BENDING BEHAVIOR OF LAPPED PLASTIC EHV CABLES*

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Abstract

One of the factors delaying the development of lapped polymeric cables has been their reputed poor bending characteristics. Complementary programs were begun at BNL several years ago to mathematically model the bending of synthetic tape cables and to develop novel plastic tapes designed to have moduli more favorable to bending. A series of bend tests was recently completed to evaluate the bending performance of several tapes developed for use in experimental superconducting cables. The program is discussed and the results of the bend tests are summarized.

Introduction

Brookhaven National Laboratory, (BNL) has been actively involved in the development of lapped plastic, EHV power transmission cables for several years. Two test model ac superconducting cables employing lapped polymeric tape as the insulation have already been built, and a 100 meter demonstration model rated at 1000 MVA, will be installed within the next two years.¹ More recently, basic studies were begun to develop a polymeric tape suitable for use as insulation in oil impregnated, EHV cables for ambient temperature use.²

Although poor compatibility between the plastic and the impregnant has been the major deterrent to the development of ambient temperature lapped polymeric cables, the reputed poor bending characteristics of this construction has been an important secondary problem. The reason for this reputation is that radial pressures in polymeric cables do not level off at a plateau value, as is the case with conventional kraft paper designs; in fact, radial pressures in a relatively thin insulation layer, have been shown to reach substantial values, see Fig. 1. The major reason for this behavior is that the tensile moduli of engineering plastics are usually considerably lower, and the compressive moduli are significantly higher than the corresponding values for kraft paper.

In order to ensure acceptable bending behavior of the experimental superconducting cables under development at BNL, a substantial effort was begun several years ago to make a computer model of the bending of synthetic tape cables and to fabricate plastic tapes designed to have moduli favorable to bending. The theoretical analysis by Gazzana-Priaroggia et al³ at Pirelli was programmed for a computer and apparatus was constructed to measure values of the mechanical properties required by the analysis.

A series of bending experiments was recently performed at BNL to compare actual damage with the predictions and also to evaluate four synthetic tapes developed at BNL for use in superconducting cables. The purposes of this paper are to review the results of these bend tests.

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Fig. 1. Experimental Values of Radial Pressure for Five Experimental Tapes.

The Pirelli Theory and Other Factors Affecting Bending Performance

There are three aspects to the theory developed at Pirelli:

1. Calculation of the radial pressure ϕ_r throughout the body of insulation. The calculation is based on the linear theory of elasticity in anisotropic materials. Non-linear materials (materials for which the material properties are a function of pressure) are accommodated by dividing the insulation radially into a number of sections having constant properties.
2. Calculation of the radial and axial pressures developed when the cable is bent. The radial pressure decreases on the inside of the bend and increases on the outside. A stable winding requires that the pressure on the inside of the bend does not reach zero. The axial pressures developed during bending would be zero if the tapes could slide freely over one another, but friction between layers leads to non-zero axial pressures, a tensile pressure on the outside of the bend and a compressive pressure on the inside.
3. Calculation of the critical pressure of a thin-walled circular cylinder loaded axially.

If the axial pressure developed by bending is greater than this critical pressure, buckling will occur. It is shown by Gazzana-Priaroggia et al³ that the critical pressure is independent of cylinder length except for

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very short cylinders, and this length independent pressure is termed P_0 . The "buckling length" is a matter of observation; it may be the length of a butt-gap, typically 0.040 inch, in which case the damage observed is called "butt-space creases", or it may be greater than the butt-gap depending on how the tapes support one another. For a typical BNL bend test cable, the normal butt-gap is narrow enough that the critical pressure of a cylinder having this length is length dependent and about 65% higher than P_0 .

There are thus three pressures to be calculated:

1. The radial pressure $\phi(r)$ developed by the lapping pressure, also termed PHIR in the present report.
2. That value of the radial pressure which, taking account of friction, will develop an axial pressure equal to the critical pressure P_0 for cylinder buckling - this value of the radial pressure is termed PMAX in the present report.
3. The radial pressure change due to bending, termed PMIN. PHIR must lie between PMAX and PMIN to avoid damage. Unlike PMIN, PMAX is almost independent of bend radius.

At present, the calculation of the radial pressure PHIR is not fully satisfactory owing to a peculiarity of the compression modulus E_3 described below, and work on this problem is continuing. Since present results are possibly subject to change, we present for the moment only a sample calculation. Table I shows the results of these calculations for one of the test cables described below, # 4 which was wound with a two-ply laminate of polypropylene, the properties of which are given in Table II.

Table I
Calculated Radial Pressure Values, Psi
Bend Radius, Inch

R, Inch	PHIR	100		75		50	
		PMAX	PMIN	PMAX	PMIN	PMAX	PMIN
0.540	24.0	30.3	4.1	30.0	5.8	29.4	9.1
0.572	15.3	28.7	4.1	28.4	5.5	27.9	8.6
0.603	14.3	27.3	3.7	27.0	5.1	26.5	7.8
0.634	14.2	26.0	3.4	25.7	4.6	25.3	7.1
0.665	13.9	24.8	3.1	24.6	4.2	24.2	6.5
0.697	13.1	23.7	2.9	23.5	3.9	23.2	6.0
0.728	11.0	22.7	2.7	22.5	3.6	22.3	5.5
0.759	5.8	21.8	2.5	21.6	3.4	21.4	5.2
0.791	0.0	20.9	2.4	20.8	3.2	20.6	4.9

The points to be noted in Table I are that PMAX changes very little with bend radius, a few percent at most. PMIN, on the other hand, increases steadily with decreasing bend radius, from a value at $R = 0.759$ inch and bend radius 100 inch of 2.5 psi to 5.2 psi with a 50 inch bend radius, a 100% increase. PHIR at the 0.759 inch radius is 5.8 psi. This implies that the winding was on the verge of collapse wrinkling at the smallest bend radius, and this was indeed observed experimentally. The calculations also imply, since PHIR is less than PMAX, a lack of butt-gap creases: on dissection of the test cable only minor creasing was observed.

The Pirelli bending theory does not cover all phenomena which are observed in bend tests. Another phenomenon observed is the tendency for windings to migrate axially during flexing of the cable. The result of such migration is to increase the standard

deviation in the distribution of butt-gaps at a given radius. Obviously, a loose winding of a slippery material will be especially prone to such migration. It is plausible also that a large spread between static and dynamic friction coefficients will increase such tendencies. It is experimentally observed that in the case of paper tapes, too large a lay angle (greater than about 83 degrees) results in an unstable winding. This is presumably due to a spring-like restoring force related to the stiffness of the winding or resistance to axial displacement, although to our knowledge there has been no analysis of the phenomenon. One might expect this stiffness to be related to the various elastic moduli, E_1 , E_2 , and G of the material, which are generally less in our plastic tapes than in paper. Hence it might be expected that a somewhat smaller lay angle might be required for stability with plastic tapes. The lay angle increases with radius and decreases with increasing tape width, so it is customary to use wider tapes at the larger radii.

Experimental

1. Determination of Mechanical Properties

The tape candidates were a 66 μ m thick two-ply polypropylene with friction-reducing "slip additive," a 100 μ m three-ply polypropylene with slip additive, a 104 μ m two-ply polypropylene, and a 102 μ m single-ply polycarbonate, both without slip additive. Slip additives are not a surface coating - they are added to the bulk material. We found, however, that tapes incorporating them deposit a powder on the rollers and guides of the taping machine, an unacceptable situation. All materials were biaxially oriented and had the highest tensile moduli available among commercial grade films. Values of those mechanical properties used by the computer program are summarized in Table II.

The tensile moduli E_1 and E_2 , taken along the machine direction and cross-machine direction respectively, were measured with a table model Instron Testing Machine. Test specimens were 7/8 inch wide by 4 inches long. The shear modulus G , was determined using a method previously developed by the Pirelli Corp. A known torque is applied to one end of a 17 inch long roll of film. This end is free to rotate and the other end is fixed in position. The inside diameter of each roll is set at 1.37 inch and the outside diameter is approximately 1.80 inch with about 50 layers of film. The amount of angular rotation subtended by the free end of the cylinder was computed from the rotation of a 2 foot long pointer attached to the rotating member. Friction measurements were performed using the ASTM "bed-sled" technique, # D1894-63.

The compressive modulus, E_3 , cannot be measured without ambiguity. The method used by Pirelli³ requires measurement of a stack of typically 100 circular discs of 1.05 inch diameter die cut from a sheet. The height of such a stack is a non-linear function of the applied pressure, and the zero pressure height, H_0 , is poorly defined. These measurements were performed for BNL by the National Bureau of Standards, and to avoid the ambiguity in the linear modulus based on the zero-pressure height, NBS reports the tangent, or differential modulus described by

$$dE_3 = H \cdot \Delta P / \Delta H \quad (1)$$

where P is the pressure and H the stack height. The slope of the P vs H curve at the stack height H is $\Delta P / \Delta H$, hence the term "tangent modulus." The usual linear modulus is given by

$$E_3 = H_0 \cdot P / (H_0 - H) \quad (2)$$

Table II

Mechanical Properties of Plastic Dielectric Tapes for Cable Bend Tests

Property	Tape # 1	Tape # 2	Tape # 3	Tape # 4	Tape # 5
Polymer Type	Polypropylene, 2 Ply	Polypropylene, 3 Ply	Polycarbonate "G", 1 Ply	Polypropylene, 2 Ply	Polypropylene, 2 Ply
Slip Additive	Yes	Yes	No	No	No
Thickness, S, Inch	0.0026	0.0040	0.0040	0.0041	0.0041
Tensile Modulus, E_1 , psi	3.33×10^5	2.73×10^5	3.04×10^5	3.14×10^5	3.03×10^5
Tensile Modulus, E_2 , psi	2.78×10^5	2.37×10^5	2.93×10^5	5.68×10^5	5.09×10^5
Differential Compressive Modulus, $d E_3$, psi (at 20 psi load)	2.25×10^3	1.00×10^3	2.60×10^3	1.49×10^3	1.425×10^3
Anisotropy Factor, ($n = E_1/d E_3$) (at 20 psi load)	148	273	117	211	213
Shear Modulus, G, psi	1.64×10^5	1.75×10^5	1.24×10^5	$1.39 \times 10^{5*}$	1.39×10^5
Friction Coefficient, μ_s (CMD to CMD)	0.26	0.23	0.45	0.37	0.42

* Estimated

Most of the mathematical development of the Pirelli theory is formulated using the linear modulus, and the present computer program follows this formulation. A small section of the Pirelli theory - almost an after thought - deals with iterating the radial pressure calculation making use of the differential modulus, but this section is not as completely developed as the rest of the theory. We are, at present continuing to use the pressure-dependent linear modulus, measured from a non-zero initial pressure at which the initial height is reasonably well defined. The NBS data are reprocessed to obtain this modified linear modulus. In the future, we hope to adapt to our program the Pirelli procedure for iteration using the differential modulus.

The anisotropy factor $n = E_1/E_3$ is, like E_3 , pressure dependent. Cables wound with a material having a high value of "n" have a large radial region - most of the insulation in fact - in which the radial pressure is almost constant. It has been shown³ that such a "plateau pressure" also arises even if "n" is pressure dependent provided that "n" is large enough at the plateau pressure.

2. Sample Preparation

Bend specimens were prepared at the BNL taping facility described elsewhere.² All samples were made with 64 tape layers wound at a lapping tension of 1.3 ± 0.1 lb over a 1.08 inch stranded aluminum core. Sixteen tapes were applied per taping head and alternate heads were driven in counter-rotating directions. Successive layers were staggered by 1/3 the tape width. The taping schedule of test cables 1-4 was identical: all tapes were 7/8 inch wide. Cable # 5 was fabricated of the same polymer as cable # 4, but 1.0 inch wide tapes were used in place of the narrower tapes in the outer two sections # 3 and # 4 (tape layers 33-64 inclusive).

3. Bend Tests

Bend evaluation tests were made of each material at three bend diameters, 50, 75 and 100 inches (15 tests total), see Fig. 2. In the course of one bend test a sequence of four bends were made on each specimen, with 180° radial rotation between successive bends. Radiographs were taken of each cable before and after bend testing using the BNL radiography system.⁴ Samples were dissected following radiography.

Results

In general, no "collapse creases" or "butt-space creases" were present following bending over the two larger diameter mandrels where the ratio of the bend diameter to the cable diameter, D/d was 50 or more. Tape migration was usually accompanied by small "butt-space ridges" that protruded outward and usually coincided with a wide butt-space from a consecutively applied tape. The pattern of tape migration found in test cable # 4 after bending at 75 inches is illustrated in the radiograph of Fig. 3. Subsequent dissection revealed the presence of 0.5 to 1 inch long annular regions of small butt-gaps (0.000 - 0.020 inch) alternating axially with regions of severely enlarged butt-gaps (0.075 - 0.095 inch). See Table III.

Cables # 1 and # 3 were found to have butt-gap creases following bending at the 50 in diameter. These creases were usually located either immediately above or immediately below an enlarged butt-gap. Cable # 4 developed severe collapse damage after bending at the 50 in diameter ($D/d = 31.6$). A pattern of "diamond-shaped creases" was present along the entire length of the bend section. These creases extended radially through the full insulation thickness and the creases were accompanied by a high density of voids. A radiograph of the internal tape disturbance of cable # 4 is shown in Fig. 4. For comparison purposes the tape

Fig. 2. Multi-Diameter Mandrel Used for BNL Bend Tests.

high modulus, paper lapped cables are known to become unstable when α reaches 83 or 84° , it may be possible that the lower modulus plastic lapped cables become unstable to bending at taping angles a few degrees smaller. Cable # 5 was built to test this assumption. This cable used one inch wide tapes in the two outer sections in place of the all - $7/8$ inch tapes of cable # 4.

The bend results with cable # 5 were significantly different from those of cable # 4. No collapse damage was present in this cable. Four butt-gap creases were found in the 3 foot evaluation section of the 50 inch bend sample. Creases were approximately 1 inch long and were oriented perpendicular to the bend direction. There was evidence of tape migration over the full length of the evaluation section. The creases were usually located below enlarged butt-gaps ($0.050 - 0.075$ inch).

Conclusions

The results of these studies represent a preliminary step towards understanding the intrinsic bending behavior of cables lapped with tapes having moduli significantly different from those of conventional kraft paper. Although there is appreciable uncertainty in the absolute values of E_3 , the lapping theory has been extremely useful as a guide in selecting taping parameters.

Fig. 3. Radiograph of Insulation of Test Cable # 4 Following Bending Over 75 Inch Diameter Mandrel.

structure of this cable prior to bending is illustrated in Fig. 5.

A possibly significant fact revealed by cable dissection was that the major damage found in cables # 1, 3 and 4 at the 50 inch bend was usually in the third tape section (tape layers 33 to 48 inclusive). In these bend test specimens the taping angle, α , reached approximately 78° in the third tape section. Since

It would be premature to claim agreement between theory and experiment, but it is encouraging that a calculation using uncertain values of E_3 shows a condition favoring the presence of collapse creases which were actually found to occur in cable # 4 following bending at the 50 inch bend diameter.

On the hypothesis that axial tape migration is related to the taping angle, α , a cable similar to # 4

Table III

Results of Bend Tests on Five Plastic Lapped Cables*

<u>Bend Diameter, Inch</u>	<u>Cable # 1</u>	<u>Cable # 2</u>	<u>Cable # 3</u>	<u>Cable # 4</u>	<u>Cable # 5</u>
100	Tape Migration, No Creases or Ridges	Tape Migration, No Creases or Ridges	No Tape Disturbance	No Tape Disturbance	Very Slight Tape Migration, No Ridges or Creases
75	Tape Migration, Some Butt Gap Ridges, No Creases	Tape Migration, Some Butt Gap Ridges, No Creases	No Tape Disturbance	Tape Migration, No Ridges or Creases	Tape Migration, Some Butt Gap Ridges, Two Butt Gap Creases
50	Tape Migration, Butt Gap Ridges, Three Butt-Gap Creases	Tape Migration, Butt Gap Ridges, No Creases	Tape Migration, Butt Gap Ridges One Butt Gap Crease	Severe Diamond Pattern Collapse Creases, High Void Concentration	Tape Migration, Butt Gap Ridges, Four Butt Gap Creases

* All cables except # 5 were wound with 7/8 inch wide tapes; # 5 had 7/8 inch tapes in layers 1-32 and one inch wide tapes in layers 33-64.

Fig. 4. Radiograph of the Insulation of Test Cable # 4 Following Bending Over 50 Inch Diameter Mandrel.

was made with wider tapes in the outer half of the windings to reduce α by several degrees. This specimen did not develop collapse wrinkles. Another interesting finding is that tape migration usually precedes butt-gap creasing in these cables. Substantial tape migration was usually found following bending at the 75 inch diameter. Butt-gap creases present after the 50 inch diameter bends usually coincided with significantly widened butt-gaps. As was mentioned earlier, according to theory a cylinder of length equal to the butt-gap has a critical pressure for buckling about 65% above P_0 . Hence increasing the butt-gap width via tape migration may reduce the critical pressure to the length independent value P_0 , and thus lead to creasing in a close-to-critical situation.

The problem of designing synthetic lapped EHV cables to have acceptable bending capability is appreciably greater than with conventional kraft paper cables. The use of the computer program enables one to design the mechanical aspects of the cable to minimize these problems. Alternative methods of attacking the problems not reported in this paper, are also being pursued at BNL. These consist primarily of modifying the moduli of synthetic tapes. Preliminary experiments with embossing techniques have lead to a significant reduction in the compressive modulus, and tapes having higher values of tensile moduli are now under development.

Fig. 5. Radiograph of the Insulation of Test Cable # 4 Prior to Bending.

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