THE APPLICABILITY of WOOD TECHNOLOGY KINETIC ENERGY

Using technology that has been known for more than thirty years, ordinary wood can be processed into flywheels having performance comparable to the best modern steel flywheels. Also, since wood is an anisotropic composite material, its rotational failure mode should closely approximate the energy-dissipating failure modes recently demonstrated with other composite materials. This characteristic, together with significant configuration advantages of the wood flywheel, will result in substantial improvements in flywheel safety, compared to solid steel flywheels. But clearly the outstanding advantage of the wood flywheel for many applications is that its cost will be a tiny fraction of the cost of other composite or steel flywheels—and even considerably less than its chief competitor, the lead-acid battery.

Introduction

RECENT STUDIES OF POTENTIAL FLYWHEEL APPLICATIONS[1, 2] have produced the rather interesting conclusion that, next to safety, the most important requirement for most future flywheel systems will be low cost, rather than high performance, as expected. There is good reason for optimism on the question of safety,[3] but until now the prospects for very low cost have not been so promising.

This discussion will be concerned with wood—a material that will give future flywheels (a) an energy storage capability comparable to the best steel flywheel;[4] (b) a flywheel safety comparable to other flywheels made of filamentary composites; and (c) a flywheel cost that will be an order of magnitude lower than the best high performance flywheels.

Superflywheel Characteristics

There are a number of flywheel configurations based on the optimum use of many new super composite materials that have a much greater strength-to-density ratio than the best isotropic materials. These Superflywheels, as they are known, use essentially straight-filament anisotropic composite materials, much like wood.[1, 2, 3]

Two basic Superflywheel configurations that are particularly applicable to the wood flywheel are shown in Fig. 1. The one thing that these configurations have in common is that the unsupported sections of the rods are radially oriented and, hence, are in pure tension during operation of the flywheel. This is why they are so applicable to the anisotropic composite material, which has strong unidirectional strength characteristics.

A third configuration, which has been described briefly elsewhere,[3] is called the pseudo-isotropic flywheel; it is shown in Fig. 2. It is comprised of many layers of thin sheets of anisotropic composite

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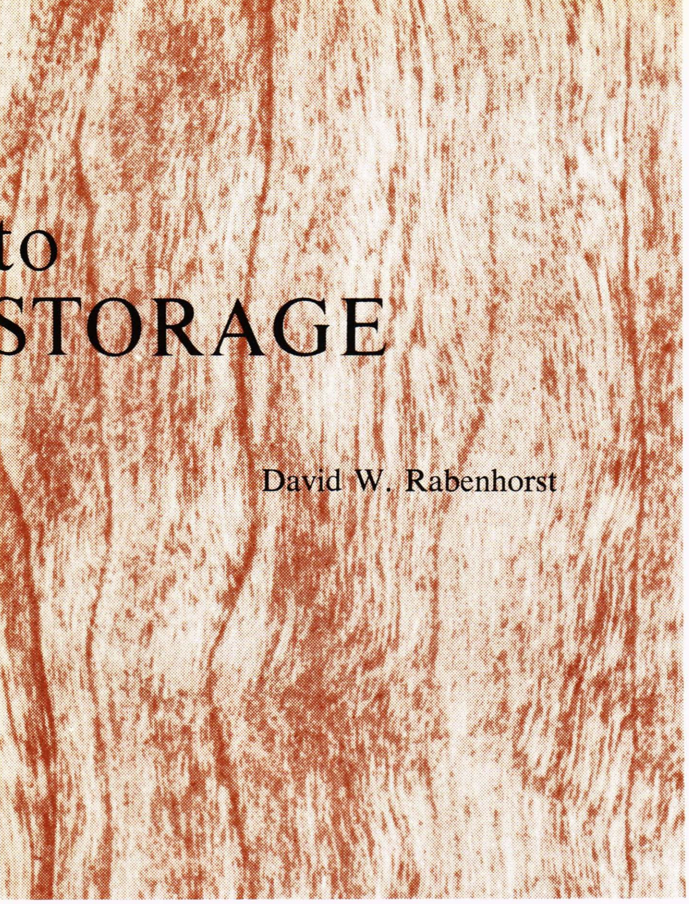
[1] D. W. Rabenhorst, *Primary Energy Storage and the Superflywheel,* APL/JHU Report TG 1081, Oct. 1970.

[2] D. W. Rabenhorst, *Potential Applications for the Superflywheel,* SAE Paper #719148, Aug. 1971.

[3] G. L. Dugger, A. Brandt, J. F. George, L. L. Perini, D. W. Rabenhorst, T. R. Small, and R. O. Weiss, *Heat-Engine/Mechanical-Energy-Storage Hybrid Propulsion Systems for Vehicles—Final Report,* APL/JHU Report CP 011, Mar. 1972.

[4] R. R. Gilbert, J. R. Harvey, G. E. Helier, and L. J. Lawson, *Flywheel Feasibility Study and Demonstration—Final Report,* Lockheed Missiles and Space Company Report LMSC-D007915, 30 Apr. 1971.



to STORAGE

David W. Rabenhorst

material, oriented to result in an averaging effect of the unidirectional properties of the sheets.

The flywheel has many advantages over other types of energy storage. Of these, two more than any of the others account for the selection of flywheel energy storage in the applicable hardware programs under way at the present time in several countries. These are:

1. The flywheel is easily capable of the maximum desired power density during both input and output.
2. There need be no limit to the number of charge/discharge cycles, or to the depth of discharge.

In addition to these advantages, the Superflywheel has three further, very important advantages over the conventional steel flywheel, namely:

1. Safety—it can be seen from Fig. 1 that the basic Superflywheel configurations are comprised of a very large number of very small elements, the failure of any one of which will represent a very small portion of the total energy in the flywheel. Thus, by making the length of each of these elements slightly different, they would be subjected to different stress levels, and it thus would not be possible for all of them to fail from overspeed at the same time. Also, in the unlikely event of the simultaneous failure of all of the elements, the impacts will be distributed evenly around the container walls. In addition, recent Superflywheel destruction tests of filamentary composite materials demonstrated that the materials disintegrate upon rotational failure in a manner in which less than 2% of the kinetic energy reaches the container wall. Together, these three features imply that Superflywheels will have significantly greater safety than any solid steel flywheel.
2. Performance—In addition to the important safety aspect, the optimal use of the unidirectional strength of the composite materials will result in Superflywheels having many times the performance of current flywheels in terms of energy density per pound of rotor.
3. Cost—Superflywheels made from promising new materials just now coming on the market will be several times less expensive than the steel fly-

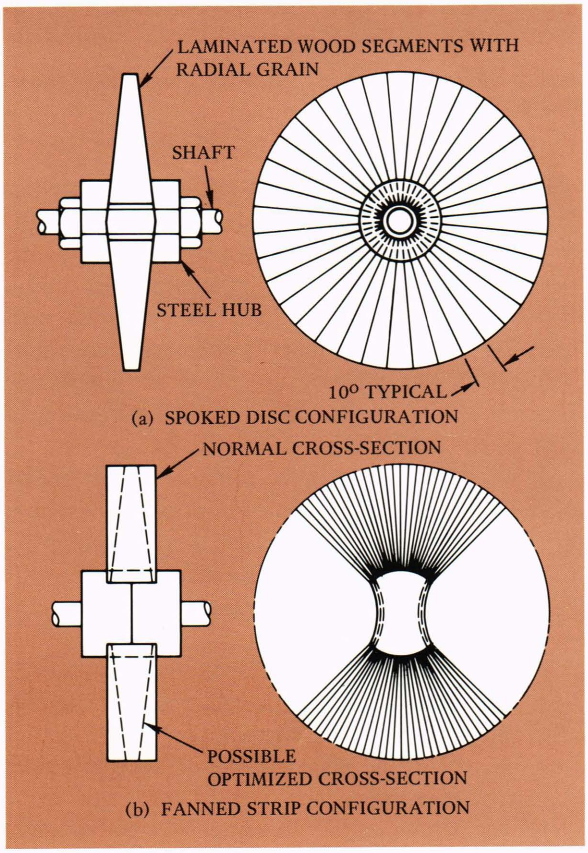


Fig. 1—(a) Spoked disc configuration; (b) Fanned strip configuration.

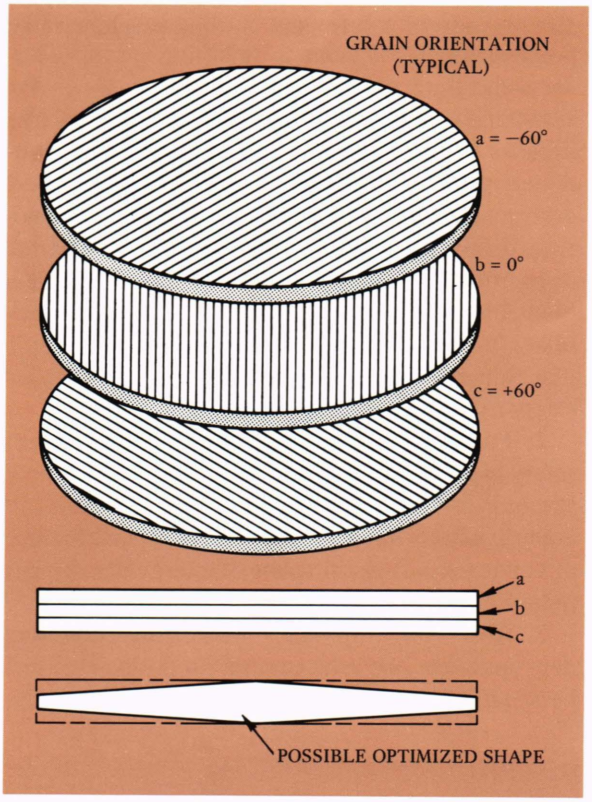


Fig. 2—Pseudo-isotropic flywheel (laminated anisotropic layers).

wheels in terms of watt-hours of stored energy per dollar, because these materials will have strength-to-density ratios more than ten times those of the best applicable steels, and at comparable costs. But by far the most important aspect of the cost question is that the Superflywheel configurations will permit the effective use of wood, which will provide another order of magnitude reduction in cost.

It would appear that the material requirements of the Superflywheel are just about ideal for wood, or, for that matter, for any high strength material. Consider the following requirements:

- Operation will be nominally at room temperature.
- The loading will be in essentially pure tension.
- Operation will be in a vacuum, with no significant oxygen or water vapor.
- There will be no corrosive or contaminating environment.
- The stress in the elements will be virtually unidirectional, although some of the configurations discussed for the wood applications will also have a low magnitude transverse requirement.
- Unlike most structural applications, there is no requirement for high modulus of elasticity.
- Unlike most structural requirements, there is no requirement for a light weight, per se. In fact, for a given strength-to-density ratio, it is usually better to have the material as heavy as possible in order to minimize the volume requirements.

The Applicability of Wood and Wood Products

Unquestionably, one of the most predominant characteristics of wood is its variability, whether this be from one species to another, or within a species because of growth defects or other damage. It is this wide range of variability that accounts for the fact that the allowable stresses for wood when used as a building material are so very much lower than the measured stress capabilities. Most of these defects can be either eliminated or avoided in the Superflywheel application.

The amount of energy that any flywheel can store depends upon the strength/density of the rotor material times some constant, K, relating to the particular geometry of the flywheel in question. Unfortunately, the ultimate tensile strength of wood is masked by so many arbitrary factors that it is often difficult to determine. It will be seen that when these factors that do not pertain to the flywheel application are eliminated, the strength-to-density ratio of most woods can be higher than those of most high strength steels. This means that, even with a much lower geometric efficiency (K factor, above), the performance of the wood flywheel will be comparable to the best steel flywheels. This would not be particularly important, were it not for the fact that the cost of the wood flywheel will be about ten times less than the comparable steel flywheel. Also, it should be many times safer than the steel flywheel, since it can comprise a large number of elements, each one made from a very frangible composite material (wood). Considerable additional cost advantages should accrue from lower fabrication expense of the wood flywheel, compared with other materials. Other advantages will be pointed out in the following sections.

The Anatomy of Wood—Wood is a naturally formed, organic material consisting essentially of elongated tubular elements called cells arranged for the most part in a parallel manner. These cells vary in dimensions and wall thickness with position in the tree, age, conditions of growth, and species of tree. The walls of the cells are formed principally of chain molecules of cellulose, highly polymerized from glucose residues, and oriented as a partly crystalline material. These chains are aggregated in the cell wall at a variable angle, roughly parallel to the axis of the cell. The cells are cemented by an amorphous material called lignin.[5]

In general terms, wood is constituted of 60% cellulose, 28% lignin, and 12% sugar and extractives. Thus, the structural composite portion of the wood only accounts for about 88% of its weight. It is also of interest that the specific gravity of these constitutents is about 1.5, regardless of the species of the wood.[6] This accounts for the fact that the ultimate strengths of various woods are startlingly close to each other, regardless of species, when they are compared at equal densities by the various means described hereafter. This is true, even though the microstructures of the various woods vary considerably.

The microstructure of wood is much like a highly oriented unidirectional space age whisker composite. The structural cells, like many whiskers, average about 0.04 mm in breadth and about 4.0 mm long for the coniferous, or so-called soft woods. A very important difference between wood and anisotropic whisker composites is that the ratio of transverse strength to parallel strength can be as much as 30% for wood, whereas it is seldom more than about 1%, or so, in the unidirectional whisker composites. This may be an advantage in some Superflywheel applications of wood, since the optimum configurations will sometimes involve transverse stress requirements.

Improving the Strength of Wood—The allowable working strength of wood can be realistically improved by a factor of about 30 over the published values for structural timber. This, of course, does not mean that these values could be safely used in the building of a house, because the house application would require consideration of most of the degradation factors that have been eliminated in the Superflywheel application.

Discussion of Defects—Most of the flywheels under discussion will be of the order of 30 to 60 inches in diameter. Therefore, it will seldom be necessary to use wood members that are more than about 2 feet long, and, more often, they will be about 1 foot long. For this reason it will be a relatively simple procedure to eliminate many of the usual defects in the wood by careful inspection. It should be easy to avoid such things as knots or other grain deficiencies, insect holes, checks, and splits. Also, it will not be necessary to make allowances for the usual methods of attachment, such as nails or bolts.

The vacuum operating environment will prevent the development of future defects from insects and fungi (rotting), since these living organisms require oxygen, moisture, and certain temperature ranges in order to survive. Without any one of these they cannot survive, and, of course, in the vacuum environment they will be deprived of oxygen and moisture.

Duration of Load—Most references report some degradation of the strength of wood with time, although there is considerable ambiguity as to just what is meant by the strength of the wood, or just what the level of degradation is. It is probably reasonable to assume that the tensile strength varies more or less as the logarithm of time, as shown in Fig. 3. On the other hand, it could be concluded from Fig. 4 that the strength of wood decreases very slowly and linearly with time. However, most references agree that the degradation effect, whatever it is, is a cumulative one.

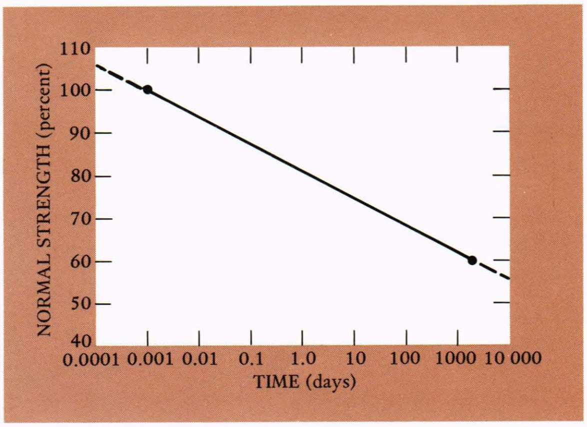


Fig. 3—Wood bending strength vs time (from Ref. 7).

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[5] H. P. Brown, A. J. Panchin, and C. C. Forsaith, *Textbook of Wood Technology*, McGraw-Hill, New York, 1949.

[6] Baumeister & Marks, *Standard Handbook for Mechanical Engineers*, McGraw-Hill, New York, 1967.

[7] Miner & Seastone, *Handbook of Engineering Materials*, John Wiley & Sons, New York, 1955.

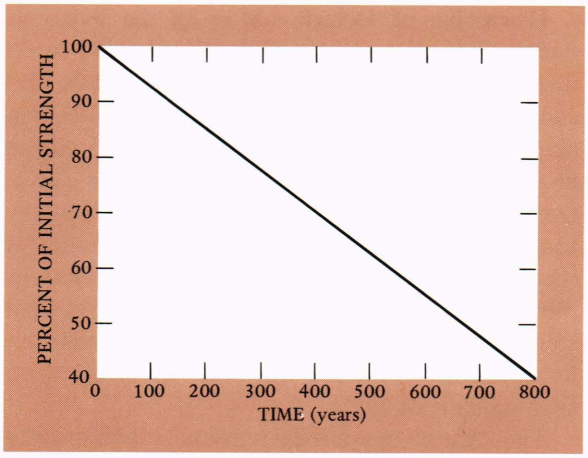

Fig. 4—Wood bending strength vs time (after Ref. 6).

In the case of the flywheel, the maximum stress corresponds to the time when the flywheel contains the maximum amount of energy (maximum speed). Since both the energy and the stress vary as the square of the rotational speed, it follows that the stress will be proportional to the energy at all times. Considering a particular flywheel operation over a speed range of, say, three to one, the stress level will vary over the operating cycle linearly with time from 100% of design stress down to about 10%, regardless of the cycling time. Therefore the average stress will be about 55% of the maximum design level.

Until more accurate data are made available, particularly in the area of tensile strength, it will be assumed that an operating strength of 50% of the tensile strength will provide a margin of safety.

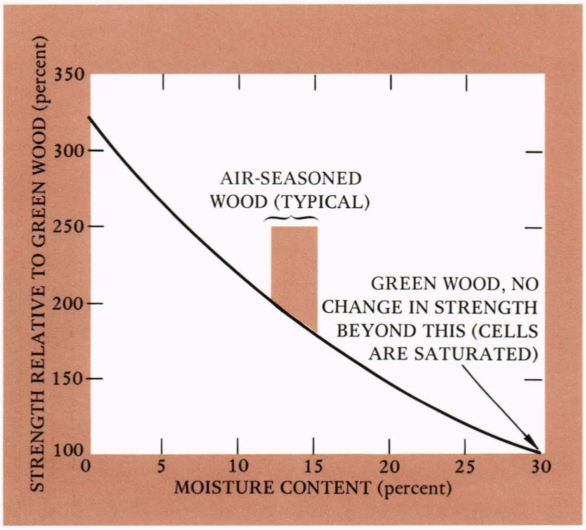

Fig. 5—Wood strength vs moisture content (from most of the cited References).

Moisture Content—Unquestionably, the most significant controllable variable concerning the strength of wood in the flywheel application is that of the moisture content of the wood. The moisture in green wood is held absorbed in part by the cell walls and in part within the cavities, in the latter case, much as water is held in a container. As the wood dries, the cell walls do not give off moisture until the adjacent cavities are empty. The condition in which the cell walls are fully saturated and the cell cavities empty is known as the fiber saturation point. The moisture in the wood at this point is about 30% of the weight of the wood. At moisture contents higher than this (they can go to about 300%), the strength is not affected, but at moisture contents less than this the strength of the wood will vary as shown in Figs. 5 and 6.

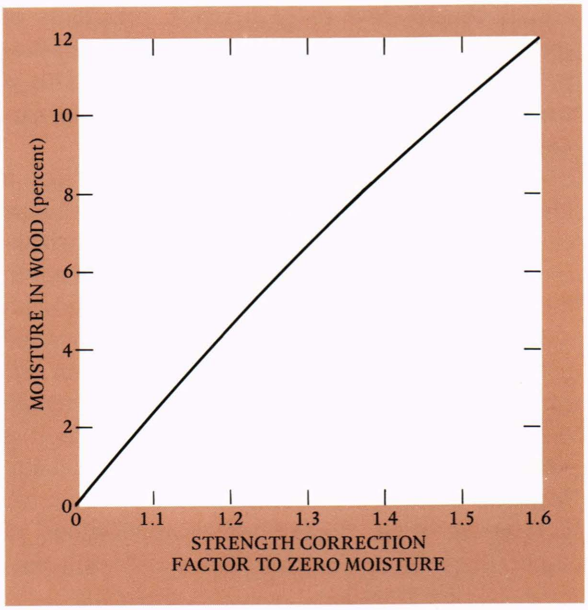

Fig. 6—Applicable strength factors for wood at various moisture levels (from Ref. 6).

The term seasoning means simply that the moisture content of the wood is brought as close as possible to the moisture level it would reach by natural means in the particular environment in which it is to be used. Generally this is assumed to be about 13% moisture. Eventually, any piece of wood will reach a moisture content corresponding to the moisture in the surrounding atmosphere. And, it is important to note, this process extends

TABLE 1

PERFORMANCE OF TYPICAL WOODS IN A SUPERFLYWHEEL

Species	*Reference*	*Ultimate Tensile Strength (UTS) at Zero Moisture**	*Weight at Zero Moisture (lb/in^3)*	*Ultimate Energy Density‡ (watt-hr/lb)*	*Usable Energy Density‡ (at 50% UTS)*
Bamboo	12	52 000†	0.0202	38.6	19.3
Birch	10	31 500	0.0252	18.75	9.40
Hickory	6	32 300	0.0277	17.5	8.75
Mahogany, Philippine	7, 8	24 200	0.0191	19.0	9.5
Pines (various, average)	7	22 000	0.0195	16.9	8.45
Redwood	7	16 000	0.0144	16.7	8.3
Spruce, sitka	6	19 500	0.0151	19.4	9.7

* Corrections to zero moisture in accordance with Fig. 6.

† The bamboo moisture was not indicated. Dry strength was probably much higher than this. Species was Bambusa Tulda.

‡ $E/W = 1.5 \times 10^{-5} \times$ strength/density; this represents the average K factor (see text) of the three applicable Superflywheel configurations.

all the way to zero moisture content, if the surrounding atmosphere is at zero moisture, such as in a vacuum. It is generally conceded, however, that as the moisture content in the wood is reduced to about 4 or 5%, it becomes increasingly difficult to remove the remaining moisture. Usually at this stage it is necessary to either bake out the moisture or use moisture-absorbing volatile solvents to remove the remaining moisture more quickly.

It is a fact that, not only is it much easier to remove the moisture from small cross-sectional pieces, but the likelihood of shrinkage damage can be eliminated by demoisturizing the wood in thin sections. It can be seen from Fig. 5 that the ratio of strengths from the green state to the state of zero moisture is more than three, and that there is nearly a factor of two difference in the strength when the typical seasoned moisture content is changed to the zero moisture state. The allowable stress levels are sometimes based upon the green strength, so it is no small wonder that the allowable strengths are so low. The zero moisture strengths of several common wood species, together with their corresponding flywheel energy storage capabilities, are shown in Table 1.

The Effect of Laminating—The basic advantages of laminating wood have been traced as far back in history as the third Egyptian dynasty, or more than 4700 years ago.[8] It is an interesting coincidence that the earliest known flywheel also existed at about this time. The wide variety of plywood available today is used chiefly to improve the two-dimensional strength and stability of structural surfaces and, occasionally, to improve three-dimensional strength in molded forms. However, the same processes that are used to give the plywood these capabilities also result in a marked improvement in the unidirectional strength properties of the plywood laminae. Even the manufacturing techniques of the veneering sheets give them greatly increased strength as well as improved economy.

Instead of being sawed and planed like other wood, the plywood laminae are peeled from the log in very thin layers by a sharp knife in a lathe arrangement. This not only results in about 40% more wood being obtained from the log, but the grain of the wood in cross section is exactly the same everywhere in the sheet. The strength averaging effect of the plywood normally permits the use of poorer grades of wood than would otherwise be practical for paneling applications. However, if plywood is made from defect-free wood, it can be made to have superior strength characteristics by this same process. Normally, the plywood lathes are 8 feet long, but they could be about 2 feet long for making the veneer for the flywheel. The shorter working length would permit a more economical elimination of wood defects in the manufacturing process and would greatly facilitate the other processes in the laminating of the wood.

A series of tests[9] has demonstrated the some-

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[8] Moore & Moore, *Materials of Engineering*, McGraw-Hill, New York, 1953.

[9] Thomas D. Perry, *Modern Plywood*, Pitman Publishing Corp., New York, 1942.

what surprising fact that the strength of wood increases as the thickness of the lamina is reduced, even if the original piece was free from visible defects. This relationship is shown in Fig. 7, where it can also be seen that there is an apparent increase in strength beyond the thinnest range of thicknesses shown in the curve. The thinnest laminae for which data were obtained for these tests was 1/48th of an inch. It is probable that some practical reason exists for not testing thinner sections, such as the fact that it was not practical to attempt to shave slices thinner than that on an 8-foot lathe. However, in the case of the Superflywheel with its 1- or 2-foot wood length, it may be possible for thinner sections to be cut; they would have even greater strength than that indicated in the curve.

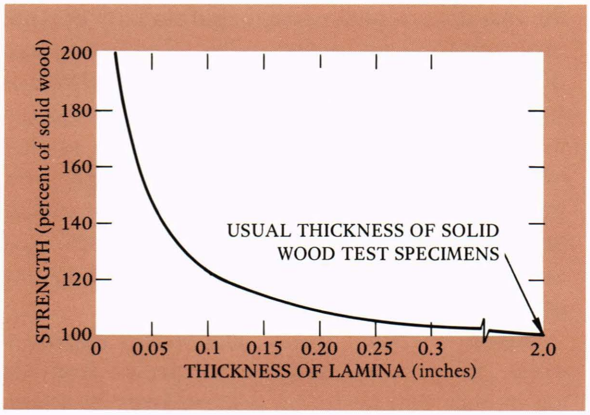

Fig. 7—Typical wood strength vs thickness of laminae (from Ref. 9).

The Effect of Compressing the Wood—Another variable in the laminating process is illustrated in Fig. 8. It is not surprising that the strength of the wood increases as the wood is compressed, since essentially all that is happening is that the cross-sectional area is being reduced. And since this area is the denominator in the usual unit strength term (i.e., pounds per square inch), the unit strength increases. However, the surprising thing here is the fact that the wood can tolerate the high pressures shown without damage to the structural fibers. In fact, Perry[9] stated that a considerable increase in strength could be expected at pressures greater than those shown in the figure.

Naturally, when the wood is compressed, the density increases as well as the strength, so the advantage is not actually as great as is shown in the strength curve in the figure. However, the strength actually increases somewhat faster than the density, so that there is a net increase in the strength-to-density ratio, as shown in the lower curve in the figure. But an increase in the density of the wood becomes a very important factor in the wood flywheel case, because it alleviates the principal drawback of the wood flywheel, namely the light weight of the wood. Even though the energy content of the wood can be made comparable to a steel flywheel in terms of, say, watt-hours per pound, it will require more volume to accommodate a pound of wood than a pound of

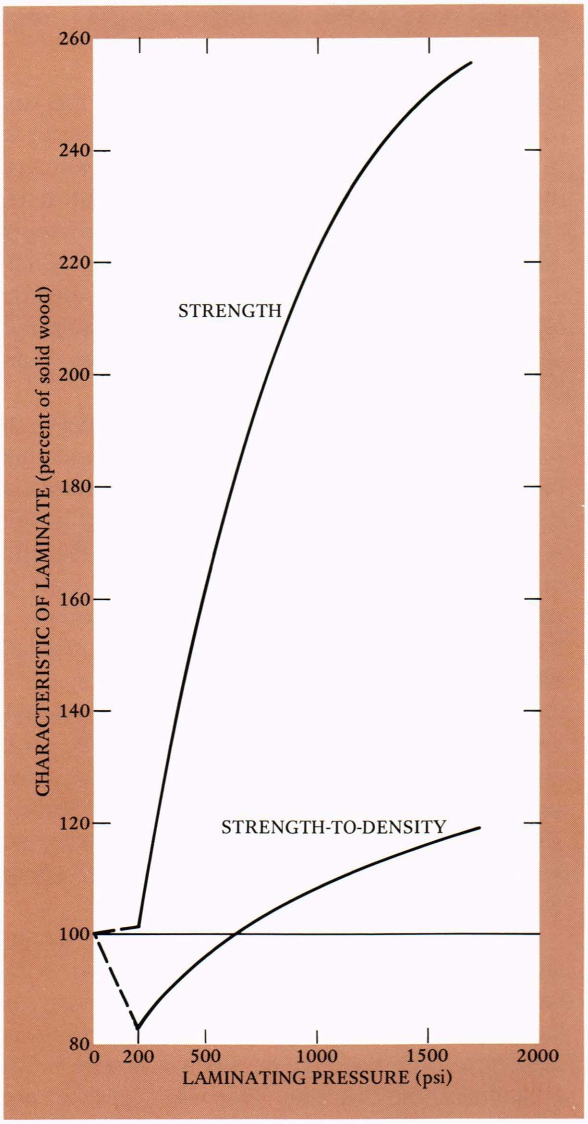

Fig. 8—Effect of laminating pressure on wood characteristics (from Ref. 9).

steel. However, the volumes of the two flywheels will not be directly proportional to the densities, since there are also the requirements for hubs, shafts, pressure vessel structure, ancillary equipment, etc. to be considered. A study of the flywheel applications list indicates that there are few, if any, situations where a steel flywheel would be otherwise applicable, where the two or three times more volume of the wood flywheel, with its obvious advantages of cost and safety, could not be tolerated. There are, of course, applications which could not tolerate either type, but this is because these applications require more performance than either can offer.

Other Factors—Although the principal veneer form to be used in the wood flywheel is the unidirectional laminate, where the grains of all of the pieces are lined up in the same direction for maximum strength, it is equally obvious that the strength of the laminate can be increased as desired in the other directions by adding laminae with their grains oriented in the desired direction. Thus, if a particular laminate requires an increased strength in the transverse direction, as would be the case for some flywheel configurations, it would only be necessary to add one ply out of every ten plies, or two if the grain is oriented transversely.

Another factor that affects the strength of the laminate is the glue used—the type, amount, and method of application. Although this has a comparatively moderate effect on the strength of the composite structure, it would be an interesting experiment to see what would happen to the strength if some of the modern super-strong adhesives were used. These could have as much as five times more adhesive strength than the adhesives usually employed in the lamination of wood.

The Applicability of Wood-Based Materials—The characteristics of some typical wood-based materials are shown in Table 2, where they are compared with similar characteristics of untreated wood. Each type has certain improved characteristics compared with the untreated wood. IMPREG, which is the least rewarding for flywheel application, is simply wood that has been carefully impregnated with a special thermosetting resin. The principal applications of IMPREG are where dimensional stability of the wood is more important than high strength.

COMPREG, on the other hand, is a wood product that is both impregnated and highly compressed. This process raises both the tensile strength and the density, but does not appreciably affect the strength-to-density ratio. Essentially, all of its strength properties are doubled, except its compression strength characteristics, which are considerably more than doubled. From Table 2 it can be seen that the compression strength across the grain of the wood is increased by a factor of nearly seven by the COMPREG process. This capability can be very important in some of the spoked flywheel configurations, as it could facilitate holding the spokes in the hub of the flywheel considerably. As a matter of interest, it was this wood product that was used during World War II to manufacture experimental wooden aircraft propellers.

STAYPAK is wood that has been highly compressed without resin by means of a special process that causes the lignin between the wood fibers to flow sufficiently so that future internal stresses are eliminated. This material is said to be con-

TABLE 2
PROPERTIES OF WOOD-BASED MATERIALS FROM REF. 10

Property	*Normal Wood (Reference)*	IMPREG	COMPREG	STAYPAK	PAPREG
Percent Moisture at Test	9.2	5.0	5.0	4.0	8 (est.)
Density at Test, pci	0.0252	0.0288	0.0468	0.0504	0.0504
Ultimate Compression Strength, psi					
Parallel to Grain	9 500	15 400	21 600	19 100	20 900
Perpendicular to Grain	2 100	3 600	14 000	9 400	18 200
Ultimate Tensile Strength, psi					
Parallel to Grain	22 200	15 800	37 000	45 000	35 600
Perpendicular to Grain	1 400	1 400	3 200	3 300	20 000
Corrected to Zero Moisture*	31 500	19 050	44 600	51 100	49 200
Shear Strength Parallel to Grain, psi	2 980	3 460	7 370	6 370	17 800
Tension Modulus of Elasticity, 1000 psi	2 300	2 510	3 950	4 610	3 640

* In accordance with Fig. 6.

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[10] U.S. Department of Agriculture, *Wood Handbook,* USDA Forest Products Laboratory, 1955.

TABLE 3
ESTIMATED PROPERTIES OF TYPICAL WOOD FLYWHEELS

Property	*Spoked Solid Disc*	*Pseudo-Isotropic Disc*	*Possible Optimized Pseudo-Isotropic Disc*	*Rim*	*Optimized Fanned Brush*
K Factor (see text)	1.3	$1.9 \times 0.52 = 0.99$	$2.82 \times 0.52 = 1.46$	1.62	1.5
Energy Density at 50% UTS, watt-hr/lb (Ref. Table 2)	8.1	6.1	9.1	10.1	9.4
RPM Factor (Rim value as reference)	2.2	1.1	2.8	1.0	2.8
Drag Factor ($\text{RPM}^{2.8}$) (Ref. 3) (Rim value as reference)	9.1	1.3	17.8	1.0	17.8
Volume Factor	Excellent	Good	Excellent	Good	Poor

Notes: 1. The spoked disc and fanned brush are inherently safer than the others, since all elements are equally disposed around the containment structure upon catastrophic failure. However, *all* types should be considerably safer than a solid steel flywheel.
2. The rim configuration (made from thin wood tape) not only has the best performance, but this estimate is the most accurate of all of the types since it is based on classical formulas, without modification. However, hub attachment may represent a formidable design problem.

siderably cheaper to produce than COMPREG, and actually has superior tensile strength, being the strongest wood product discovered to date in this present study. However, even though it is the strongest wood, there are some others that have a higher strength-to-density ratio, hence higher energy storage capability per pound. The importance of STAYPAK, however, is its high strength-to-density ratio, together with its high density, the latter characteristic giving it one of the highest energy per volume capabilities studied.

PAPREG is a product comprised of many sheets of resin-impregnated paper that are laminated together under high pressure. Although the tensile strength of this material is slightly less than those of IMPREG and COMPREG, it has some rather outstanding capabilities that are applicable to some of the Superflywheel configurations.

First, it will be noted that its tensile strength perpendicular to the grain is about six times those of the other products in the table. This characteristic will be particularly important when applied to the various disc configurations to be described. It is quite unusual to find a filamentary composite in which the matrix strength is nearly half the tensile strength! Equally important is the fact that not only is the compression strength (perpendicular to the grain) nine times that of the untreated wood, but also the shear strength between the laminae (parallel to the grain) is nearly three times greater than any other listed in the table.

There are about 1600 varieties of bamboo grown throughout the world, and no discussion of the applicabilities of wood-based materials to the Superflywheel would be complete without including it. Although technically it is a grass, bamboo has many wood qualities that make it especially suitable for kinetic energy storage. Unfortunately, it has been extremely difficult to obtain much accurate test data on tensile strength, etc. Most of the 1500 report titles reviewed so far have dealt with other properties, but a recently initiated computer search is expected to produce reports that will be more pertinent.

So far, the useful information that has been received[11] seems to indicate that bamboo will have energy density and cost factors more than twice those of wood, and this advantage is expected to improve as better data become available.

Discussion of Flywheel Configurations

The estimated properties of some typical wood flywheel configurations are shown in Table 3. It is not the purpose of this discussion to attempt to select the best configuration, but to indicate the applicability of wood and to point out the basic features of each configuration.

Spoked Solid Disc—The spoked solid disc configuration is a variation of the circular brush Superflywheel configuration described elsewhere.[2, 3] Its principal features are shown in Fig. 1. The spokes are thicker axially at the hub end but fan out at the flattened tip end so that they form the solid disc. In this manner, all available volume of the spinning disc geometry is occupied by the energy storing wood material, and, thus, the maximum energy per volume is achieved. The spokes

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[11] H. H. Sweath et al., *Industrial Raw Materials of Plant Origin. V. A Survey of Bamboos,* Engineering Experimental Station, Georgia Institute of Technology, Atlanta, 1953.

can have a mass ratio (hub to tip) equivalent to a tapered bar, so a slight increase in energy density would be expected over the "nontapered" thin bar flywheel. A second advantage of having the solid disc configuration is that the flywheel may have considerably less drag than the same size circular brush configuration. This special arrangement is more applicable to wood than to the other usual filamentary composites because the load that the steel hub has to carry will be about four times less for the wood flywheel since that is about the ratio of its strength to the other materials. This fact also facilitates the bonding of the spokes to the hub plates. The radial spoked disc is undoubtedly the safest of the configurations being considered, since its large number of components will, upon catastrophic failure, be evenly distributed around the containment structure. However, with wood as the principal flywheel material, this feature may not be as important as it would be in the case of other materials which may be capable of storing five or ten times the amount of energy per pound.

The Pseudo-Isotropic Disc—The pseudo-isotropic disc configuration, shown in Fig. 2 and described elsewhere,[3] is particularly applicable to the wood flywheel, since it is comprised of a series of unidirectional plies of wood laminated in three equally disposed orientations, quite similar to ordinary plywood. Again, the configuration probably works considerably better using wood than other filamentary composites, inasmuch as the wood can have a matrix strength as high as about one third of its tensile strength, whereas the usual fiber composite materials typically only have matrix strengths from 1 to 10% of their tensile strengths. This feature also implies that a pseudo-isotropic flywheel with an optimized cross-section shape may be possible, as indicated in Fig. 2 and in Table 3. The pseudo-isotropic disc is especially well suited to the use of the various wood-based materials, including paper.

The Rim Flywheel—Wood is more suitable for the rim configuration than any of the usual composite materials for the same reasons given above. The lack of achievement of the theoretical energy capabilities with rim type flywheels in the past has been due largely to the fact that the transverse strength of the filamentary unidirectional composites was insufficient to carry the differential radial stresses. These stresses tend to separate the filaments long before sufficient rotational speed has been reached to tax the maximum tensile strength in the filament direction. Using wood (and wood-based materials) this problem should be greatly reduced, if not eliminated, and the significant advantages of the rim flywheel in this application should be realizable. These advantages over the other types include the highest energy density and the lowest rotational speed for maximum safety, and the lowest drag.

It is also important to note that the rim configuration probably has the least questionable performance estimate of all of the types mentioned, since its formula is a classic one and is used without modification.

Discussion of Cost Factors

The cost of a wood flywheel can be conservatively compared with other types by comparing the cost of the wood with the other materials. If the relative costs of manufacturing the respective flywheels and their containment arrangements were identical, then the comparative costs of the rotor materials would be an accurate indicator of the relative flywheel costs. These manufacturing costs are not the same for all types, however, and it is probable that they are considerably lower for the wood flywheel than any of the others, largely because of its slower rotating speed and ease of fabrication. Thus, a comparison of the relative costs of flywheel materials will give a conservative indication of the wood flywheel costs. Since the main purpose of any flywheel is to store energy, it is reasonable to equate the flywheel costs in terms of the unit cost of the energy stored.

TABLE 4
ESTIMATED COST FACTORS

Material	*Predicted Usable Energy (watt-hr/lb)*	*Projected Material Cost ($/lb)*	*Rotor Cost Factor (watt-hr/$)*
Bamboo	19	0.12	160
Wood	8	0.20	40
Steel Wire	10	0.45	22
Fiberglass	30	1.75*	17
PRD-49	62	3.85*†	16
Fiber-B	56	3.85*†	15
Glass	20	2.00	10
Boron	45	186.00	2/10
Graphite/Epoxy	42	325.00*	1/10
Future Est.	42	30.00*	1

* Includes $1.00 per pound for converting material to usable form.

† Based upon discussions with Dupont personnel. Current (subsidized) price for Fiber-B to tire manufacturers is $2.85 per pound.

The flywheel applications are predominantly electrical. That is, either they are charged by an electric motor, or they drive an electric generator as the output. For this reason the energy term used to describe their performance is watt-hours per pound.

The cost factors of various typical flywheel materials are given in Table 4. Here it can be seen that wood appears to offer at least twice the cost effectiveness of the nearest competitor, and the possibility exists that it will be at least as effective in comparison with known future composite materials. For this discussion, the cost of the wood has been estimated from the information in the following tabulation on the cost of various wood products; the information was obtained from sawmills and appropriate wholesalers of wood-based materials.

Retail cost of sawed green wood	3 to 4¢ per pound
Finished kiln dried wood, wholesale	4 to 6¢ per pound
Internal grade plywood, wholesale	8 to 12¢ per pound
Kraft paper, wholesale	10¢ per pound

On the basis of these actual values it is conservatively estimated that the average cost of wood products in the wood flywheel will be about 20¢ per pound, which is the value shown in Table 4. It is reasonable to expect that this cost can be improved 30% in the foreseeable future. These estimates do not reflect the additional cost of fabricating the respective flywheels, which should bias the final costs considerably more in favor of the wood flywheels.

It is also interesting to note that the cost factor of the wood flywheel is about ten times less than the cost factor of the equivalent solid steel flywheel and about four to six times less than the cost factor of a lead-acid battery having equivalent performance. Of course, *no* lead-acid or any other known battery can have the performance independence from depth of discharge, ambient temperature effects, and number of cycles that the flywheel would have.

Other Factors to be Considered

A great many tests are required to prove out the various hypotheses in the foregoing discussion. As far as is known, there has never been an application of wood embodying these requirements of pure tension loading for long periods in a vacuum environment. Theoretically, there should be no particular problem with the vacuum, as the principal structural components of wood (cellulose and lignin) have molecular weights of about 1,000,000,[12,13] indicating that they should have very low vapor pressures.[12]

It should also be determined by suitable tests just how good the static fatigue performance of the wood is in the vacuum environment. According to similar tests with other composite materials, it would appear that this property should show marked improvement in the oxygen-free, moisture-free environment.

The ultimate strength characteristics of wood-based materials have never really been determined, since there has never been a real requirement for strength-to-density ratios beyond the present allowables. For example, it is not known just how much strength improvement could be accomplished with lamina thicknesses of less than the minimum thickness made to date. Many of the values quoted are more than 30 years old. Perhaps the main reason that higher pressures were not used was that it was not practical to use these higher pressures at that point in time, considering the 8-foot-by-4-foot dimensions of the plywood sheets. The microstructure of wood cells is comprised of several layers made up of bundles of microfibrils about 150 Å wide, each of which in turn is made up of a large number of elemental fibrils about 35 Å wide.[13] This structure suggests that these components, which are principally responsible for the wood strength characteristics, can tolerate the consolidation effect of extreme pressures, even though the wood cells themselves may be distorted. Also, the use of modern polymers should improve the interlayer strengths by three or four times the strengths quoted.

A thorough engineering evaluation of the flywheel configuration most applicable to the various wood technologies should be made. Questions of optimum rotor configuration, hub attachment, rpm's, containment structure, ancillary equipment, and, of course, final cost estimates and comparisons need to be investigated.

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[12] Discussion between the author and Dr. Fred Shofizadeh, Director of the Wood Chemical Laboratory, University of Montana, Missoula.

[13] A. J. Panshin and Carl deZeeuw, *Textbook of Wood Technology*, McGraw-Hill, New York, 1964.