Non-Elastic Effects during Compression of Fiber Reinforcements

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SUMMARY: Many techniques used for the production of fiber-reinforced polymer composite articles require compression of the reinforcement to achieve desired material composition and properties. A common approach in the literature has been to assume non-linear elastic deformation of the reinforcement when modeling composites manufacturing processes. However, previous research has demonstrated viscoelastic behavior, as well as permanent deformation. These fibrous materials also respond differently if a liquid resin is introduced within the reinforcement structure, which is significant to a range of composites manufacturing processes. A series of experiments were designed and carried out to further investigate these non-elastic effects, and to establish their relative importance. Specifically, the aim has been to determine the proportion of each type of deformation and its variation with respect to time. Material behavior during and following cyclic loading and unloading has also been studied.

KEYWORDS: viscoelastic recovery, permanent deformation, elastic springback.

INTRODUCTION

A wide variety of manufacturing processes have been developed to produce fiber-reinforced polymer composite articles. Such articles find application in industries as diverse as marine, automotive and space, to name a few. Of particular concern to this research are the Liquid Composite Manufacturing (LCM) group of processes, wherein a resin is injected into the mold containing the reinforcement. These techniques require compression of the fibrous reinforcement to achieve the desired material composition and properties. To include compression deformation in LCM process simulations, a standard technique has been to assume that the reinforcement deformation is non-linear elastic [1,2]. However, previous research has demonstrated viscoelastic behavior, as well as permanent deformation [3][4]. These materials also respond differently if a thermo-set (low viscosity) polymeric resin is introduced within the reinforcement structure, which is of particular significance to LCM processes [5].

A series of experiments were designed and carried out to further investigate these non-elastic effects, and to establish their relative importance. Specifically, the aim has been to determine the proportion of each type of deformation and its variation with respect to time. Material behavior during and following cyclic loading and unloading has been studied.

This research will help in further understanding the forces required for molding, and the distribution of stresses acting on the mold. The long-term goal of this work is the development of a comprehensive reinforcement deformation model, incorporating the different kinds of deformation observed. This will be important for improving simulation of composites manufacturing processes in general.

EXPERIMENTAL WORK

Dry reinforcement samples comprising 10 layers each (200 mm x 200 mm) were cut from Continuous Filament Mat (CFM, 450g/m^2) and Plain Weave Fabric (PWF, 600 g/m^2) E-glass material. The glass fiber preforms were compacted to a target final fiber volume fraction (V_f) on an 'Instron' 1176 Universal Testing Machine with a 200 kN auto-ranging load cell. Following compaction, the strain was held constant for varying periods of time. The testing machine crosshead was then returned rapidly to its initial (un-compacted) position, thus enabling the reinforcements to recover thickness. A rectangular aluminium plate was placed on the reinforcements, and two laser displacement gauges mounted on the crosshead measured the recovery of the preforms by reading the position of the plate. Fig. 1 shows this arrangement. The constant stress on the preforms as a result of the plate was 120 Pa. The presence of the plate not only facilitated the measurement of the preform height at any given time (by allowing the laser displacement gauges to be focussed on it), but also provided a constant stress on the preforms to clearly define the initial height/volume fraction. The mounting of the laser gauges on the moving crosshead enabled the direct measurement of the preform height at any given time. The final V_f was chosen considering the type of reinforcement material, and typical values used in composites manufacturing. The compaction load was also monitored throughout the experiments.

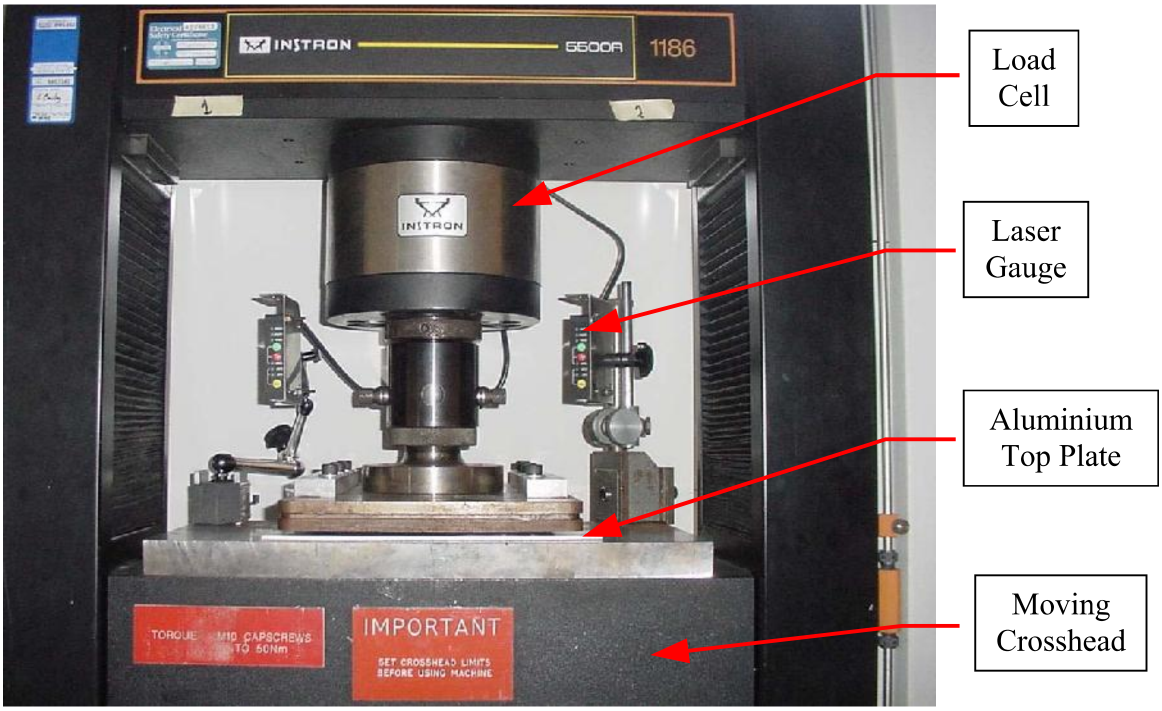

Fig. 1 Experimental set-up

Three CFM specimens were compacted to a target final V_f of 40% at a compaction speed of 5 mm/min. The strain was held at the final V_f for a time period of 6 sec, 10 min and 100 min respectively. At the end of this holding period, the testing machine crosshead was rapidly (at 100 mm/min) returned to its initial (un-compacted) position, thus enabling the preforms to recover height. Readings were taken for a period of 25 minutes following the start of preform recovery.

In a separate experiment, a sample was subjected to 20 cycles of loading and unloading to the same final and initial V_f as above, and at the same compaction and return speed (5 mm/min). Following the last cycle, readings were taken for 25 min to record the recovery of the pre-form.

For PWF, the testing programme was the same as that given above for CFM, except that the target final V_f was 60%.

RESULTS AND DISCUSSION

Continuous Filament Mat (CFM) Glass Fiber Reinforcements

Fig. 2 (a) and Table 1 show the results obtained for the CFM material where the strain was held constant for varying periods of time at the final V_f. It is interesting to note that the time intervals of constant strain used had no impact on the various quantities shown in the table, and that they are almost identical in all three cases. (The constant strain period is not included in the plots for ease of comparison).

From the experimental data it was found that it took about 2.5 sec for the load to substantially diminish from the start of rapid return of the crosshead [from the compacted to its initial (un-compacted) position]. From this point of negligible load, the preforms recovered height rapidly for about 8 sec. This period of rapid recovery represents the elastic springback of the reinforcements. Recovery was recorded for a further 25 minutes. During this period slow but steady increase in the height of the preforms continued to take place. This prolonged recovery is the viscoelastic or time-dependent recovery of the preform. The un-recovered deformation at this stage was treated as permanent deformation. In reality, viscoelastic recovery does not actually cease at that stage, but continues at a very slow rate. Displacement gauge readings were noted about 16 hours later, and increase in preform height of about 0.2 mm was found to have occurred during that time.

From Table 1 it can also be seen that elastic springback and permanent deformation are significant components, while viscoelastic recovery is a small proportion of the total deformation of the preform. This could be due to the nature and structure of CFM glass fiber reinforcements. The layers of material sit loosely on one another, and a considerable proportion of the bulk volume of the reinforcements is empty, enabling significant elastic and permanent deformation to take place.

The compaction load data was also recorded in all tests, but is not presented here.

A direct comparison of the stress on the preform can be made for the tests where the strain was held constant for 10 min and 100 min. Stress relaxation occurs during this time, and the longer the duration of constant strain, the greater is the stress relaxation.

Table 1 CFM and PWF Glass Fiber Preforms: Components of Deformation

	CFM (V_f = 40%) Compaction Speed = 5mm/min				PWF (V_f = 60%) Compaction Speed = 5 mm/min			
Strain held for	6 sec	10 min	100 min	20 cycles load/unload	6 sec	10 min	100 min	20 cycles load/unlo ad
Height								
Initial, mm	33.7	34.5	34.4	34.6	7.1	7.5	7.6	8.0
Compacted, %	12.0	11.4	11.7	11.6(last)	42.5	39.9	41.5	43.6(last)
After elastic spring-back,%	60.6	60.6	60.1	42.4(last)	71.2	70.1	70.0	62.9(last)
Final, %	64.5	64.7	64.0	44.2(last)	81.7	79.8	80.0	67.6(last)
Deformation, mm	29.7	30.6	30.3	30.6	4.1	4.5	4.5	4.5
Elastic spring-back, %	55.2	56.0	54.8	34.9(last)	49.6	48.1	46.7	34.4(last)
Visco-elastic recovery,%	4.5	4.1	4.4	2.0(last)	18.4	18.4	19.0	8.0(last)
Permanent deform, %	40.3	39.9	40.8	63.1(last)	32.0	33.5	34.3	57.6(last)

The preform subjected to 20 cycles of loading and unloading showed a steady decline in un-stressed thickness as the test progressed, and this tended to a constant value towards the end of the test. A plot of stress vs V_f, Fig. 3 (top), also shows a shift of curves towards the right, which becomes diminished as the experiment progresses, and is almost negligible towards the end. There is little change in stress vs V_f from cycle-to-cycle at that stage. This shows that the reinforcement reached a steady state and no further permanent deformation was taking place.

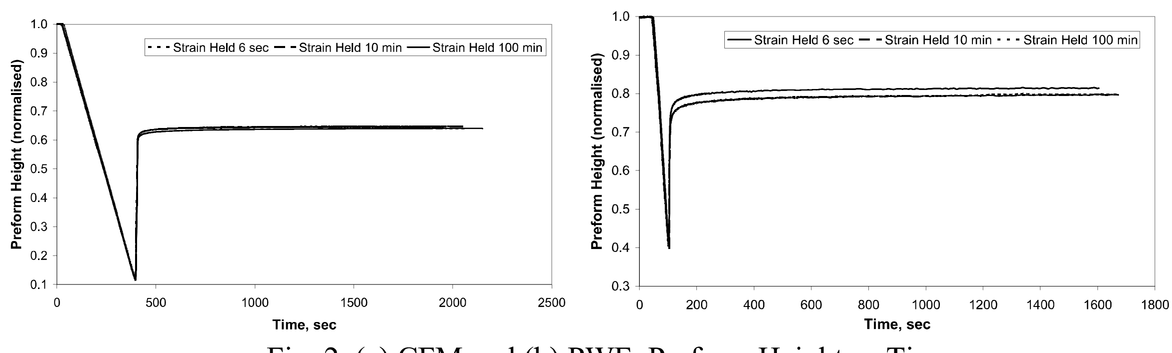

Fig. 2 (a) CFM and (b) PWF: Preform Height vs Time
(Note: Constant strain period has not been shown for ease of comparison).

There is however a difference between the target V_f (as set by pre-determining the motion of the machine crosshead) and the actual V_f achieved (as calculated from the displacement gauge readings). The actual V_f is around 42.5%. This difference of about 0.25 mm between the machine and gauge readings is consistent throughout the experiment. A better method for the future would be to set the crosshead movement required based on the gauge readings.

Plain Weave Fabric (PWF) Glass Fiber Reinforcements

Fig. 2 (b) and Table 1 highlight the results of the constant strain tests on PWF reinforcements. As in the case of CFM reinforcements, the time durations of constant strain have not had any effect on the different components of deformation, and the plots of preform height vs time are almost identical. However, there is more significant viscoelastic recovery, which is comparable to the elastic springback and permanent deformation. Once again, this phenomenon could be attributed to the architecture of PWF glass fiber reinforcements. Woven materials fit naturally and efficiently into compact volumes, unlike CFM. There are also two other factors that come into play when woven reinforcing fabrics are compacted – stacking and nesting. Stacking refers to the manner in which consecutive layers of material are stacked to form the reinforcement. During compaction, layers naturally try to fit into grooves that exist between consecutive tows, and this is referred to as nesting. These issues may account for the fact that both elastic and permanent deformation are less compared to those of CFM, while the time-dependent viscoelastic recovery is comparable to both those quantities. Other issues discussed earlier with regard to CFM (time taken for the load to be released after compaction and constant strain period, rapid elastic springback, slow viscoelastic recovery and very small viscoelastic recovery after many hours) also apply to this material; however, the values computed are different. Again, as in the case of CFM, stress relaxation occurs when the strain is held constant, and longer the time period, greater is the reduction in stress.

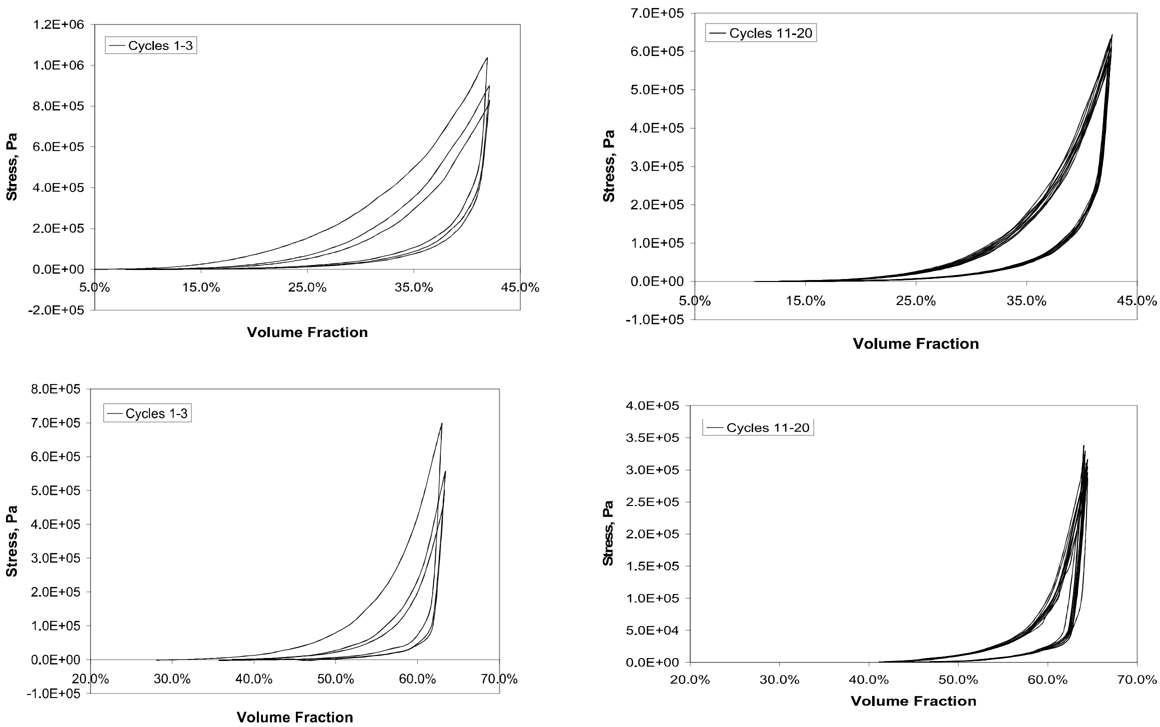

Fig. 3 Stress vs V_f - Cyclic Loading and Unloading: a) and b) CFM cycles 1-3 and cycles 11-20. c) and d) PWF cycles 1-3 and cycles 11-20.

The results for the cyclic loading and unloading test qualitatively mirror those for the CFM. As in the earlier case, as the test progressed, the reinforcement tended to reach a steady state, Fig. 3 (bottom). The elastic springback and viscoelastic recovery components tended to diminish, while the permanent deformation increased. The earlier comment regarding the target and actual V_f applies here also, with the actual V_f being around 62.5%.

CONCLUSIONS

1. The existence of viscoelastic recovery and permanent deformation has been clearly demonstrated. This highlights the complex non-elastic behavior that occurs during compression of fiber reinforcements.
2. The elastic spring-back, viscoelastic recovery and permanent deformation of CFM and PWF glass fiber reinforcements are not affected by the time durations of constant strain used.
2. Viscoelastic recovery in CFM is almost an order of magnitude less than elastic springback and permanent deformation, while this was significant in PWF.
4. The cyclic loading and unloading experiments show that the reinforcements reach a steady-state, and no further permanent deformation takes place. There is little change in stress vs V_f towards the end.

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