Procedure for Zone Winding of Extended-Length Netted Composite Shells

V. S. PICHUGIN and V. N. KESTELMAN*

Development Products, Inc., P.O. Box 8303, Radnor, PA 19087

SYNOPSIS

The subject of this paper is the extended-length netted wound composite shells operating in cantilever loading conditions. The winding method that enables the attainment of various thicknesses of the netted shell zonewise is discussed. The distinguishing feature of this formation is the introduction of the sectional expansion mandrel into the production process. The efficiency of the elaborated method is based on the known dependence of the composites' mechanical properties on the tension of the reinforcing filler. On completion of winding, the blank is heated and, with the mandrel sections moved apart in the axial direction, the required level of fiber tension is created in each zone. The improved quality of the material enables increasing of the load-carrying capacity of the items at the simultaneous reduction of their mass. Use of the procedure is most expedient for the manufacture of items from high-modulus reinforcing materials. The field of application is the production of vital shell structures, such as helicopter tail booms, masts of vessels, and power transmission line supports.

1. INTRODUCTION

Recent years have witnessed the expanding practical applications of reinforced polymers in the highly loaded parts and assemblies of items. The latter include large-sized shell structures among which the large-sized extended-length items, such as helicopter tail booms, masts of vessels, and power transmission line supports, can be identified as a separate group.

Such items are produced mainly using the winding method, which is the most basic and most rational method for the manufacture of the parts shaped as bodies of revolution. The existing level of the winding procedure development enables manufacture of shell structures that outperform similar metal items. The expanding requirements for performance characteristics and the creation of the novel high-modulus and high-strength reinforcing materials, however, require further improvement of the winding procedure, ensuring high quality of the structures at the maximum extent of the physical and mechanical properties of the fillers.

Among the diverse types of the composite structures, the shells with the netted load-bearing framework occupy a specific place.[1] The manufacturing of such a spatically reinforced framework, being essentially the system of the mutually intersecting ribs of two and more directions, substantially differs from the processes for manufacturing the conventional shell structures, e.g., tanks, pressure bottles, and pipes.

Known at present is a number of methods for forming the netted shells. This is winding involving the use of the moving curing front,[2] winding in the slots of the shaping elements,[3] and winding involving the use of the limiting pins.[4] The use of the expansion mandrels for the manufacture of the netted carbon-filled plastic shells[5] proved to be very efficient.[5] It has been found that as the tension of the reinforcing elements increases the load-carrying capacity of the shells, diameter 380 mm, increases by more than 200% at the simultaneous reduction of mass and deformability.

The application of the well-known constructions of the mandrels for manufacture of the extended-

* To whom correspondence should be addressed at Development Products, Inc., P.O. Box 8303, Radnor, PA 19087.

Journal of Applied Polymer Science, Vol. 48, 1765–1772 (1993)
 CCC 0021-8995/93/101765-08

length structures, however, may turn out to be ineffective as it is problematic to create the identical level of the reinforcement tension over the item length (due to the action of the friction forces in the course of unwinding). The sectional expansion mandrel[6] for winding the extended-length closed shells enables preventing the diversity of the filler tension over its coil length but it prohibits the zone winding of the item.

Thus, known at present are the separate manufacturing techniques for winding the shell structures from composites, whose integration may enable solving the posed task, i.e., to elaborate the process for manufacturing the extended-length netted shells exhibiting the minimum mass. This imposes some requirements on the mandrel design, i.e.:

- It should be sectional and of the expansion-type, thus enabling effecting the zone winding of the shell and creating the predetermined level of the reinforcement tension within each zone.
- The mandrel should be fitted with the matrix with the shaping elements so as to ensure the required profile of the ribs.
- As regards the end face portions, as well as the boundaries of the sections, provision should be made for the limiting pins so as to reduce consumption of the expensive fillers.

2. ZONE-WINDING METHOD

Let us consider the pattern of the suggested method for forming the extended-length netted shells, shown in Figure 1. The mandrel comprises the center shaft 1, mounted thereon shaping sections 2, 3, and 4 and flange 5, securing pins 6, 7, 8, and 9, and pins 6 and 9 are arranged in one row, whereas pins 7 and 8, in two rows. The number of the sections is no less than that of the winding zones over the item length. Section 2 is fixed to the shaft, whereas sections 3 and 4 and flange 5 are able to move in the axial direction by actuator 10. Sensor 11 is intended to monitor the change in the axial force value in the course of the item manufacture. Sections 2, 3, and 4 and flange 5 are fitted with rigid coupling means 12 and locking means 13, enabling joining them together pairwise.

The method for manufacturing the variable-thickness extended-length shells is as follows: In laying the material on each section, it locks in position using limiting pins 6, 7, 8, and 9 arranged on one edge of the winding section and the adjacent edge of the subsequent section, and the pins are arranged in two rows on the last section. In winding the material on the first (in the clockwise direction) section, it is made to run from the above section start to the end, bypassing the second in the run pin 7 of the subsequent section. Thus, coil 14 is produced. In winding the subsequent section, its first pin 7 is bypassed first, the material is laid on the section surface, and, next, the second in the run pin 8 of the subsequent section is rebypassed. As a result, coil 15 is produced, etc. Proceeding from one zone to another, the extended-length netted shell is wound.

The mandrel operates as follows: On winding the netted shell according to the predetermined pattern, sections 2, 3, and 4 and flange 5 are disjointed (by removal of coupling means 15) and actuator 10 operates so as to cause flange 5 to move relative to shaft 1. Through the wound blank, flange 5 carries along sections 3 and 4 in the axial direction. In doing so, section 2 remains immobile and creates in the entire blank the tension Q_1 level required for the first zone (zone l, with item minimum thickness h_1). Subsequently, section 3 is fixed relative to section 2 using any locking mechanism 13 and the sections are joined rigidly using coupling 12. Thus, section 3 is rigidly coupled with center shaft 1.

This done, further travel of flange 7 over section l_2 enables creation of tension Q_2 and sections 3 and 4 are locked relative to one another and joined integrally. Finally, predetermined force Q_3 is created over section l_3.

The main technological parameter of the process is the total axial force. The relation between axial force Q_{ax} and tension T_{bn} falling on one bundle is of the form[5]

$$Q_{ax} = 2T_{bn}znk \cos \varphi$$

where z stands for the number of one spinning ribs; n, for the number of the spiral layers in one rib; k, for the number of bundles in one layer; and φ, for the angle of laying the spiral layers on the cylinder (degrees).

In spite of some complications of the tooling design, the suggested method offers a number of essential advantages, the most important of which are as follows:

- possibility of winding the extended-length netted shells with a varying number of the reinforcing elements in the zones;
- possibility of winding the zones using various materials;
- reduction of the reinforcement tension diversity over the coil length (due to breaking down the coil into the shorter zones);

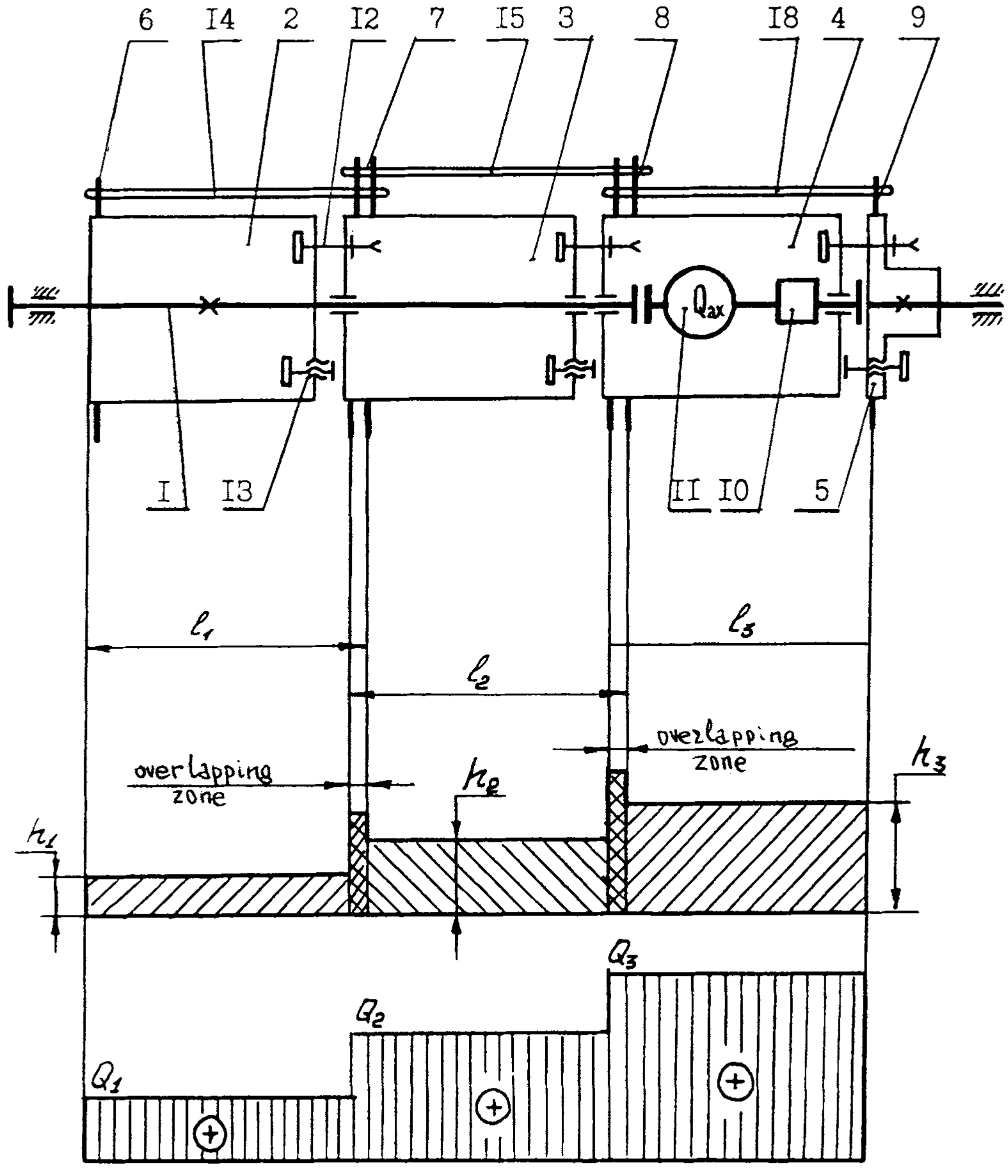

Figure 1 Pattern of method for forming extended-length netted shells.

- reduction of the produced items mass; and
- reduction of the winding cycle.

3. ASSESSMENT OF SHELLS' MASS REDUCTION POSSIBILITY

Let us assess the possible reduction of the mass of the netted shells due to the use of the suggested method for zone winding.

Let there be preset the shell mass (thickness) variation over its length $h = f(l)$ (cf. Fig. 2). Let us arbitrarily break down the item lengthwise into three zones: Let us denote theoretically the required thickness of the shell at the start of zone I by h_0, and at the end of zone 3, by h_e (the shell termination zone). Let us denote the actually attained thicknesses of the shells in zones 1, 2, and 3 by h_1, h_2, and h_3, respectively. In this case, we have $h_3 = h_e$. The zones of transition 1–2 and 2–3 witness an abrupt change in the item thickness, which is caused by the overlap of the material of two zones. The values of abrupt changes h'_1 and h'_2 are minor and amount to about 0.1 h_1 and 0.1 h_2, respectively (this is explained by denser packing of the fibers and squeeze-out of the excess binder in the transition zones).

The analysis of Figure 2 indicates that to attain the minimum mass of the item, i.e., approaching the

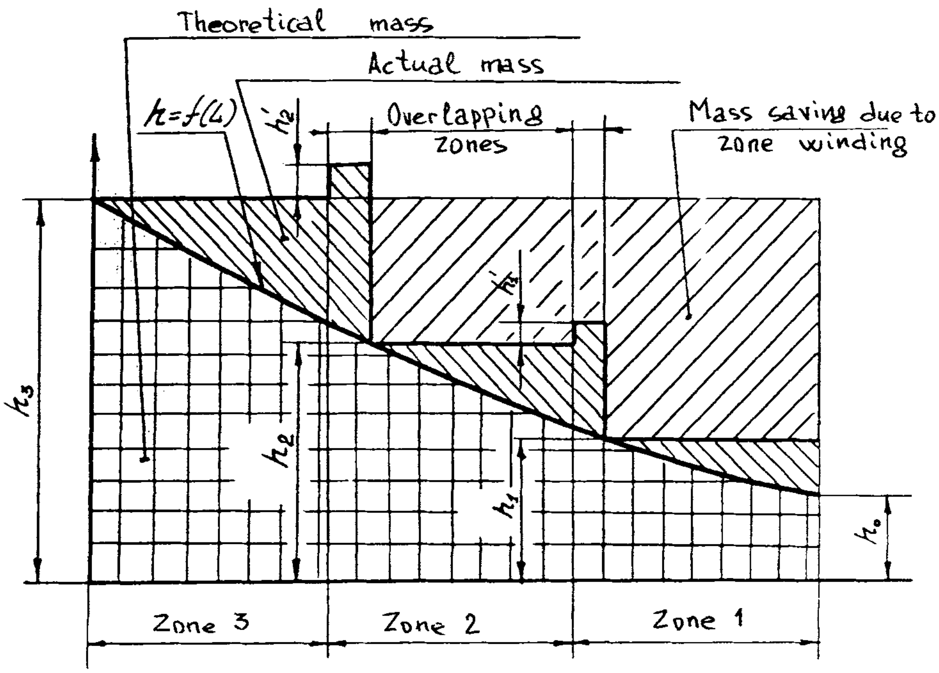

Figure 2 Determination of mandrel section number.

theoretical value by the shell thickness in each zone, the number of the zones should be increased. The existence of the overlapping zones (areas of material overlap), however, results in that the optimal number of the winding zones at the predetermined overlapping value takes place. Usually, the overlapping zone length is taken as a multiple of the cell rib length.

In addition, the minimum number of the zones (the mandrel sections) is affected as follows: In performing the blank release operation (creation of the predetermined tension of the filler), the tension level within each zone changes in the manner shown in Figure 3, i.e., some reinforcement tension difference is observed due to the action of the friction forces. Here, denoted by ΔT, is the tension drop in the center portion of the zone. Value ΔT is assigned proceeding from the condition of the minor (3–5%) reduction in the filler mechanical properties. Thus, the minimum number of the zones can be determined as

$$Z_{\min} = \frac{L}{L_{\max}}$$

where L stands for the item length, and $L_{\max}$, for the maximum length of a filament on the mandrel, at which the tension drop within the zone does not exceed ΔT.

Value $L_{\max}$ can be determined on prederiving experimentally the relations shown in Figure 4. Here, the following designations are introduced: T_1 and T_i stand for the required tension levels in the first and ith zones, respectively; t_1 and t_i, for the heating temperatures of the first and ith zones in performing the release operation, respectively; L_{cr1} and L_{cri}, for the critical lengths of the first and ith zones at the predetermined contact pressure, respectively; and $L_{\max 1}$ and $L_{\max i}$, for the maximum lengths of the sections for the first and ith zones, respectively.

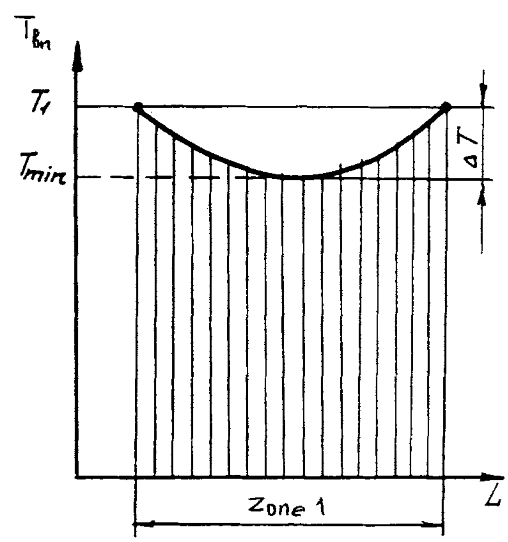

Figure 3 Change in reinforcement tension over zone length.

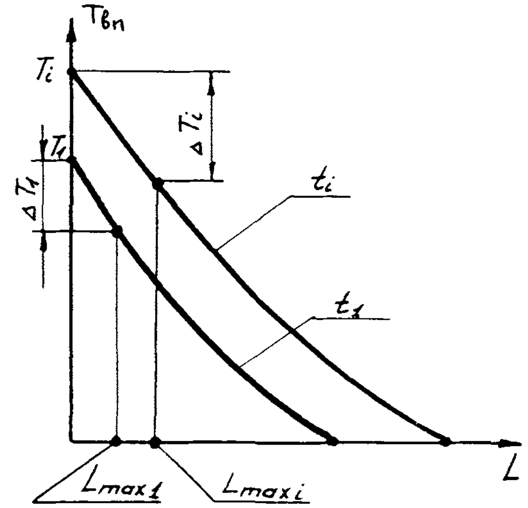

Figure 4 Determination of mandrel section limiting length.

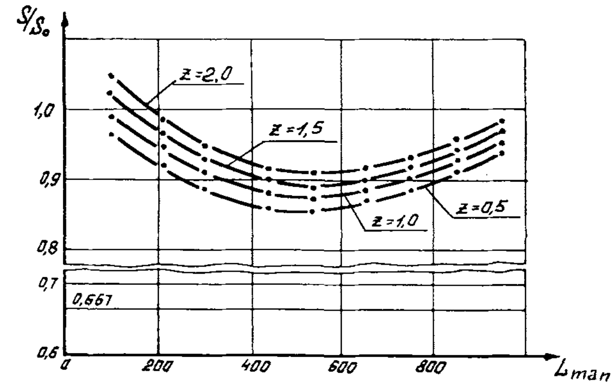

Figure 6 Nonuniform breakdown of mandrel into two sections.

Let us analyze the change in the shell's relative thickness (mass coefficient) in the course of zone winding of the item with the diameter of 200 mm and length of 1.15 mm (thickness changes linearly from h_e = 6 mm to h_0 = 2 mm). The values of the overlapping zones equaled accordingly 0.5, 1.0, 1.5, and 2.0 of the cell rib length equal to 35 mm. The results of the calculations presented in Figures 5–7 enable us to make the following major conclusions:

1. As the overlapping zone length increases, the optimal number of the sections approaches one.
2. As the zonewise difference of the ribs height (thicknesses of the shells) decreases, the breakdown effect substantially reduces and the optimal value of the mass coefficient is displaced toward the unity number of the sections.
3. The difference between the ideal (for our case s/s_0 = 0.667) and the minimum values of mass coefficients s/s_0 at the uniform breakdown of the mandrel into N sections varies from 0.92 to 0.82, depending on the extent of the overlapping zone and the number of the zones, i.e., we obtain the mass saving by 8–18% (cf. Fig. 5).
4. The nonuniform breakdown of the mandrel into the sections enables further decreasing of coefficient s/s_0, and this effect is not identical for a different number of the sections. For instance, for N = 2, the nonuniform breakdown effect occurs only at the overlapping zone length equal Z = 2 and equals only 0.08% as compared to the uniform breakdown (cf. Fig. 6). The increase of the number of the sections up to 3 (cf. Fig. 7) improves the efficiency of the nonuniform breakdown, and with the overlapping length growth, the length of the first section grows with the

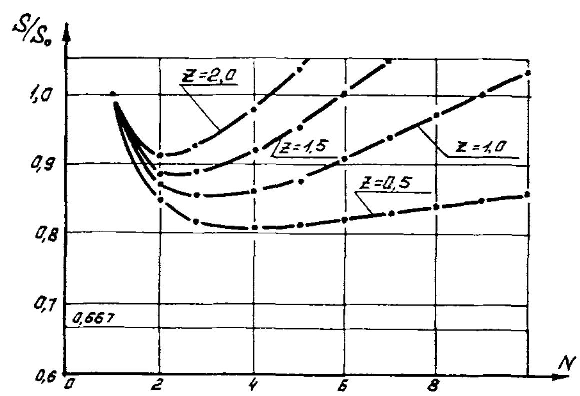

Figure 5 Uniform breakdown of mandrel into N sections.

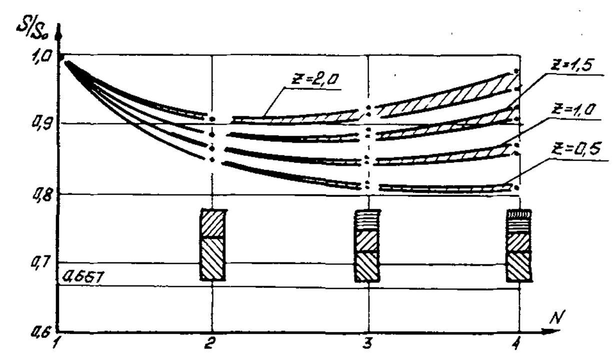

Figure 7 Nonuniform breakdown of mandrel into two, three, and four sections.

length of the center section unchanged. The maximum effect is 0.89% at the largest overlapping zone. The nonuniform breakdown into four sections is even more efficient and enables reducing of the mass coefficient by 3.12% at the maximum length of the overlapping zone. Thus, as the number of the sections grows, the s/s_0 reduction intensity builds up and the length of the sections from the larger thickness of the item to the smaller thickness sequentially decreases.

5. Account must also be taken of the limitation imposed on the length of the sections, associated with its multiplicity of the item netted framework cell length, which, in some instances, levels the advantages offered by the nonuniform breakdown.

4. PROCEDURE FOR MANUFACTURING PATTERN NETTED SHELLS

The efficiency of the suggested procedure was estimated experimentally using the shells, diameter 200 mm and length of 1.15 mm, produced by the wet winding method from the carbon-filled plastic based on the YKH-5000 carbon filament and the ЭХО-MK epoxy binder.

The procedure for manufacturing the master shells formed according to the standard procedure (without zone winding and blank release) includes the following basic stages:

The layer of the fluoroplastic film 20 μm thick is laid with overlapping on the assembled mandrel. The film is locked to the mandrel surface by winding the ring loops of the MCKM-155 brand adhesive tape in its end-face portions. Subsequently, the mandrel is mounted on the winding machine and the elastic sections are arranged on the mandrel surface and locked in position with screws so as to prevent displacement. This done, the reinforcing material is wound by laying the latter into the slots of the elastic sections and forming the end frames. Structurally, the shell consists of 10 spiral layers of the XKH-5000 material forming the load-bearing framework and 11 layers of the end frames of the same material. The pattern was wound by the layer-by-layer alternation of the spiral layers and ring layers of the frames according to the reinforcement layout:

$$\overset{1}{I}\underset{1}{X}\overset{2}{I}\underset{2}{X}\underset{3}{I}\cdots\overset{10}{I}\underset{10}{X}\overset{11}{I}$$

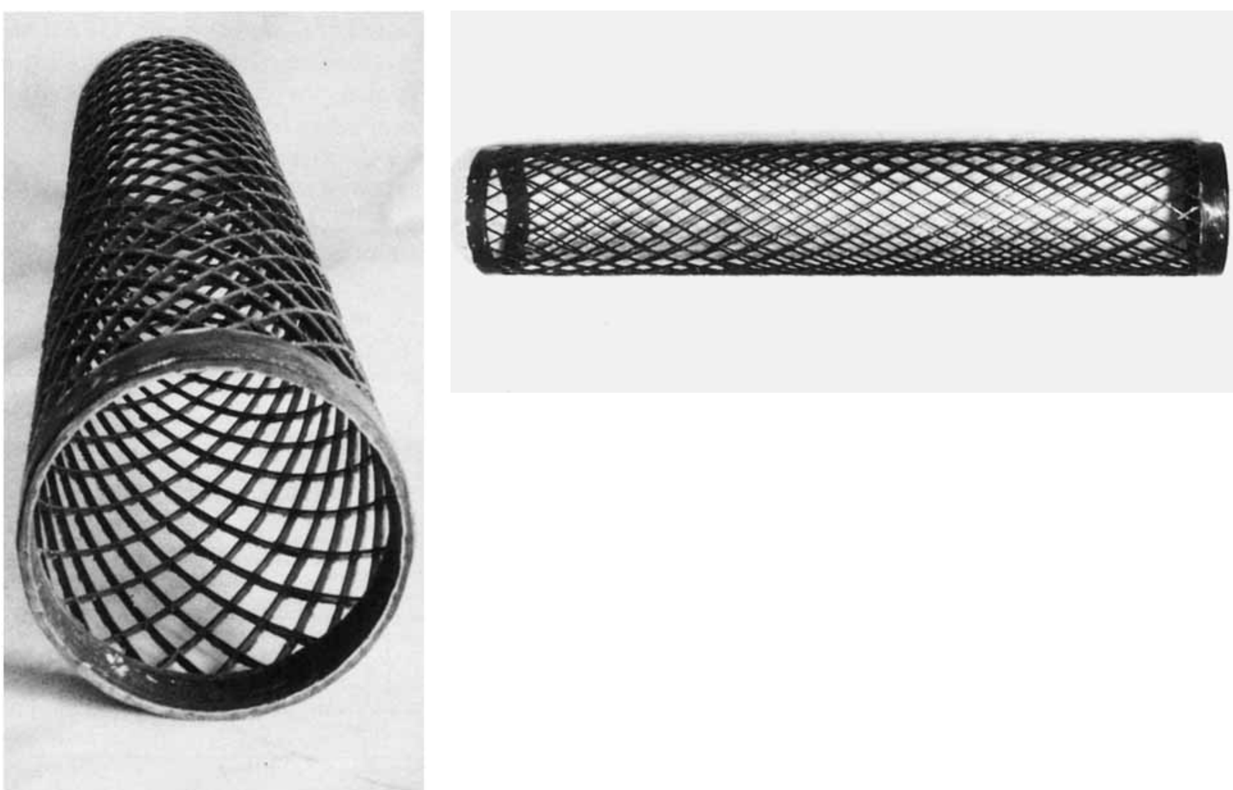

Figure 8 Pattern netted shell, diameter 200 mm.

where I stands for the ring layer of the material reinforcing the frame, and X, for the spiral layer of the material reinforcing the load-bearing framework.

The technological parameters of winding are as follows:

- number of the filaments exhibiting the linear density of 390 tex in a tape = 2;
- tape tension = 20 N; and
- binder temperature = 50–60°C.

On forming the structural depth of the structure (filling the slots of the elastic section), the drain layer is wound using the unimpregnated roving brand PBMH. The blank is subjected to heat treatment in the conditions being the best for a given type of the binder, taking into account the thermal characteristics of the mandrel material:

- temperature rise up to 80–85°C during 1–1.5 h;
- exposure to 80–85°C during 2–2.5 h;
- temperature rise up to 130–135°C during 1–1.5 h;
- exposure to 130–135°C during 2–2.5 h;
- temperature rise up to 150–155°C during 0.5–1 h;
- exposure to 150–155°C during 3–3.5 h;
- cooling down to 100°C during at least 6 h; and
- subsequent free cooling.

Heat treatment is followed by the process working of end faces, removal of the mandrel, and benchwork finishing of the shell. The finished pattern shell is shown in Figure 8 (two views).

Several additional operations are performed in the manufacture of the batch of the experimental shells in addition to the above operations. The distinguishing feature of this batch is zone winding of the netted framework (in our case, the three-zone winding was performed) with additional tension of the filler. Ten layers of the reinforcing material were arranged in the first zone; six layers, in the second zone; and three layers, in the third zone. Whatever the case, the length of the areas of the adjacent zones overlapping equaled that of the lattice cell. The number of the YKH-5000 filament layers, forming the end frame, is assumed to be similar to the master shells. The technological parameters of winding were also maintained identically. Subsequently, the blank with the mandrel was placed inside the thermal chamber and exposed to a temperature of 60 ± 5°C for 1 h. Further, the mandrel was released according

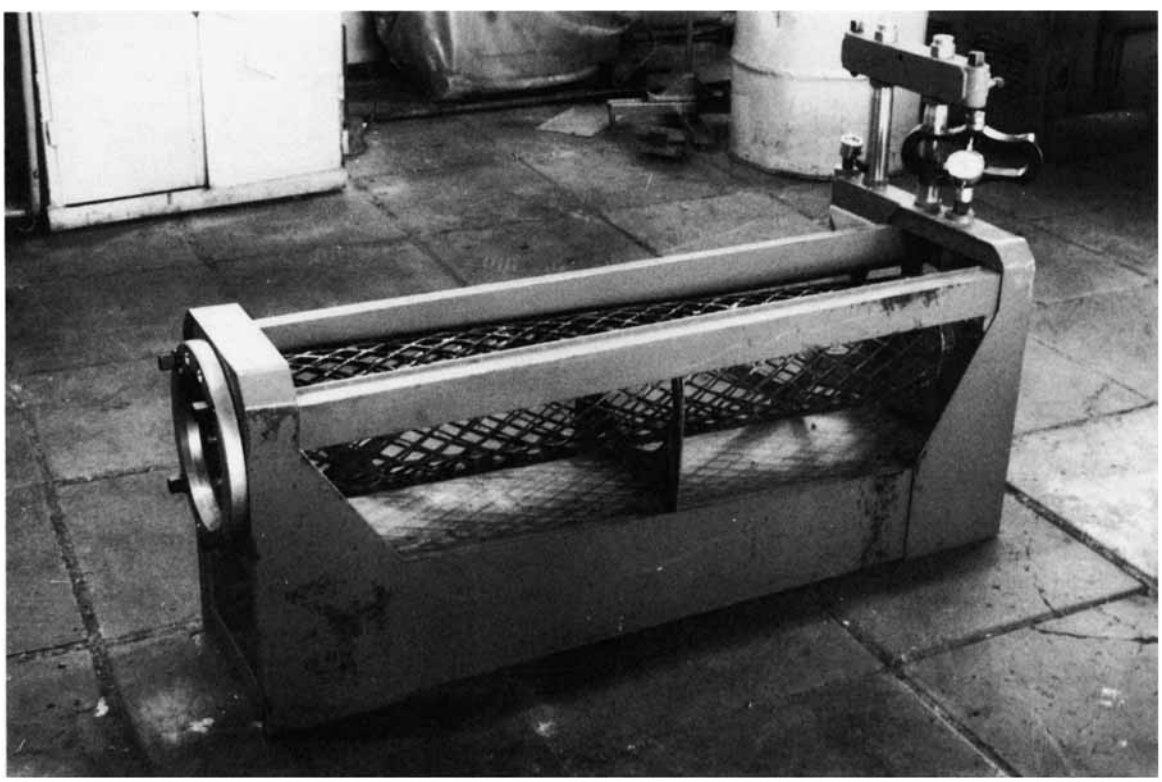

Figure 9 Testing shells.

to the above-described method. As a result, the tension of reinforcement in each zone was 45 N/bundle, which corresponds to its optimal values for the used material.[5] The items were subjected to heat treatment in the standard conditions.

5. TEST RESULTS

The tests of shells were conducted on a special rig (cf. Fig. 9), enabling the cantilever loading with the concentrated force at the rigid one-sided termination. Subjected to tests were two batches of the shells, i.e., three master shells and three experimental shells according to the suggested procedure.

The preliminary analysis of the test results indicated increase of the flexural stiffness at the simultaneous reduction of the shell mass. For instance, the mass reduction by 18–22% was achieved for the investigated items. In doing so, the maximum deflection of the experimental shells was 40–55% less than that on the master shells in the identical load conditions.

CONCLUSIONS

As a result of the work done, the following major conclusions can be made:

1. Elaborated is the method for zone winding of the extended-length netted shells with thicknesses varying over the item length and enabling the creation of the predetermined level of the filler tension in each zone.
2. It has been found that the application of zone winding (without reinforcement tension) enables the reduction of the items' mass without changing their load-carrying capacity. As regards the shells investigated in work, the mass reduction is 8–18%.
3. The pretests indicated the higher stiffness of the structures manufactured according to the suggested procedure due to creation of the reinforcing filler optimal tension at the simultaneous mass reduction. As regards the shells made of the carbon-filled plastic (ЧКН-5000 + ЭХД-МК), achieved is the mass reduction by 18–22% as compared to the master shells at the cantilever-attached item deflection reduction by 40–55%.

References

1. V. A. Bunakov and V. D. Protasov, *Mechan. Compos.*, **6**, 1046–1053 (1989).
2. V. V. Vorobey, V. A. Kalinnikov, and V. I. Demichev, *Coll. Technol.*, **4**, 3–8 (1987).
3. U.S. Pat. 4137354, cl. 428-116 (1949).
4. E. I. Stepanichev et al., USSR Author's Certificate No. 1,548,069, cl. B 29C53/82 (1988).
5. V. S. Pichugin, A. G. Korobeinikov, and E. I. Stepanychev, *Proc. Compos.*, **6**, 1119–1122 (1990).
6. V. S. Pichugin et al., USSR Appl. No. 4,701,653/31-05(078306) (June 6, 1989). vs. which the decision of granting the Author's Certificate was taken.

Received February 19, 1992
Accepted August 21, 1992