ABSTRACT

The paper discusses failure modes for composite high speed flywheel-rotors for energy storage application and an optimization of the energy distribution between rotational and translational energy of the debris. The paper shows a proposed test rig for destructive spin tests, measuring the tangential and radial forces and the torque at the containment.

FAILURE MODE AND SAFETY CONSIDERATIONS OF HIGH SPEED ROTORS

In the last few years high speed rotors have become more and more popular. New materials allow the manufacturing of light rotors with high energy densities. The fields of application of these rotors are for example energy storage, medicine, chemical engineering and transportation. For the application of such rotors, safety considerations necessitate their operation in safety containments. In case of a rotor failure the containment must retain all debris. The failure behaviour of the rotors depend much on the type of rotor-material. Isotropic materials show a different failure behaviour than orthotropic materials. Large, sharp-edged fragments with high energy content, composed of hard materials are more likely to penetrate a safety containment than many small fragments. Small fragments put a well distributed load on the containment and therefore avoid lumped overload.

FAILURE OF ISOTROPIC MATERIALS ROTORS

It is well known that isotropic-material rotors only break into a few fragments which have a mainly translational motion with only little rotation (Figure 1). Large fragments with high translational speeds are difficult to retain in a safety containment. Fragments with rotational speeds are not likely to penetrate a containment. Their rotational energy

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dissipates due to friction on the walls of the containment and also between different fragments. (Genta, 1985; Coppa, 1983)

Since the translational energies of isotropic-material debris are much higher than the rotational energies the containment must be designed to retain this type of debris to avoid penetration. The use of massive steel containers or even concrete tunnels is recommended.

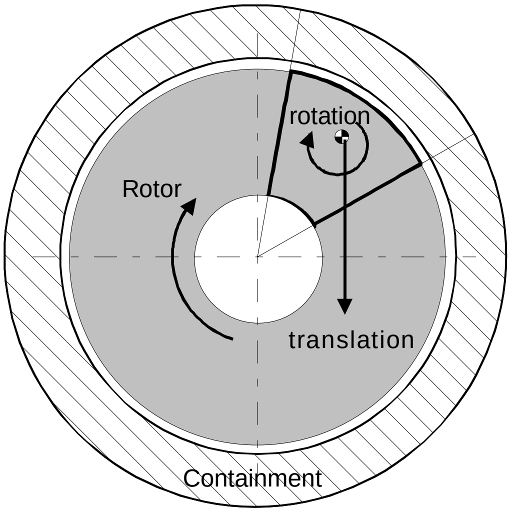

Figure 1: Failure Mode of a Metal Rotor

FAILURE OF ORTHOTROPIC MATERIAL ROTORS

ASPES AG develops low cost high speed composite rotors. The rotors are manufactured with the woven ribbon winding process. (Widmer, 1985) A woven ribbon is impregnated with epoxy resin and wound directly onto a steel hub. Variation in pretension and the selection of different fibres material layers allow the optimization of radial and tangential stress distribution within the thick rim rotor.

Modern composite high speed rotors (Photo 1) are operated at peripheral speeds in the range of 500 to 1’000 m/s. These rotors are run in an evacuated safety containment to avoid drag-losses and to minimize damage in case of a rotor failure.

Photo 1: High Speed Composite Rotor

Orthotropic composite rotors show a more benign failure behaviour with development of many small fragments during the burst. This small debris has less energy content than large ones and therefore allows lighter containments and less safety requirements than needed for mobile applications.

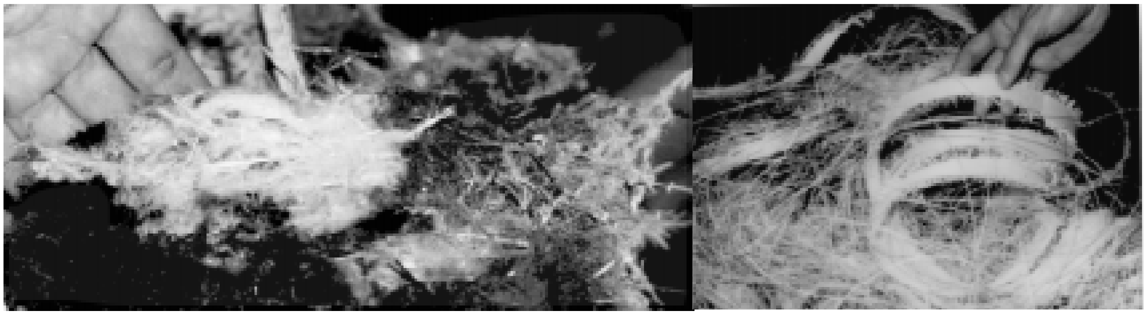

Photo 2: Debris of a High Speed Composite Rotor

Photo 2 shows two significant types of debris: very small powder-like composite material and pieces of the fibre ribbon. The composite powder indicates that part of the stored kinetic energy is converted into tensile break energy. The ribbon type fragment indicates that some of the initial energy is dissipated in the delamination of the composite. However from this post-failure photo (Photo 2) it is not clear how much composite powder developed during the initial failure of the rotor and how much pulverized during the spin down of the debris at the walls of the containment.

From this observation, two failure hypotheses can be formulated: The failure is either due to breaking of the fibers or due to delamination however rotor design can influence both types.

FAILURE THEORY

To understand the failure modes of composite rotors and their influence on the containment and therefore on safety, it is important to consider the following theory.

First of all, the translational and rotational energy of a fragment can be estimated without any energy dissipation. This gives an idea of the amount of energy to be absorbed by the containment energy dissipation.

Secondly it is possible to estimate the energy dissipation by deformation work during the failure of the rotor. Deformation work will mainly be transformed into heat. The understanding of the crack propagation will round up the theory.

TRANSLATIONAL AND ROTATIONAL ENERGY

The kinetic energy (E_{kin}) of a rim type rotor is

(1)

Where J: momentum of inertia
m: mass
r_o: outer radius
r_i: inner radius
ω: rotational speed

Neglecting the breaking energy, it is possible to calculate the translational and rotational energy of any size of fragment using the law of conservation of energy.

Assuming a fragment with an extent α then the radius r_S to its centre of gravity (Figure 2) becomes

(2)

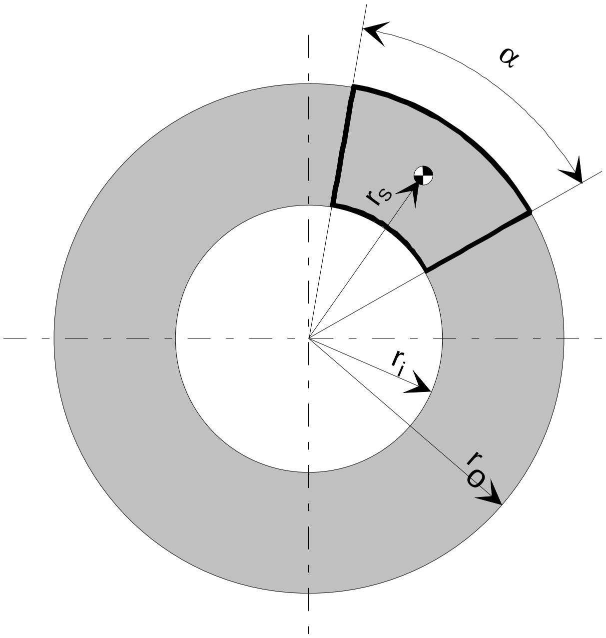

Figure 2: Geometry of a Fragment

The fraction of translational energy at break-speed compared to the total kinetic energy stored in the rotor will be:

(3)

Where m_f: mass of the fragment
m_r: mass of the rotor.

The fraction of rotational energy at break-speed compared to the total kinetic energy stored in the rotor will be:

$$\frac{E_{kin,rot,break}}{E_{kin}} = \frac{\alpha}{2\pi} \tag{4}$$

The results of the equations (3) and (4) are plotted in diagrams 1 and 2 for disk-type and rim-type rotors.

Diagram 1 shows the total tangential and radial energy of the broken rotor at different fragment sizes expressed with the angle α. It is assumed that the rotor breaks into equally shaped fragments.

Diagram 2 shows the energy of a single fragment. The size of the fragment is expressed with the angle α.

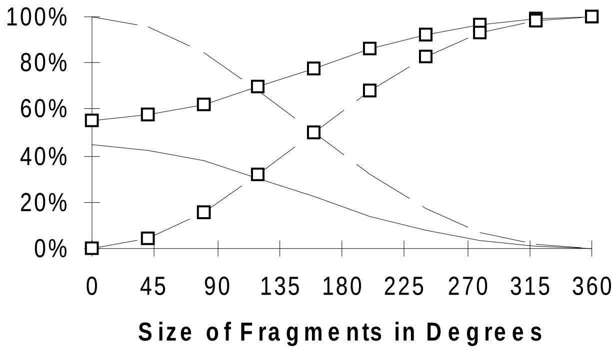

Diagram 1: Total Energy at Different Fragment Sizes

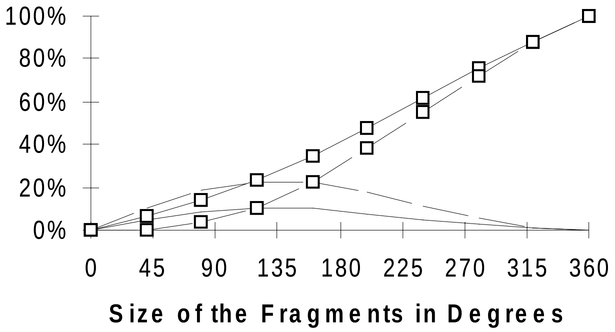

Diagram 2: Energy of a Single Fragment

—□— disk-type rotors, rotation

—— disk-type rotors, translation

– □ – ring-type rotors, rotation

– – – ring-type rotors, translation

This shows a smaller translational energy for thin rim fragments than others. Small translational energies do not easily penetrate the containment of the rotor. The large amount of rotational energy can dissipate at the walls of the containment over a long period of time and is therefore not dangerous.

However, the well distributed load on the containment from the powder-like fragments of composite material is assumed to be very small.

ENERGY DISSIPATION

The rotors discussed in this paper show clearly two types of debris: the fine powder-like composite material, indicating breaking of the fibres and long fibre ribbons, indicating delamination failure.

From observations made in burst tests it is difficult to make a statement about the amount of energy dissipated through initial delamination, the energy dissipated through initial breaking fibers and the energy dissipated through friction at the walls of the containment after the initial burst. The shape of the debris after the burst therefore does not allow any conclusions about the situation at the beginning of the burst or during the burst.

By considering only the deformation work of the two possible modes of failure (delamination or breaking fibres) no satisfactory results are obtained. According to these data only a fraction of the initial energy content can be dissipated by delamination and breaking energy.

The deformation work (E_f) for the tensile breaking of the fibres is:

$$E_f = \frac{1}{2} * \int_V \sigma_{\mathrm{II}} * \varepsilon_{\mathrm{II}} * dV \tag{5}$$

The deformation work (E_d) for delamination is:

$$W_d = \frac{1}{2} * \int_V \sigma_{\perp} * \varepsilon_{\perp} * dV \tag{6}$$

The specific breaking energies for composite material are shown in Table 1.

Fibre Material	Fibre Orientation	Spec. Deformation Work (kN/m^2)
GRP E-Glas 60 vol%	90°	163
	0°	27’234
CRP 60 vol%	90°	45
	0°	16’597
GRP S-Glas 60 vol%	0°	81’318
Kevlar® 119 60 vol%	0°	61’959
Dyneema®	0°	241’231
Spectra 900®	0°	16’900
Steel	0°	900

Table 1: Specific Deformation Work for Composite Material

This data shows the importance of the type of material used in order to convert most of the energy dissipated into initial breaking energy. The effect of delamination on the dissipated energy seems to be smaller than the breaking energy of the fibres.

By choosing the right fibre the failure behaviour of such rotors is influenced. The goal of the rotor-design should be to dissipate as much energy as possible into breaking energy and at the same time minimize translational energy of the debris.

CRACK PROPAGATION IN COMPOSITE MATERIAL

Crack propagation in composite material is completely different from that in an isotropic material. In case of the failure of an isotropic rotor, a crack can develop very fast, beginning with an elastic deformation which results in a plastic deformation and finally develops a crack orthogonal to the direction of the initial overload.

Orthotropic material failure starts with a shear overload in an interlaminar region. After an initial fibre failure, the crack develops not orthogonal but in direction of the laminate. In the case of our rotors the crack develops in a circumferential direction. This does not result in an immediate failure of the rotor, but as soon as the first fibre reaches its ultimate break load an initial braking of a fibre occurs and a second interlaminar failure can develop. This phenomenon produces an imbalance of the rotor.

TEST RIG FOR BURST TESTS

The hypothesis discussed above has never been proven by practical tests. Therefore all safety containments have to be overdesigned and many users of high speed rotors still fears the failure of composite rotors. To prove the hypothesis that most of the energy content of the rotors is dissipated in the delamination, breaking and rotational energy during the first phase of the rotor failure, we suggest the following test rig.

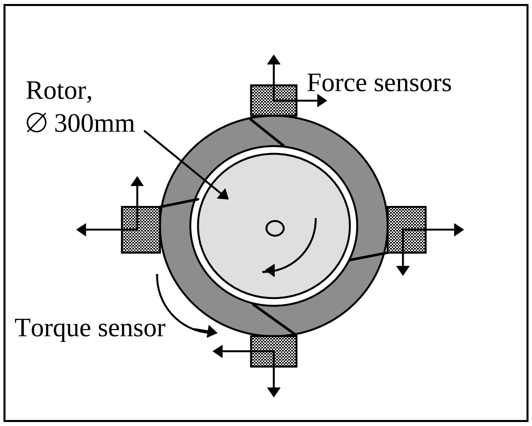

Figure 2: Sketch of the test rig with directions of measured forces

The test rig is mounted in a conventional burst test facility and is able to measure the reaction of radial and tangential forces as well as the torque of a bursting composite rotor.

The forces and torques are obtained at a measuring rim equipped with piezo-capacitive force sensors.

Rotors with different material combinations will be manufactured and their failure behaviour studied within the test rig.

CONCLUSION

Practical burst tests of different composite high speed rotors are carried out in a special test rig to obtain experimental data on the load applied to the safety containment.

Tangential and radial forces as well as the torque measured on the test containment ring, will be monitored and stored with a high speed data logger. The data obtained will serve as a basis for the model of calculation of high speed rotor containments.

Without such tests it is almost impossible to identify and optimize the failure mode of a rotor and discussions about safety of high speed rotor containment lack of realistic data.

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Title: Failure of Tangentially Wound Composite Energy Storage Flywheels
(Safety aspect of rotor bursts)

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