The Compressional Behavior of Glass-fiber Sheets and the Forming Pressure of *FRP*

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Abstract

Purpose :

To increase the glass fiber content of *FRP* which influences its mechanical character, the glass fiber must be compressed. An investigation has been made into the compressional behavior of a glass fiber pile and its bearing on the relation between the thickness of *FRP* and the forming pressure.

Results :

Compressional experiments on plain, satin and non-woven glass fibers have shown that a glass fiber pile is compressed by two stages. In the first stage, except under very low pressure, the thickness of the pile diminishes according to the formula $\log t_0 = -m_1 \log p + b_1$. In the second stage, the thickness of the pile decreases according to the formula $\log t_0 = -m_2 \log p + b_2$.

Here m , b take different values depending on the state of the cloth and the presence or absence of uncured resin. The experiments have shown also that the relation between the thickness of the lamination and the forming pressure is $p = (n\theta/t)^{1/m}$. The experiments have also led to the formula $\beta = \beta_1 p^m$ as the relation between the glass fiber content and the forming pressure.

Introduction

To laminate glass fiber-reinforced plastics to a desired thickness by the bag method or by the matched-die method. We have to know how much forming pressure is needed. Otherwise we cannot design the forming press.

A lamination of any desired glass content is obtainable by the matched die method by controlling the number of glass sheets, provided a clearance is given, and the forming pressure is induced on the surface of the die according to number of glass sheets. In the case of the bag method, the glass content of a lamination is fixed mainly by the forming pressure, and the thickness of the lamination is given by the number of sheets.

Therefore, by clarifying the relation among pressure, thickness and glass content, we can build the basis for the forming of *FRP* and, moreover, know beforehand the strength of *FRP* while we are doing laminating.

We will investigate the compressional behavior of glass fiber sheets, and go on to study the relation among the forming pressure, the thickness and glass content of a lamination.

Fig. 1 Experimental instrument to compress glass fiber pile

2. Compressional Behavior of Glass Fiber Sheets

(1) Instrument: The experiment was made with the instrument shown in Fig. 1 and which was attached to a 10T Amsler oil-type universal testing machine. ④ is the glass fiber sheets placed between

polished plates ②③. They were compressed by ⑨⑧④ and ⑮①② while the testing machine ⑮⑦ worked. ⑤ is a case. ⑥⑦ are guides. ⑳㉑ are dial gauges of a 1/100 mm scale, placed 100 mm from the center. ⑩ is apparatus to adjust the relative position of ⑮ and ①—⑧.

(2) Specimens: Three types of glass fiber sheets were used: non-alkalie glass fiber sheet satin (A), alkalie glass fiber sheets, plain woven (B), and non-alkalie glass mats (C). Each sample was cut in size 70 mm×60 mm, and 30 cut pieces made into one specimen.

(3) Experiment: The relative position of ⑮ and ①—⑧ was so adjusted that the specimens ④ were compressed uniformly. Then a desired pressure was given them by the testing machine. The reduction in height corresponding to pressure began to be read on the dial gauges when ⑮ contacted ①. We read the indication after compressing the specimens for 3 minutes, because the height of the specimen remained unchanged even after 2 minutes.

(4) Results of experiment: Fig. 2 shows the results of the experiment on specimen A. The abscissa was given by the common logarithm of the compression pressure on the sheet $\log_{10} p$. The ordinate was given by the common logarithm of the thickness of one sheet $\log_{10} t_0$.

The figure shows that the results of the measurement are plotted along two straight lines having different inclinations, and that these relations hold good for specimens B and C also.

The relations are expressible by this formula:

$$\log t_0 = -m_1 \log p + b_1 \quad \dots \dots (1)$$

$$\log t_0 = -m_2 \log p + b_2 \quad \dots \dots (2)$$

(1) is the formula for the first stage, (2) for the second stage. The constants in these formulas

Fig. 2 Relation between thickness of dry glass cloth of cloth A and compression pressure

ord. thickness of glass cloth mm (log.)
abs. pressing pressure kg/cm² (log.)

and the calculated pressure at the intersecting point are given in Table 1, as an example. *D, W, N, R*, respectively, mean dried, wetted and natural glass fiber sheets used without and with resin.

(5) Discussion: To investigate the behavior of glass fiber sheets during the process of compression, plain woven glass fiber sheets were set with polyester resin in a state of compression and photographed with a magnifying lens. Figs. 3 and 4 show the so-called first stage and Figs. 5 and 6 the second stage.

It was observed from the photographs that, in the first stage, the cross sections of the fiber bundles were deformed, in that they decreased in height and spread sideways, because a glass fiber itself is rigid and its elastic modulus is large.

Therefore, with the decrease in the height of a bundle, the points of contact between pieces of glass cloth increase. So does the total spring constant, i.e., elastic deformation resistance.

Table 1 Examples of Experimental Results

Sample		Before cross point		After cross point		At cross point	
		Coefficient m_1	Constant b_1	Coefficient m_2	Constant b_2	$\log_{10} p_k$	Compression press. p_k kg/cm ²
Cloth A	DA	0.1165	-0.6785	0.0897	-0.7101	1.22	16.5
	WA	0.1190	-0.6800	0.0974	-0.7054	1.18	15.1
	RA	0.0967	-0.7373	0.0743	-0.7586	0.96	9.1
	DB	0.1257	-0.6704	0.1119	-0.6777	0.53	3.4
Cloth B	WB	0.1264	-0.6791	0.1138	-0.6835	0.35	2.2
	RB	0.1281	-0.6968	0.0997	-0.7151	0.64	4.4
Cloth C	NC	0.1405	-0.2954	0.1029	-0.3358	1.07	11.7
	RC	0.0933	-0.5535	0.0859	-0.5584	0.88	7.6

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 3 ~ 6 Magnified photographs of compressed glass cloth pile

Fig. 7 Relation between forming pressure and thickness of FRP using cloth A

ord. thickness of FRP per sheet of glass cloth mm
weight of a sheet of laminated glass cloth (g)
abs. forming pressure kg/cm²

Fig. 8 Relation of forming pressure and thickness of FRP using cloth B

ord. thickness of FRP per sheet of glass cloth mm
weight of a sheet of laminated glass cloth (g)
abs. forming pressure kg/cm²

The restraining force, which is another factor in resistance to deformation, is induced by friction between filaments. It is assumed, therefore, that the restraining force increases approximately in proportion to the pressing pressure (p); and that deformation resistance in the glass fiber layers is affected mutually by these things, as the formula shows:

$$K = -\frac{\Delta p}{\Delta t} = k_1 \frac{p}{t} \quad \dots\dots(3)$$

$$\log t = \frac{1}{k_1} \log p + c_1 \quad \dots\dots(4)$$

If height t is replaced with t_0 which means the thickness of a glass fiber sheet, and if the coefficient is also changed, then formula (4) will be the same as formula (1).

From the magnified photographs we can understand that the criss-crossing of fiber bundles, contact between one bundle with another and twist-imposed restraint made it difficult for the cross section of a fiber bundle to be deformed at the end of the first stage, consequently the regular wave of the fiber bundles was disturbed and the bundles shifted either to the open space near the crossing point, or the open space created by lack of the fiber bundle.

Accordingly, although the proportional coefficient differs somewhat from that in the first stage, the deformation resistance induced by an elastic or frictional factor is proportional to the compressed pressure and is in inverse proportion to the thickness of the layers, to wit:

$$K = k_2 \frac{p}{t} \quad \dots\dots(5)$$

Therefore, formula (2), like formula (4), is given for the second stage.

2. Forming Pressure of FRP

The foregoing has explained that the thickness of glass fiber sheets of the same kind is diminished by compression, the formula of diminution being $\log t_0 = -m \log p + b$. The layers of compressed glass fiber sheets, however, differ in thickness according to the kind and number of the sheets.

What follows is an investigation of whether the formula holds good as to the forming of FRP and of the relation between forming pressure and the glass fiber content which influences the strength of FRP.

(1) Method of experiment

Polyester mixed with a catalyzer and a promoter was poured into a mold coated with separating agent.

As air bubbles were removed, glass fiber sheets were dipped, one by one, in the mixture. Then they were subjected to pressure-reducing in a sealed vessel to remove bubbles.

The samples were compressed by an Amsler universal testing machine with uniform pressure and were cured by electric heating plates and with ultrared lamps.

After curing and cooling, the thickness of the formed samples was measured with a micrometer. The specimens were made of three kinds of glass fiber sheets, *A*, *B* and *C*, and polyester Epolac *G*.

A is a non-alkalie glass fiber satin woven cloth surface-treated with volan. *B* is an alkalie glass fiber plain woven cloth treated with silan. *C* is a non-alkalie glass fiber mat treated with volan. They were cut in size 140 mm × 170 mm. We used 40 sheets of *A*, 50 of *B* and 25 of *C*, so that the finished thickness was about 7 mm.

The glass fiber sheets used were weighed or their thickness was measured for the calibration of data.

(2) Result

On the assumption that the formula just described was tenable, the measured values were plotted in the following figures which had log-log coordinate. The ordinate is for the mean thickness of the FRP lamination per sheet of glass cloth. The abscissa is for the forming pressure.

(i) Results on *A*

Fig. 7 gives the results on cloth *A*. The thickness of the formed specimen was corrected according to the weight of the glass cloth used. The black marks show the non-corrected values. The white marks show the corrected values. The triangular marks show the weight of the laminated glass cloth, the value of which was used for correction. The straight line means the average of the weights.

The inclination I, II shows the coefficient $-m_1$, $-m_2$ obtained by the above-mentioned pressing experiment on polyester-soaked cloth *A*. The full lines which cut through the dots have the same inclination as $-m_1$, $-m_2$. The broken line shows $\log (t/n) = -m_1 \log p + b \pm b_e$, where added constant $\pm b_e$ is the value obtained by multiplying the coefficient of variant, which is obtained for the weight

of *A* sample, by constant b_1 . The value of the slightly bent point shown in the figure is the same value as is obtained by the pressing experiment on polyester-soaked cloth *A*.

The foregoing shows that the relation between the thickness of *FRP*, reinforced with material *A*, and the forming pressure is not different from the $p-t$ relation if polyester-soaked cloth *A* is compressed. Note, however, that the thickness of *FRP* has to be corrected according to the unevenness of the glass cloth. Remember also that, under a forming pressure higher than that on the slightly bent point, the thickness of *FRP* deviates from the line obtained by the compressing experiment.

(ii) Results on cloth *B*

Fig. 8 shows the experimental results on *FRP* made of cloth *B* and polyester. Here again, because it was not possible to avoid that error in the laminated sample which is caused by the unevenness of the reinforcing material, the measured amount was corrected as in the case of (i).

The explanations about the various marks in Fig. 7 apply here also.

Note in connection with Fig. 8, however, that the corrected experimental values in the second stage are plotted beside the chain line having an inclination of $-m_2$. Indeed, they changed their course and headed for this line at the end of the first stage.

The reason for this fact is presumably this: Polyester resin which enters the glass cloth is squeezed out by pressing force, setting takes while the adhesive force between cloths diminishes and the lamination is expanded by the elasticity of the glass fiber when the pressure is removed.

Such a phenomenon, it seems, is likely to occur in any reinforcing material, and when it does occur, the measured values tend to deviate upward from the line of the second stage. Therefore, the $p-t$ relation should be applied in the first stage where the adhesive force of resin is good. Of course, the lamination is useless if adhesion is poor. In that case the formula for the second stage is not needed.

Fig. 9 shows the results on *FRP* reinforced with cloth *C*. We notice here, too, that the relation between the thickness of *FRP* and the forming pressure is the same as in the two cases cited earlier.

(3) Formulas concerning the factors in the forming of *FRP*

So long as a lamination is used for practical purposes, the formula on the relation between the thickness and forming pressure of *FRP* is:

Fig. 9 Relation of forming pressure and thickness of *FRP* using cloth *C*

ord. thickness of *FRP* per sheet of glass cloth mm
thickness of a sheet of laminated mat mm
abs. forming pressure kg/cm²

$$\log (t/n) = -m \log p + b \quad \dots\dots(6)$$

which is rewritten thus:

$$tp^{m/n} = \log^{-1} b \equiv \theta \quad \dots\dots(7)$$

so that, when $p=1\text{kg/cm}^2$ and $t=t_1$, then:

$$\theta = t_1/n \quad \dots\dots(8)$$

Accordingly, θ means the thickness of a resin-soaked glass fiber sheet under 1 kg/cm². If we take t_a as the thickness of a resin-soaked glass fiber sheet under any pressure p_a , then the coefficient m is given as $m = (\log t_1 - \log t_a) / \log p_a \quad \dots\dots(9)$

This coefficient m should be determined experimentally for each reinforcing material, because it differs according to the construction and the condition of the surface of the glass fiber sheet and the nature of the resin used. Thus, where m and θ of a reinforcing material is known, the pressure needed for forming is given by following formula which is formula (7) rewritten:

$$p = \left(\frac{n\theta}{t} \right)^{\frac{1}{m}} \quad \dots\dots(10)$$

However, the number of the glass fiber sheets for lamination should be calculated by this formula[1]:

$$n/t = \beta \rho_g / w \quad \dots\dots(11)$$

where β is the glass fiber content, in volume, of *FRP*. ρ_g is the specific gravity of the glass fiber and w is the weight of a glass fiber sheet per unit area.

The mechanical characteristics of *FRP* are affected by the content of the material which reinforces the glass fiber and the relation between the

content of the glass fiber and the forming pressure is obtainable from formulas (10) and (11), thus:

$$p = (\theta \beta \rho_g / w)^{1/m} \quad \dots\dots(12)$$

θ , m , w , ρ_g being values peculiar to the reinforcing material, the forming pressure should be the function of the glass fiber content, in volume, of lamination. Therefore, if β_1 is the glass fiber content in volume at 1 kg/cm², the coefficient of $\beta^{1/m}$ is $1/(\beta_1)^{1/m}$ and the forming pressure of *FRP* are decided by the glass fiber content and the kinds of the reinforcing material and the resin.

4. Conclusions

Compressional experiments have made it clear that piles of three kinds of glass fiber sheets all diminish in thickness according to the formula $\log t_0 = -m_1 \log p + b_1$ in the first stage, and according to $\log t_0 = -m_2 \log p - b_2$ in the second stage. If the results of the experiment on the resin-soaked reinforcing material are used for m_1 and b_1 , then the thickness of *FRP* also follows these formulas.

However, *FRP* gets poor with the squeezing out of resin from the glass fiber in the compressional process in the second stage and, in this condition, is not suitable for practical use. The formula on the forming pressure and the thickness of *FRP*, then, is obtainable by developing the formula for the first stage into $p = (n\theta/t)^{1/m}$.

The relation between the thickness of *FRP* and the number of glass fiber sheets for lamination is given by the formula $n = t\beta\rho_g/w$.

To make a stronger *FRP*, the forming pressure must be increased to obtain a higher glass fiber content.

(1) Number of sheets from the reinforce, (2) forming pressure, (3) required thickness, (4) required glass fiber content of *FRP*, and also (5) the capacity of forming press are obtainable from the above formulas.

Literature

- [1] S. Otsuki; *Reports of Ind. Res. Inst. Osaka Pref.*, **19**, 9 (1958)