinning disk have been performed using ANSYS [20]. Modelling of the composite disk using SHELL181 element is governed by the first order shear deformation theory.

Thickness variation of the disk having four plies has been determined according to Eq. (3) using chosen values of \(k\), \(w_0\) and \(\delta\) from Table 1. The corresponding finite element model of the disk with varying thickness is shown in Fig. 3. Thickness at inner \((h_{r_o})\) and outer \((h_R)\) radii of the disk has been assumed to be constant as fibre orientation at these locations is obtained to be 90° from Eq. (1). Two approaches have been used to model the filament wound disk. Firstly, the disk has been modelled using conventional approach (CA) according to which the disk is modelled as a laminated circular plate composed of four plies \([+\phi(r), -\phi(r)]_s\) with each ply having the fibre orientation angle of either \(+\phi(r)\) or \(-\phi(r)\) all over the disk (see Fig. 4(i)). Interlacing of plies is not considered in this case. Clearly, the actual texture of filament wound composite disk produced due to the interlacing of the plies is not reflected accurately through conventional modelling. So to model the actual mosaic pattern configuration in the second approach, the disk has been partitioned into four and six mosaic units placed uniformly around the circumference as shown in Figs. 5(i) and 6(i), respectively. Correspondingly, the finite elements have been combined into the respective alternating groups. The composite material for the finite elements from each of these groups has been defined as either \([+\phi(r)/-\phi(r)/+\phi(r)/-\phi(r)]_s\) or \([-\phi(r)/+\phi(r)/-\phi(r)/+\phi(r)]_s\) laminate for both four and six-unit finite element models. Modelling and stress analysis of a filament wound composite disk with constant thickness and various number of mosaic units around circumference have been presented by Uddin et al. [21].

For each mosaic pattern unit, the layer configuration through the thickness of the disk is defined as layer by layer assembly starting from the bottom to the top. So, the bottom layer is counted as layer 1 and additional layers are stacked and numbered from the bottom to the top in the positive direction of the coordinate
normal to the reference surface. The middle plane of the laminate has been chosen as the reference surface. The layers of the filament wound composite disk under consideration have been reinforced along the radially varying fibre orientation trajectories $\phi(r)$ defined by Eqs. (1) and (2).

5 Stress analysis of the filament wound disk

Dimensions of the considered filament wound disk and material properties used for FEA of 4-unit and 6-unit models are listed in Table 1. The disk has been rotated about its central axis at a constant angular velocity. Displacement and rotation boundary conditions have been applied at the nodes on inner and outer radii along both $x$ and $y$ axes (see Fig. 4(i)) of the working plane to prevent in-plane rigid body motion in both radial and circumferential directions and out-of-plane rigid body motion in axial direction.

Radial ($\sigma_r$), tangential ($\sigma_\theta$) and shear ($\tau_{r\theta}$) stress distributions obtained for the top layer (layer 4) of different models are shown in Figs. 4 to 6. As can be seen, the stress distributions in the disk models with mosaic pattern differ substantially from those calculated on the basis of conventional modelling of laminated shells. The comparison of contour plots of various stresses for 4-unit (Fig. 5) and 6-unit (Fig. 6) disks clearly illustrates that the number of mosaic units around the circumference has significant effect on generated stress profiles that show diverse stress distributions at different locations of the disk.

Moreover, the levels of maximum values of stresses due to rotational loading are also influenced by the incorporation of actual structural characteristics, such as mosaic pattern. For instance, the peak radial stress obtained from 4 and 6-unit models is about 22 and 45 percent higher, respectively than that from conventional finite element analysis. Similarly, the maximum level of $\sigma_\theta$ predicted from 4 and 6-unit models is about 31 and 15 percent higher, respectively compared to that from conventional analysis. Contour plots of $\tau_{r\theta}$ also indicate greater fluctuation of the level of magnitude in case of mosaic pattern configuration. Contour plots of stresses along and across fibres, $\sigma_1$, $\sigma_2$ and shear stress, $\tau_{12}$ acting in different plies of the disk also demonstrate the distinctive variation of stress values among various mosaic units.

It follows from the contour plots of stresses shown in Figs. 5 and 6 that in the real structure of the filament wound disk the stresses vary considerably from one mosaic unit to the adjacent ones both in the radial and circumferential directions. This is illustrated in Figs. 7 to 11. Stress distributions around circumference (0° to 180°) have been shown at a radial distance of 0.23885 m for both 4 and 6-unit disks (see Figs. 7 to 9). At this radial location, two different mosaic units are arranged circumferentially in alternating fashion. These units are denoted as “Zone A” and “Zone B” in the stress plots.

Distributions of both radial, $\sigma_r$ and tangential, $\sigma_\theta$ stresses around circumference of 4-unit disk (see Fig. 7) show that the stress values are substantially different from those obtained from the conventional finite element analysis. The real variation of stresses in the disk due to mosaic pattern configuration is not predicted by the conventional approach. Furthermore, the distributions of both $\sigma_r$ and $\sigma_\theta$ obtained from FEA of models with mosaic pattern maintain noticeably different levels of stress values at various locations compared to that calculated by conventional technique. With regard to the levels of magnitude predicted by conventional FEA, maximum 78 percent difference in $\sigma_r$ values and 75 in $\sigma_\theta$ values are realized.

Similarly, distributions of both $\sigma_r$ and $\sigma_\theta$ around circumference for 6-unit disk (see Fig. 8) also demonstrate the difference in calculated stress values from one mosaic unit to the adjacent ones while the conventional technique predicts different distributions of stresses. The circumferential distribution of $\tau_{r\theta}$ shown in Fig. 9 also illustrates highly varying values predicted from both 4 and 6-unit disks. On the other hand, conventional FEA predicts dissimilar fluctuation of shear stress values. Circumferential distributions of $\sigma_1$, $\sigma_2$ and $\tau_{12}$ obtained from FEA of disks with mosaic pattern configuration also reflect the influence of the specific mosaic pattern texture of the composite materials. Therefore, the circumferential distributions of stresses clearly indicate the limitations of the conventional finite element analysis approach in analysing filament wound spinning composite disk as actual mosaic pattern is not incorporated in the conventional modelling.

To demonstrate the limitation of the conventional approach in analysing filament wound spinning composite disk, stress distributions along the radius have also been plotted for a radial section of the disk. The stress distributions in the radial cross-section orientated at 45° counter clockwise from $+x$ axis are shown in Fig. 10 for 4-unit disk and in Fig. 11 for 6-unit disk. The first unit of the mosaic pattern located in this radial cross-section and referred to the inner radius has been denoted as “Zone 1” and other consecutive units have been numbered sequentially.

Comparison of stress distributions in different zones also clearly shows the variation of stress values obtained from mosaic pattern models and conventional
FEA. Results obtained from conventional FEA of 4-unit disk do not reflect the variation of both $\sigma_r$ and $\sigma_\theta$ in different mosaic units as shown in Fig. 10. With regard to the results obtained from conventional technique, various levels of variation of stress values are achieved from disks with mosaic pattern configuration. The maximum level of difference in $\sigma_r$ values reaches 55 percent, whereas values of $\sigma_\theta$ maintain 63 percent difference compared to the values determined using conventional FEA.

Similarly, the distributions of $\sigma_\theta$ and $\sigma_2$ along the radius for the conventional model and 6-unit disk shown in Fig. 11 also demonstrate the difference of calculated stress values. For this case also, the maximum levels of difference in $\sigma_\theta$ and $\sigma_2$ values reach 55 and 35 percent, respectively compared to the values from conventional analysis. Depending on the location of radial cross-section, the maximum level of variation of stress values predicted from mosaic pattern models fluctuates considerably in comparison with those from conventional FEA. The difference of calculated stress values in various mosaic units can be observed also in the distributions of $\tau_{1\theta}$ and $\tau_{12}$. Hence, the significant influence of filament winding mosaic pattern on the stress state of the filament wound composite flywheel disk can be observed also from radial distributions of stresses at different radial cross-sections.

The influence of mosaic pattern configuration on the stress state of the disk can be clearly noticed also by comparing the calculated maximum values of stresses acting in different plies. As can be seen from maximum values of stresses listed in Table 2, the overall maximum stress values predicted using mosaic pattern models are substantially different from those values obtained using conventional FEA (e.g. $\sigma_1 = 2355$ MPa (conventional) and $\sigma_2 = 2832$ MPa (6-unit disk) in layer 3). It appears that with the increase of number of mosaic units from 4 to 6 and corresponding reduction in the relative size of each unit, maximum values of stresses acting along and across fibres, $\sigma_1, \sigma_2$ increases. It indicates that the level of stresses developed in the filament wound flywheel disk could be underestimated to a certain extent by the stress analysis on the basis of conventional mechanics of laminated shells.

6 Conclusions

The finite element modelling and analysis of the filament wound composite flywheel disk have been performed to demonstrate the effect of mosaic pattern created during a filament winding process on the stress distributions and effectively on the strength of the structure. The real structure of the filament wound disk composed of the interlaced plies has been replicated more accurately in the finite element modelling. The calculated stress values in different layers obtained from the disk models with actual thickness variation and mosaic pattern differs substantially from the stresses determined using conventional analysis technique of laminated shells. The results clearly show the sensitivity of the mechanical behaviour of filament wound composite disk to the effect of mosaic pattern configuration on stress distributions in different plies. The actual stress distributions could remain undetermined if mosaic pattern as well as real thickness variation is disregarded in the analysis process. The methodology proposed in this work would be helpful in designing filament wound spinning disks having radially varying fibre orientation angles.
Fig. 3. Finite element model with varying thickness

(i) Conventional model

(ii) $\sigma_r$

(iii) $\sigma_\theta$

(iv) $\tau_{r\theta}$

Fig. 4. Conventional finite element model and corresponding contour plots of radial, tangential and shear stresses in annular filament wound composite spinning disk
Table 1: Dimensions and material properties for a filament wound composite spinning disk

<table>
<thead>
<tr>
<th>Dimensions (m)</th>
<th>Material</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius ( R ) – 0.30</td>
<td>IM6 – Epoxy (carbon-epoxy)</td>
<td>( E_1 = 203.0 \times 10^9 ) Pa</td>
</tr>
<tr>
<td>Inner radius ( r_o ) – 0.1016</td>
<td>Density – 1600 kg/m(^3)</td>
<td>( E_2 = 11.2 \times 10^9 ) Pa</td>
</tr>
<tr>
<td>( h_{r_0} ) – 2.5( \times )10(^{-2})</td>
<td>( k = 484; \delta = 0.7 \times 10^{-3} ) m</td>
<td>( G_{12} = 8.4 \times 10^9 ) Pa</td>
</tr>
<tr>
<td>( h_R ) – 1.0( \times )10(^{-2})</td>
<td>( w_0 = 4.0 \times 10^{-3} ) m</td>
<td>( v_{12} = 0.32 )</td>
</tr>
<tr>
<td>( v_{23} = 0.47 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. 4-unit finite element model and corresponding contour plots of radial, tangential and shear stresses in annular filament wound composite spinning disk
Fig. 6. 6-unit finite element model and corresponding contour plots of radial, tangential and shear stresses in annular filament wound composite spinning disk.

Fig. 7. Distributions of (i) $\sigma_r$ and (ii) $\sigma_\theta$ around circumference for 4-unit disk.
Fig. 8. Distributions of (i) $\sigma_r$ and (ii) $\sigma_\theta$ around circumference for 6-unit disk

Fig. 9. Distribution of $\tau_{r\theta}$ around circumference for (i) 4-unit and (ii) 6-unit disk
Table 2: Maximum stresses from FEA of conventional and mosaic pattern models

<table>
<thead>
<tr>
<th>Filament winding patterns</th>
<th>$\sigma_r$ (MPa)</th>
<th>$\sigma_\theta$ (MPa)</th>
<th>$\sigma_1$ (MPa)</th>
<th>$\sigma_2$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer number</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Conventional model</td>
<td>1080</td>
<td>890</td>
<td>1931</td>
<td>1954</td>
</tr>
<tr>
<td>4-unit disk</td>
<td>884</td>
<td>868</td>
<td>1564</td>
<td>1556</td>
</tr>
<tr>
<td>6-unit disk</td>
<td>1254</td>
<td>1064</td>
<td>1887</td>
<td>1908</td>
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References