COMPRESSION OF THERMOSETTING FABRIC MATERIALS

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INTRODUCTION

Most research into the behaviour of resin impregnated, stitched fabric materials deals with solid state properties (See, for example, [1] and included references). In this paper we report on a study which has been made of the deformation of a number of continuous carbon-fibre mats, both stitched and woven, when subjected to compressive forces normal to the plane of the fabric. The compressive forces were applied both at constant load and constant approach speed. Two significant features for the processing and manufacture of parts formed from these materials were the resin percolation and the elastic recovery when the load was removed, the latter being a possible source of distortion and residual stresses in cured components.

DESCRIPTION OF THE SQUEEZING TEST PROCEDURES AND MATERIALS

Two types of squeezing flow have been used in this study. Both consist of squeezing a prepared sample between two identical parallel square plates that are initially separated by a distance H_0 (figure1). Constant load squeezing is performed by applying instantaneously, at time $t = 0$, a prescribed load F to the upper plate. The motion of the plate is recorded as a function of time. This procedure has been used for continuous unidirectional thermoplastic composites [2]. For some of the tests the load was removed at a later time in order to observe elastic recovery of the sample. The second procedure uses the same geometrical configuration but the upper plate is attached to a drive system with which a constant approach speed is applied. In this case, the normal force generated by the flow is measured by means of a load cell located beneath the lower plate.

Square plates with sides of 40 mm and 60 mm were used for the constant load tests and square plates with sides of 40 mm, 60 mm and 120 mm for the constant speed tests. The largest plate size was dictated, for each of the flow modes, by restrictions imposed by the appropriate apparatus. Each individual test was performed at a constant temperature of 60, 80 or 100 °C. At these temperatures no significant changes in viscosity takes place over the time-scale of the experiments.

Three basic types of continuous carbon fibre-reinforced material were considered: unidirectional (UD) tape and both woven and stitched fabric prepregs. The matrix in all cases was a thermosetting resin. Of the woven and stitched materials, two forms of each were used in order to compare the effects of differences of weave and stitching on the material response. The two woven forms considered were a '2x2 twill' weave and a '5-harness satin' weave. A cross-sectional view through the fabric is shown in figure 2. It can be seen that the satin has a much looser weave than the twill and this is reflected in its response.

Two tri-axial non-crimped stitched fabric (NCF) materials were considered: high drape and standard drape, both forms being available as dry and pre-impregnated mats. The principal difference between the two drapes is in the stitching. The standard drape has parallel, straight lines of straight stitching with a separation of 5 mm, whereas the high drape is stitched in parallel lines of zig-zag stitching with a separation of 5mm. The fibre lay-up is identical for both, i.e. at –45°/90° /+45° to the lines of stitching, and both had the same polyester stitching material.

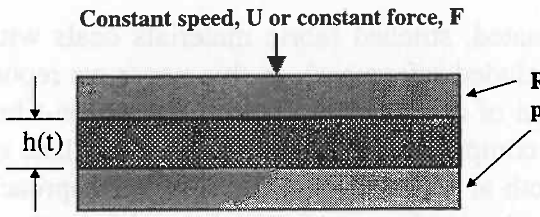

Figure 1: Schematic drawing of the squeezing flow geometry.

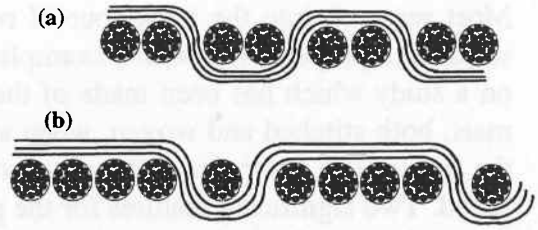

Figure 2: Schematic drawing of: a) 2x2 Twill weave and b) 5-Harness Satin weave

SQUEEZING FLOWS

Constant load squeezing tests, were performed on all materials covering a range of temperatures (60, 80 and 100^0 C) and for a series of applied loads (24.5, 49, 98 and 127 N), the objective being to determine the effects of resin viscosity, geometry and scale on the material response. The response of all the materials with the exception of the dry NCF was characterised by an initial rapid consolidation process followed by a slow deformation tending towards a limiting value. There was no indication that the lay-up of the composites had any significant effect on the flow process.

The response of the dry standard drape was an immediate compression to its final deformation. That limiting plate separation was highly dependent on the applied load as is clearly demonstrated in Figure 3. Temperature was found to have no significant influence on these tests. The dry high drape responded similarly although it was noted that the limiting plate separations for the high drape were slightly larger, for each of the loads, than those obtained with the standard drape.

In the case of impregnated standard drape, after an initial very rapid compression, the sample compressed less rapidly than the dry material but continued to compress to smaller plate separations than the limiting values seen for the dry sample (Figure 3). The presence of the resin serves as a lubricant and hinders the 'locking' of the fibre network. At all loads, the impregnated standard drape compressed further than the high drape. This observation was also valid at each of the temperatures tested. In other respects the behaviour of the two drapes was similar and showed the characteristic initial rapid compression with the limiting deformation dependent on both load and temperature.

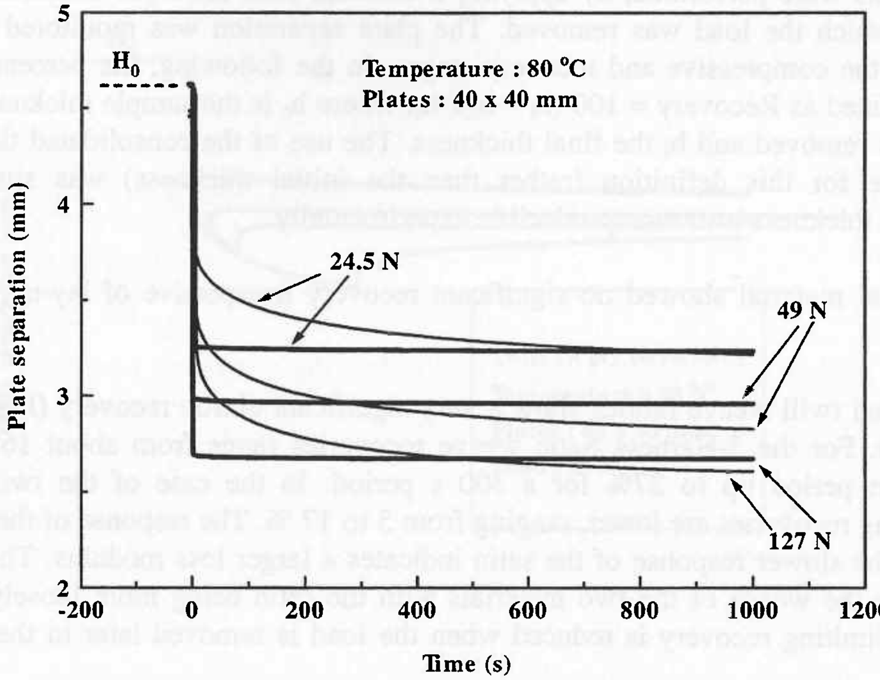

Figure 3: Compression data for dry (thin lines) and impregnated Standard Drape for three loads.

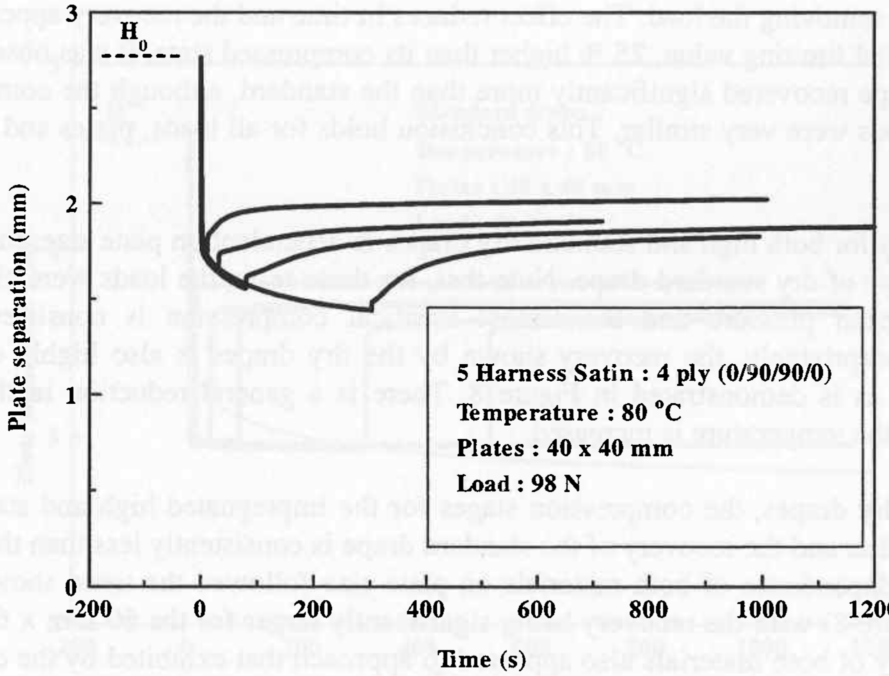

Figure 4: Compression and recovery data for the 5-Harness satin weave. Load is removed 10, 35, 80 and 300 s after application of the load.

Recovery tests were performed, by applying a constant load for a pre-determined period of time, after which the load was removed. The plate separation was monitored continuously during both the compressive and recovery stages. In the following, the percentage recovery has been defined as Recovery = 100 $(h_f - h_c)/ h_c$, where h_c is the sample thickness at the time the load was removed and h_f the final thickness. The use of the consolidated thickness h_c as the reference for this definition (rather than the initial thickness) was simply that the consolidated thickness is more reproducible experimentally.

Unidirectional material showed no significant recovery irrespective of lay-up, plate-size or temperature.

Both satin and twill weave fabrics show a very significant elastic recovery (Figures 4 and 5, respectively). For the 5-Harness Satin weave recoveries range from about 16% for a 10 s consolidation period up to 27% for a 300 s period. In the case of the twill weave, the corresponding recoveries are lower, ranging from 5 to 17 %. The response of the twill is more elastic and the slower response of the satin indicates a larger loss modulus. This reflects the difference in the weave of the two materials with the satin being more loosely woven. The long- time, limiting recovery is reduced when the load is removed later in the compression process.

Results for the dry standard NCF (Figure 6) are very revealing. Although the compression appears to reach its limit at very short times, the recovery is progressively less the longer one waits before removing the load. The effect reduces in time and the recovery appears to reach a still substantial limiting value, 25 % higher than its compressed state. It was observed that the dry high drape recovered significantly more than the standard, although the compressions for the two drapes were very similar. This conclusion holds for all loads, plates and temperatures considered.

The recovery for both high and standard dry drapes is dependent on plate size. In Figure 7, we show the case of dry standard drape. Note that, for these tests, the loads were chosen to give the same mean pressure and the almost identical compression is consistent with this. Somewhat surprisingly, the recovery shown by the dry drapes is also highly dependent on temperature as is demonstrated in Figure 8. There is a general reduction in the amount of recovery as the temperature is increased.

As for the dry drapes, the compression stages for the impregnated high and standard drapes are very similar and the recovery of the standard drape is consistently less than that of the high drape. The dependence of both materials on plate size followed the trend shown by the dry drapes (Figure 8) with the recovery being significantly larger for the 60 mm x 60 mm plates. The recovery of both materials also appeared to approach that exhibited by the corresponding dry fabrics as the plates got larger. The influence of temperature on the recovery was also similar to that shown by the dry drapes. As for the dry drape, there is a reduction in the amount of recovery as the temperature is increased. This is in contrast to the woven materials that show the expected increased recovery at the higher temperatures.

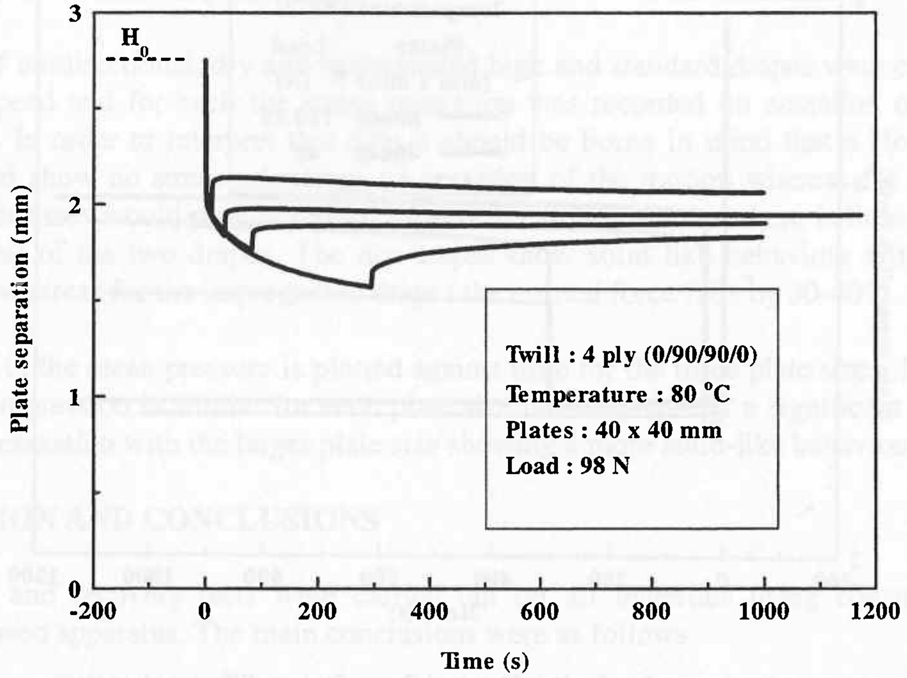

Figure 5: Compression and recovery data for the twill weave. Load is removed 10, 35, 80 and 300 s after application of the load.

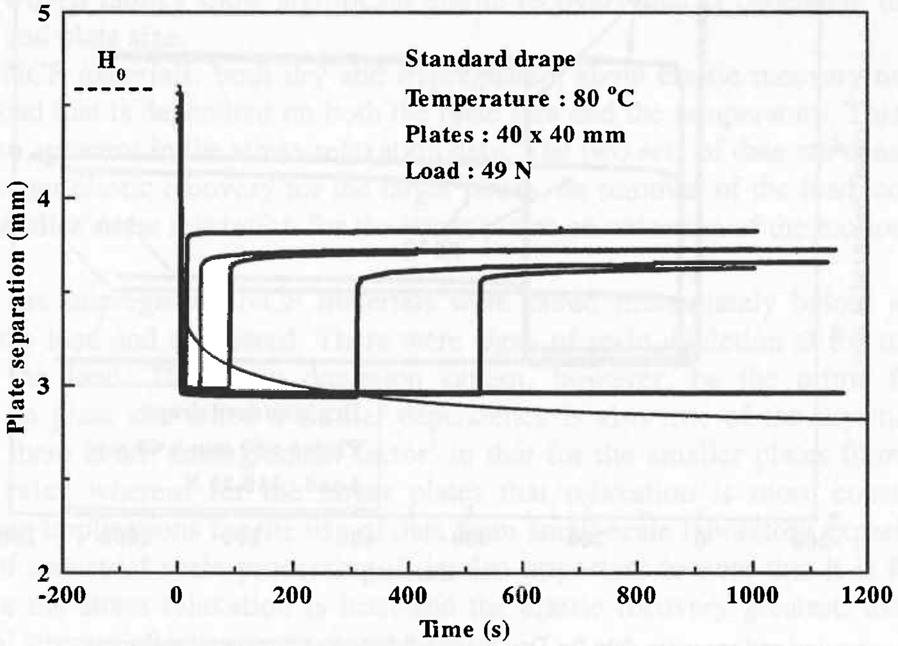

Figure 6: Compression and recovery data for Dry Standard Drape.

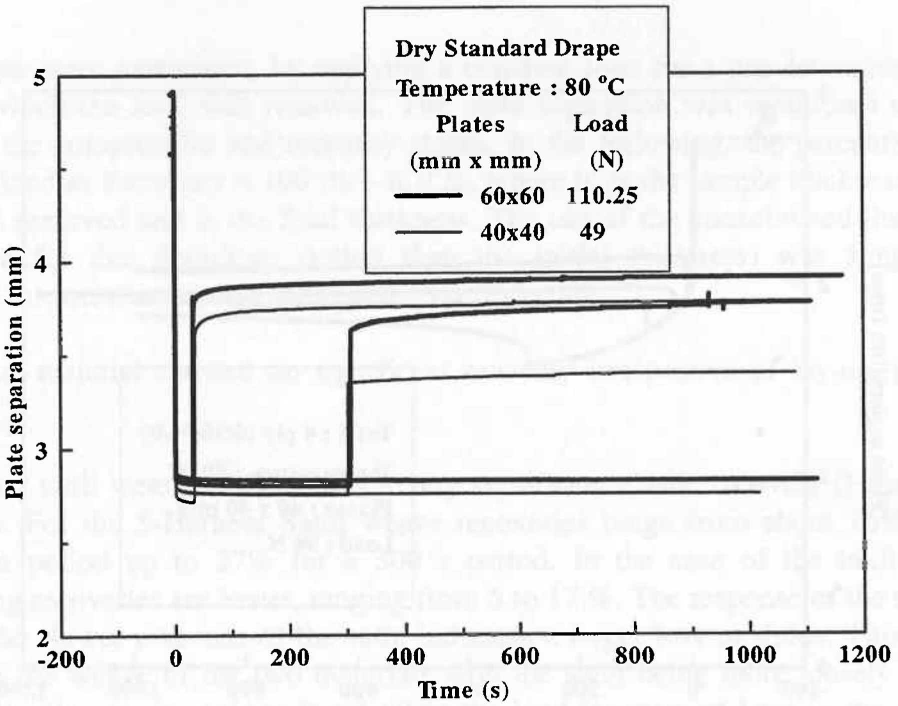

Figure 7: Compression and recovery data for Dry Standard Drape for two different plate sizes.

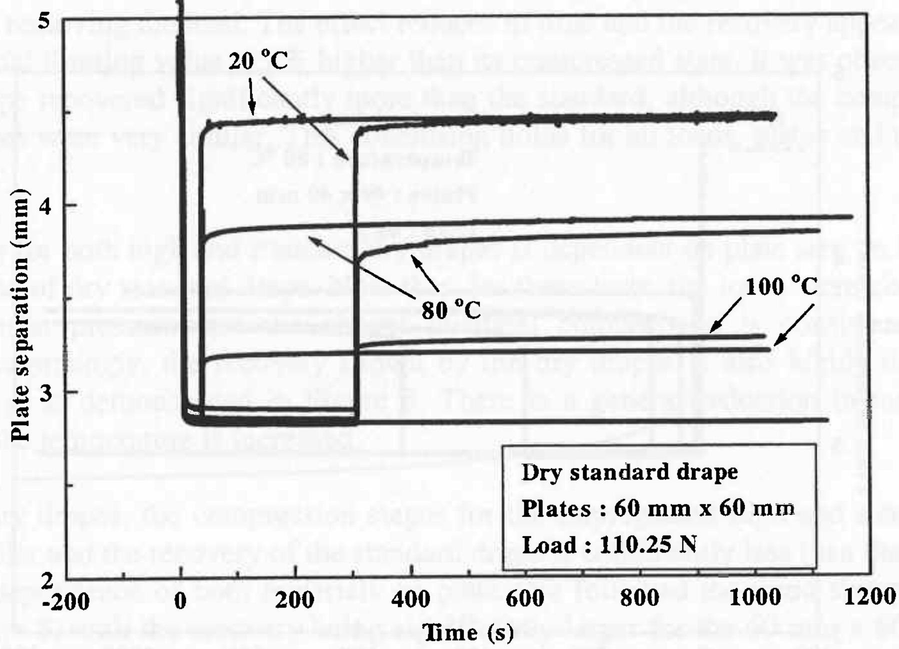

Figure 8: Compression and recovery data for Dry Standard Drape at three temperatures.

CONSTANT SPEED SQUEEZING

Samples of unidirectional, dry and impregnated high and standard drapes were compressed at constant speed and for each the stress relaxation was recorded on cessation of the motion (Figure 9). In order to interpret this data it should be borne in mind that a Hookean elastic solid would show no stress relaxation on cessation of the motion whereas for a Newtonian liquid the stresses would rapidly reduce to zero. It can be seen that there is little difference in the response of the two drapes. The dry drapes show solid like behaviour with little stress relaxation whereas for the impregnated drapes the normal force falls by 30-40%.

In Figure 10, the mean pressure is plotted against time for the three plate sizes. It can be seen that the compression is similar for each plate size but that there is a significant difference in the stress relaxation with the larger plate size showing a more solid-like behaviour.

DISCUSSION AND CONCLUSIONS

Squeezing and recovery tests were carried out on all materials using constant load and constant speed apparatus. The main conclusions were as follows:

(i) The unidirectional materials show little or no elastic recovery on removal of the load and little stress relaxation on cessation of the motion in the constant speed apparatus. This does not, of course, imply that there will be no residual stresses arising from the consolidation process in a cured specimen.

(ii) The woven fabrics show significant elastic recovery that is dependent on the weave, load and plate size.

(iii) The NCF materials, both dry and impregnated, show elastic recovery on removal of the load that is dependent on both the plate size and the temperature. This dependence is also apparent in the stress relaxation data. The two sets of data are consistent in that the larger elastic recovery for the larger plates, on removal of the load, corresponds to the smaller stress relaxation for the larger plates on cessation of the motion.

Samples of the impregnated NCF materials were cured immediately before and after the removal of the load and compared. There were signs of resin depletion at the top plate after removal of the load. This resin depletion cannot, however, be the prime factor in the dependence on plate size since a similar dependence is also true of the dry materials. It is evident that there is an 'entanglement factor' in that for the smaller plates fibre interactions can readily relax whereas for the larger plates that relaxation is more constrained. This conclusion has implications for the use of data from small-scale laboratory experiments in the simulation of industrial scale processing. It is also important to note that it is for the larger plates, where the stress relaxation is least and the elastic recovery greatest, that the risk of large residual stresses after curing is greatest.

The temperature dependence is highly complex. It is clear that, in addition to the expected behaviour resulting from a reduced resin viscosity at higher temperatures, the stitching has a very significant influence.

REFERENCES

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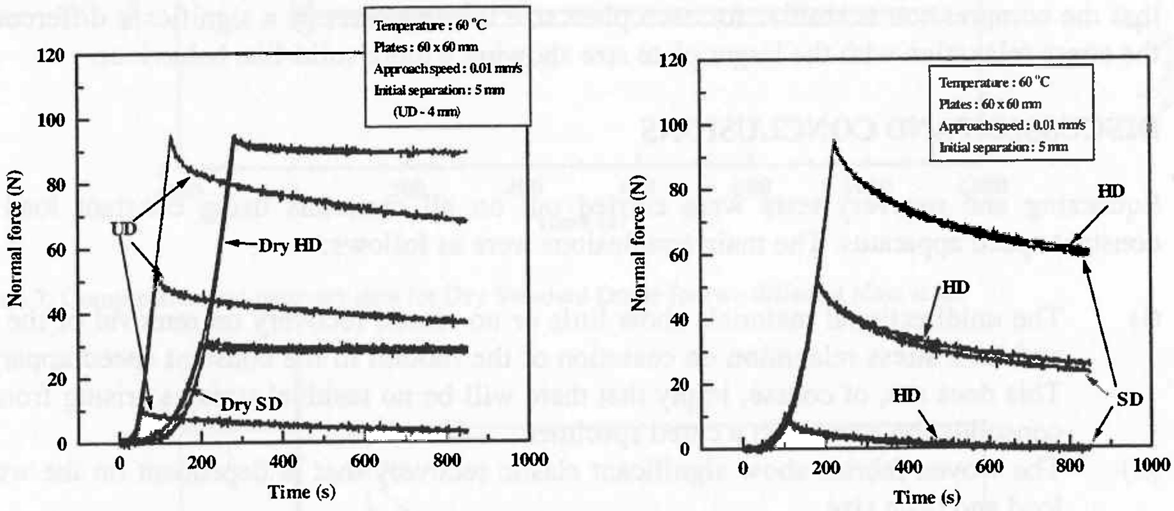

Figure 9: Stress relaxation following constant-speed compression.

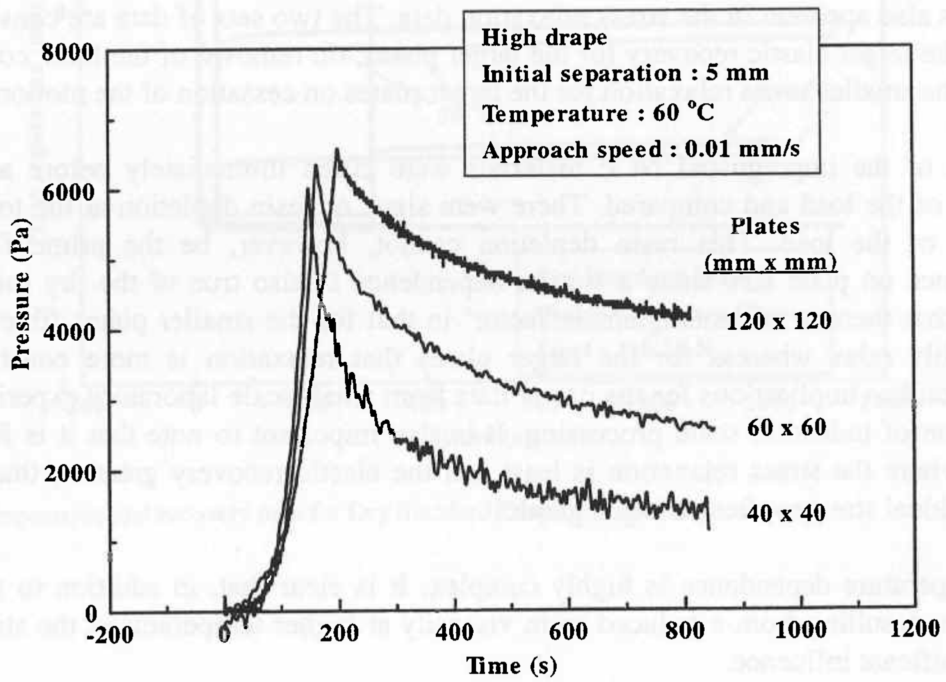

Figure 10: Stress relaxation following constant-speed compression for High Drape using different plate sizes.