

FILAMENT WINDING: AN OVERVIEW

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ABSTRACT: The intent of this paper is to present a general overview of filament winding, as introductory to the deliberations at this session meeting. It represents the skimming-off of the generalities from an exhaustive, larger work. These generalities are based on data and information which are not included since (1) their mass is prohibitive and inclusion of selected material might lead to overemphasis, and (2) such inclusion might detract from the impact of the papers to follow. Under these conditions, the theme of this paper is: Filament Winding; how it looks today, and what should be done about it.

INTRODUCTION:

It has been stated on a number of occasions that filament winding is an art and not a science. This relates directly to end item procurement, particularly of large pressure vessels. In their fabrication, trial and error have taken precedence over applied technology. This statement is at present less and less true. There has been a continuing demand for high grade fibers and binders and close controlled winding, in order to produce reliable, high-quality products. This implies the recognition that there must be a number of back-up programs on materials and techniques, to assure immediate quality and continued improvement. From the standpoint of design stress analysis, eventually filament winding must lend itself to a more rigorous mathematical treatment than probably any other phase of the plastics industry. It is recognized that for any particular structure, the fiber reinforcement and matrix

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material forming the composite, as well as the design analysis itself, must be tailored to meet a specific set of conditions.

It is quite apparent, even from a cursory evaluation of filamentary, that a new and important industry is about to evolve - unique and separate from the other efforts in the reinforced plastics field. However the materials, techniques and design analyses developed in improvement of filament winding will have a profound effect on the whole reinforced plastics industry. It is thus extremely urgent that the art be expanded into a science; that the art of fabricating a large, functional, filament-wound structure be converted into the science of designing with optimum materials and processing techniques and quality controls for the production of any needed end item; and this with a reasonable assurance of success.

The development of filament winding has always received its greatest impetus from the missile and rocket industry. Specifically it has been associated with high performance solid propellant rocket motors. Today the relationship between filament winding and missiles is even more evident.

A review of the present state of the art in regard to the materials and the processes utilized by the winders reveals a rather confused picture. In many cases standards are nonexistent, and the interchanges of information are limited. The general condition is attributable to two facts:

- Filament winders are tied to rigorous schedules, to meet weapon system requirements. Consequently, trial and error methods have been used to resolve such important problems as material selection, handling of discontinuity stresses at port opening and the equator, and even to determine the optimum winding pattern.
- The competition in this industry is severe, and each of the filament winders has shrouded much of his operation in secrecy. Therefore, practically no information on advances is available for dissemination

to the industry in general. In some cases, this information is not even made available to the military activity sponsoring the program. As a result, the filament-wound end items generally being fabricated, even though they meet the system requirements, are inefficient in relation to their potential; that is, considering the broad spectrum of possible filament and matrix materials, both metallic and nonmetallic.

It is true that in recent months, notable advances in technology have been made, as manifested in more sophisticated designs and higher ultimate burst levels. Material programs related to specific weapon systems will continue to lend support to the field as they have in the past. These programs, however, are not sufficient in themselves to resolve all of the problems faced by the industry.

WHY FILAMENT WINDING:

Relatively few materials are suitable for use in fabricating the present day high quality rocket motor cases. Only the glass filament wound composites, the wire wound composites, and certain alloys of steel and titanium can be considered as offering the maximum capabilities.

A number of factors will influence the decision in selecting the material for any motor case. Considerations such as minimum weight, problems associated with fabrication, economics, and finally the reliability of the finished product must be reviewed in the light of a specific design.

Minimum weight alone is dependent on several factors, and one cannot be singled out as the criterion for making a judgment. The minimum weight can be decided on the basis of ultimate burst strength, or the buckling characteristics of the motor case. Generally for the upper stages with small length to diameter ratios, minimum weight has been of great importance while buckling is less critical. In the intermediate stages, with higher length to diameter ratios, the minimum weight is still important, but buckling

becomes more critical. In the booster or first stages the minimum weight is less important and buckling may be critical. It is of interest that the motor cases to date which have used filament winding have been upper stages with relatively low length to diameter ratios.

One of the principal advantages of filament winding, particularly in motor cases, is the high strength-to-weight ratios which can be obtained. To achieve high efficiencies with missiles, the weight of the inert parts must be held to a minimum. The total weight of a rocket motor chamber will be the accumulated weights of the outer casing, the insulation, the nozzles, the skirt attachments, and the various metallic bosses and other metallic components. The relative weight percentages of each of these depends on the size and design of the motor case. Filament winding offers weight saving in the casing, and with the single-nozzle motor, in the nozzle as well. At present the insulation requirements are about the same with the plastic or metal case. Future indications point to a weight saving through the use of heat resistant filament wound motor chambers in which the amount of insulation can be reduced.

In general filament winding fabrication has been cheaper than metal fabrication through the lower tooling costs involved. As another advantage, particularly for rocket motor cases, the filament wound end items are less limited in size. Raw material costs have been low, although representing a small percentage of the total cost of motor cases. With the smaller items, however, the advantages of low tooling and raw material costs will tend to disappear.

The following is an estimate of the comparative costs of metal and filament wound motor cases, based on production lots.

<u>Material</u>	<u>Cost/Unit</u>	<u>Tooling Cost</u>
Steel	\$50,000	\$600,000
Titanium	60,000	600,000
Fiber Glass	11,000 - 15,000	100,000
Wire wound	12,000 - 15,000	100,000

Efforts to achieve high strength to weight ratios have been attempted in motor cases with at least two steels - H-11 and Tricent. These were treated to a 250,000 psi yield-strength level. There were numerous low stress level failures. However, the limitations were not in strength (since the alloys could achieve the required levels) but in fabrication. It was not possible to fabricate these materials with the degree of perfection required because of the brittleness of the steel at the high stress levels. Generally failures originated from very small flaws, and it was practically impossible to eliminate all of them.

A number of motors have been made from a titanium alloy with 6 percent aluminum and 4 percent vanadium. This material exhibited a strength of 138,000 psi and a strength density of 0.85×10^6 inches lb. The program failed in reaching the desired strength-to-weight ratio.

A nominal target of 1×10^6 inches strength to weight for a motor case can, however, be met at once with fiberglass reinforced plastic with a yield strength of 80,000 psi. Table 1 gives some idea of the range of values that are expected from filament wound structures.

A recognized disadvantage of the filament wound structure has been its low modulus of elasticity compared to that of steel and of titanium. Again because of its directional properties, a filament wound composite can not be said to have one modulus, but the modulus will depend on the winding geometry. The modulus is designated as being in the hoop or longitudinal direction. For a unidirectional composite winding, a modulus as high as 8 to 10×10^6 psi

has been reported. However, in a motor case, it is rare that values over 5×10^6 psi are encountered in one direction, without sacrificing the modulus in the other direction. On the other hand, the moduli for the metals are: 30×10^6 psi for steel alloys and 15×10^6 psi for titanium alloys. Steel wound composites would have a hoop modulus of about 14×10^6 psi with a longitudinal modulus of about 7×10^6 psi.

If buckling is taken as the criterion, at the same critical load and at the same weight, a filament wound cylinder would require a modulus of about 7.5×10^6 psi for performance equivalent to steel. This deficiency of fiber glass structures has been a matter of concern and several government-sponsored developments have been aimed at raising the modulus. The modulus of the glass itself has been raised from $10-12 \times 10^6$ psi to $15-17 \times 10^6$ psi, and one such glass is currently being evaluated in filament wound composite structures.

DESIGN FOR APPLICATION:

Within the military picture, in which structural weights of weapon systems are of great concern, the item must be adequate (not underdesigned) but not overly adequate (overdesigned) so that a nonessential burden is imposed. For this reason, in design of filament wound items, it is necessary for the designer to achieve a design analysis to meet the optimum mechanical requirements of the desired part and to design the materials system which will yield the strengths and stress-resistance and lightness of weight which are demanded of the part in its application.

Since most of the classical design formulas make certain basic assumptions, such as of the homogeneity of the material, it is not completely correct to use these classical formulas in a design involving a nonhomogeneous plastics-glass material. The response mechanisms to load of the fiber and of the resin are different. This is due to their widely different

stress-strain relationships, and the interaction between these two components in the system is as yet not fully understood.

Any design procedure, either based on a composite response or treating the structure as a monolithic material, might be perfectly valid if proper inputs are used for each design technique. The monolithic approach has been used in the past with some degree of success. The netting analysis which treats the system as if only the glass fibers existed is an improvement on the monolithic approach and has gained wide acceptance by the industry. It is realized that the underlying assumption which states the non-contributing characteristics of the resin to the composite system is in error; but until a completely workable design system, backed up with experimental data, is obtained, the netting analysis can continue to be successful.

It is recognized by filament winding designers that the use of a netting analysis will not provide information on absolute response mechanisms. The strains are measurable, but the transitions to stress are only questionable approximations; but when these figures are fed back into the original design formulas they provide an acceptable measure of predictability in the performance of subsequent filament wound structures. This predictability and reliability will improve as additional performance data are made available. Until a more convenient or more accurate performance-based design technique is developed, the netting analysis remains the best available approach for design purposes.

A number of people have treated all the responses of the composite system including the resin, and it would appear that eventually the design techniques and formulas will be based on this more thorough approach to the problem.

It is important to remember that since fiber glass has definite directional properties, the composite responses will obviously depend

upon fiber orientation and direction. These include both stresses, strains, moduli, and expansion coefficients. Another factor which will affect the mechanical properties of this composite material is the geometric relationships between individual fiber strands.

It has been demonstrated that a netting analysis for glass reinforced plastics is valid for simple geometric shapes, such as are found in pressure vessels, motor cases, spherical containers, and radomes. The loading conditions in these demonstrated successes have been either simple internal loads or a combination of internal pressures and external loads.

Again greatest emphasis has been placed on the internally pressurized vessel or the rocket motor case. When treating such a pressure vessel, the netting analysis can be used for both the cylindrical portion and for the end dome of the unit, at the same time. In actuality, this is how the vessel is fabricated. A low-angle helical pattern is laid down, furnishing the longitudinal reinforcements in the cylinder and at the same time forming the end closure of the vessel. Additional windings are then added to meet the hoop strength requirements and to produce an overall 'balanced' design.

A great deal of experience and performance data have permitted technically adequate treatments of both the cylindrical portion and the end dome region of motor cases. Unfortunately there has not been this experience in the treatment of the discontinuity stresses in the junction of the cylindrical section and the end dome. Also, the treatment of skirts, metallic pole pieces and port openings has been handled mostly on a trial and error basis. There is little information dealing with these areas as design stress problems.

Because of their potential advantages, glass filament wound structures have been used as externally pressurized vehicles, air frames, radomes, and axially compressive loaded cylinders. Again, these efforts have been limited and the available data are not sufficient for a complete design treatment or analysis for these types of applications.

TESTING FOR MATERIALS EVALUATION, QUALITY CONTROL AND ACCEPTANCE:

A test program for filament wound structures, as with any other reinforced material, will serve the general function of providing reliable design data, quality control of all raw materials going into the fabrication, and acceptance of the finished wound item.

The testing of wound structures is somewhat more complicated than that of molded glass-reinforced parts. The properties are more sensitive to the fiber direction of the winding, and the resin contents are lower and therefore more critical than for other reinforced items. The general shape of filament wound structures - that is, cylindrical with end domes - and the fact that in many cases the fibers are cut: both tend to complicate testing further, and to interfere with the interpretation of the results.

While the general filament wound structure has been designed to put reinforcing fibers in tension, there are many instances where other types of loading are encountered. Thus a variety of special tests are required, in order to obtain data on structures under special conditions of loading.

The varied uses to which filament wound structures are placed require that they be tested under varied conditions, reflecting the conditions to be encountered in ultimate functioning. Characteristic endurances required of such end items are listed in Table 2.

The properties of the finished wound structures which are of greatest interest are listed in Table 3. These represent the strengths and the effects which are of concern, particularly to the designer.

A number of the properties mentioned may be independent of the winding geometry. Several of the more important ones vary with the winding angles. Also, some vary with resin content. Thus, data on these properties are meaningless unless the winding geometry and the resin content are known.

A few comments on the testing of filament wound end items may be in order.

Motor cases and other pressure vessel structures can be hydrostatically tested to determine hoop stress and longitudinal stress. At the same time, moduli in both directions can be determined; usually by strain gages although dial indicators and wire extensometers have also been used. Almost invariable today, vessels are lined in order to prevent weepage which would occur somewhat below burst pressure.

Final burst pressure is greatly affected by the rate at which the internal pressure is applied; the faster rates giving higher burst pressures.

In some cases, small pressure vessels of 6" to 12" diameter are used for test specimens. These are contrasted with subscale motor cases ($1/3$ to $1/2$ scale), and finally with full-scale cases which can be hydrostatically proof-tested at a pressure below burst, or hydrostatically tested to burst, or statically fired. To date there has not been a satisfactory correlation within this series of tests, and there has been marked disagreement as to how far the smaller scale tests can be extrapolated.

It appears that, at the present time, expensive destructive testing of full scale models is required to determine allowable stresses with any degree of confidence. The reasons for this lack of confidence are: that motor cases contain cut fibers at ports, which means that failures may be more sheer than tensile; and that discontinuity stresses at the equator (where skirt attachments are made) and at the polar pieces are dissimilar for motor cases than for small scale specimens. Unfortunately, small scale tests must thus be considered only as a quality control of raw materials, uniformity and reproducibility of processing, as in study of process variables, or as some indication of a fabricator's technique; but not as a source of absolute values for burst strengths.

A number of other procedures have been adapted for testing tensile properties and the modulus of fibers. In some cases the fiber is tested alone, or it may be coated with wax or polyvinyl alcohol, or it may be tested as a composite rod. However, since fiber tensile strength is the most important property to be considered, it is felt that this is best measured from a composite structure as in the NOL Ring Burst Test. However the testing of fibers alone should not be neglected, particularly since such a test can serve as a fast process control.

Packaging of the fibers is another important aspect. A package should be so constructed as to reduce the possibilities of twist to a minimum. Twisting of the strand during winding causes abrasion of the filaments and unequal fiber tension, resulting in a lowering of the composite strength.

A number of suggested tests for fibers are listed in Table 4. These are classified as to end-use condition (filaments, strands, yarns, rovings); and by implication a number relate to the condition of the finished package.

As for the evaluation of materials, the basic raw materials going into a filament wound structure are the glass reinforcement with its finish and the resin-catalyst system. Depending on the end application, a number of other materials may be involved. With a motor case, for example, the case liner material, the separate aft insulation, the metallic skirts and bosses, and the mandrel materials - all will have a bearing on the performance of the finished winding. However, despite the importance of such materials as these, quality control testing is mostly restricted to the basic glass fiber reinforcements and the resin matrix.

As to specific test methods, the NOL Ring Test has received wide acceptance as a test procedure. This test can be made to serve a number of purposes such as the testing of the fibers, the effects of finishes on fibers, the effects of resin systems variations and to some extent it can simulate some process variables such as degree of cure, winding tension, and so forth.

In the NOL Ring Test, a glass reinforced ring is wound from continuous yarn or roving. The specimen dimensions are 6.0 inches outside diameter, $1/8$ inch wall thickness, and $1/4$ inch in axial length. A number of variations have been made by people using this test, principally in the dimensions of the ring specimen used, which has been ranged from 2 to 18 inches in diameter.

Cured rings can be tested in a number of ways so as to yield parameters such as tensile strength and tensile modulus, flexural strength and flexural modulus, compressive strength, and fatigue strength. Tensile strength was originally measured by using a split ring fixture and pulling the ring under a tensile load. This procedure was not satisfactory, because of non-uniform loading and the change of curvature at the two points of separation. Tensile strength and tensile modulus could not be determined with any degree of reliability.

The method of testing was revised to allow the hydraulic loading of the test specimen. This method now gives greater reliability, both in hoop tensile values and in modulus. Actual values run about 30% higher for the hydraulic burst than for the tensile pull. A number of laboratories are still using the split disc method of testing, but results and reliability strongly favor the hydraulic burst method.

Reducing the hoop stress of the composite ring to fiber stress gives an accurate determination of the inherent fiber properties. This can serve as a reliable quality control on the yarns and roving. At the same time, variations which are due to the resins, degree of cure, resin content, etc, are plainly discernible.

In a finished composite structure the shear and tensile strengths of the resin and its elongation are probably the most significant properties, if the resin is to perform its function as a matrix for the reinforcements. However, there are a number of other properties which can be critical.