

**Protocol for the Prediction of Creep of
Plastic Components**

A Woolf and C S Brown

August 1996

All correspondence concerning this protocol should be addressed to:

C S Brown
Centre for Materials Measurement & Technology
National Physical Laboratory
Teddington, Middlesex
United Kingdom
TW11 0LW

Tel: 0181-943 6769
Fax: 0181-943 6046

Protocol for the Prediction of Creep of Plastic Components

by

A Woolf and C S Brown

SUMMARY

This protocol provides a step by step guide to a new approach to the prediction of creep of plastic components. This new approach has the objective of taking into account anisotropy introduced during moulding and also the component's age after manufacture (physical ageing).

Two commercially available software packages have been adapted to meet this objective. One of these packages, Panda/Compbeam, is suitable for plate or beam-like components and is marketed by NPL. The other package, Moldflow, is suitable for any component and has the additional advantage of modelling flow during processing and shrinkage and warpage after moulding. This protocol outlines the data requirements, the software and hardware needed and the steps the user needs to follow to predict the deformation of a component of interest under in-service conditions.

This new approach is illustrated using four different materials (PP, PBT, glass filled PP and glass filled PBT). Plate-like components were injection moulded and the creep of these anisotropic components measured at a number of applied stresses, material ages, moulding conditions and orientations. The results showed good agreement between the two models (within 5% on average) but only fair agreement with the experimental measurements (within 15% on average). The main reason for the lack of agreement was not due to difficulties in predicting creep, but due to a lack of agreement between the initial measured deformation values and the predicted deformation values. Nevertheless, the ability to predict creep of complex components to within 15% is significantly better (about four times better) than ignoring creep altogether.

CONTENTS

1	INTRODUCTION	1
2	PROTOCOL FLOWCHARTS	3
	Flowchart 1. Choice of Software Package	
	Flowchart D. Stages of Data Preparation	
	Flowchart PC. PANDA / COMPBEAM package	
	Flowchart M1. MOLDFLOW Mode 1 (fibre reinforced components) package	
	Flowchart M2. MOLDFLOW Mode 2 (unreinforced components) package	
3	PROTOCOL DETAILS	8
4	EXAMPLES OF THE PREDICTION OF CREEP OF COMPONENTS	12
5	UNCERTAINTIES	15
6	DEFINITIONS	16
7	REFERENCES	17
8	ACKNOWLEDGEMENT	17

Figures 1 - 6

1 INTRODUCTION

The purpose of this Protocol is to help industry predict the creep properties of plastic components. The Protocol was developed in response to the following background :-

- Commercial finite element analysis programs exist for the design of plastic components but generally do not include provision for the prediction of creep.
- The injection moulding process can alter the structure of parts so that the assumption of uniform and isotropic properties is not valid, ie some information on anisotropy and uniformity is required, particularly for fibre reinforced components.
- Currently, mathematical creep models exist eg [1] but in order to apply them to complex plastic components considerable expertise is required.
- No clear guidelines currently exist on how to predict creep properties of anisotropic plastic components.

1.1 THE BASIS OF THE PROTOCOL

The protocol is based on the use of commercially available software packages to predict the time dependent deformation of anisotropic components either from creep modulus data on polymer matrices and fibre properties or from creep modulus data obtained from strips cut from standard plates. In order to illustrate the use of the protocol, creep data have been obtained from suitable specimens cut from plates made from polypropylene (PP), polybutylene terephthalate (PBT) both with and without glass fibre reinforcement, and modelled to produce creep moduli. Two packages MOLDFLOW and PANDA have been used to model injection moulded anisotropic plates and to predict the performance of the plates in service. The predictions have been validated by comparison with laboratory experimental measurements, see Section 4 and [4] for full details.

1.2 INDUSTRIAL USERS

Those people most likely to find the Protocol of benefit are expected to include:

Designers - in processing companies
 in mould making companies
 in end-use companies

Independent consultants

Companies specifying products likely to be affected by creep

Quality assurance departments

Software suppliers

Software consultants

Users of MOLDFLOW

Users of PANDA or COMPBEAM

1.3 BENEFITS OF USING THE PROTOCOL

The protocol can be used at the design stage to :

- a) avoid failure in service
- b) reduce costs by eliminating unnecessary over design
- c) increase confidence in the use of plastics in load bearing situations.

1.4 STATUS OF THE PROTOCOL

This version of the protocol is 1.0. Suggestions for improvements arising from using the protocol are very welcome and will be included in the next version.

Initial validation has been completed, see section 4 and [4] for full details. Further validation at higher stresses has also been completed which shows a similar degree of agreement. (Details of the high stress results can be supplied on request). The protocol attempts to provide useful guidance to the plastics industry, however NPL Management Ltd cannot accept responsibility for any loss caused by use of the protocol.

1.5 RELATED BEST PRACTICE GUIDE

A guide to the laboratory measurement of the basic materials parameters that characterise the creep of plastic materials is also available from NPL entitled: *Creep Measurement of Plastics, NPL Best Practice in Materials Measurement 002, 1996, by P.E. Tomlins.*

1.6 HOW TO USE THE PROTOCOL

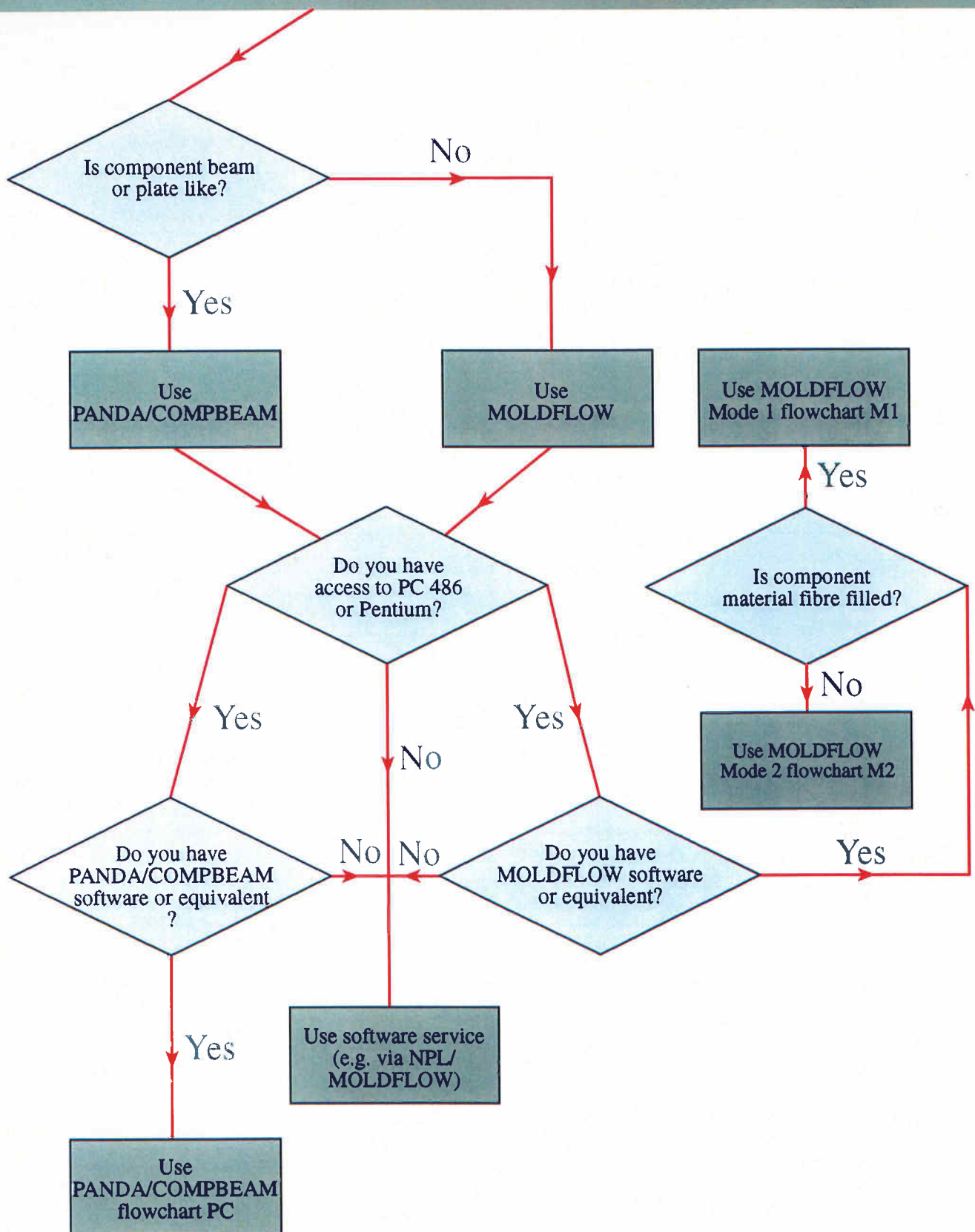
The protocol consists of a series of flow charts followed by a description indicating in more detail what should be done at each stage. Flowchart 1 shows how to choose which software package should be used. There are three options:

- PANDA/COMPBEAM for simple beam or plate-like components with uniform properties
- MOLDFLOW mode 1 for any fibre reinforced component
- MOLDFLOW mode 2 for any unreinforced component.

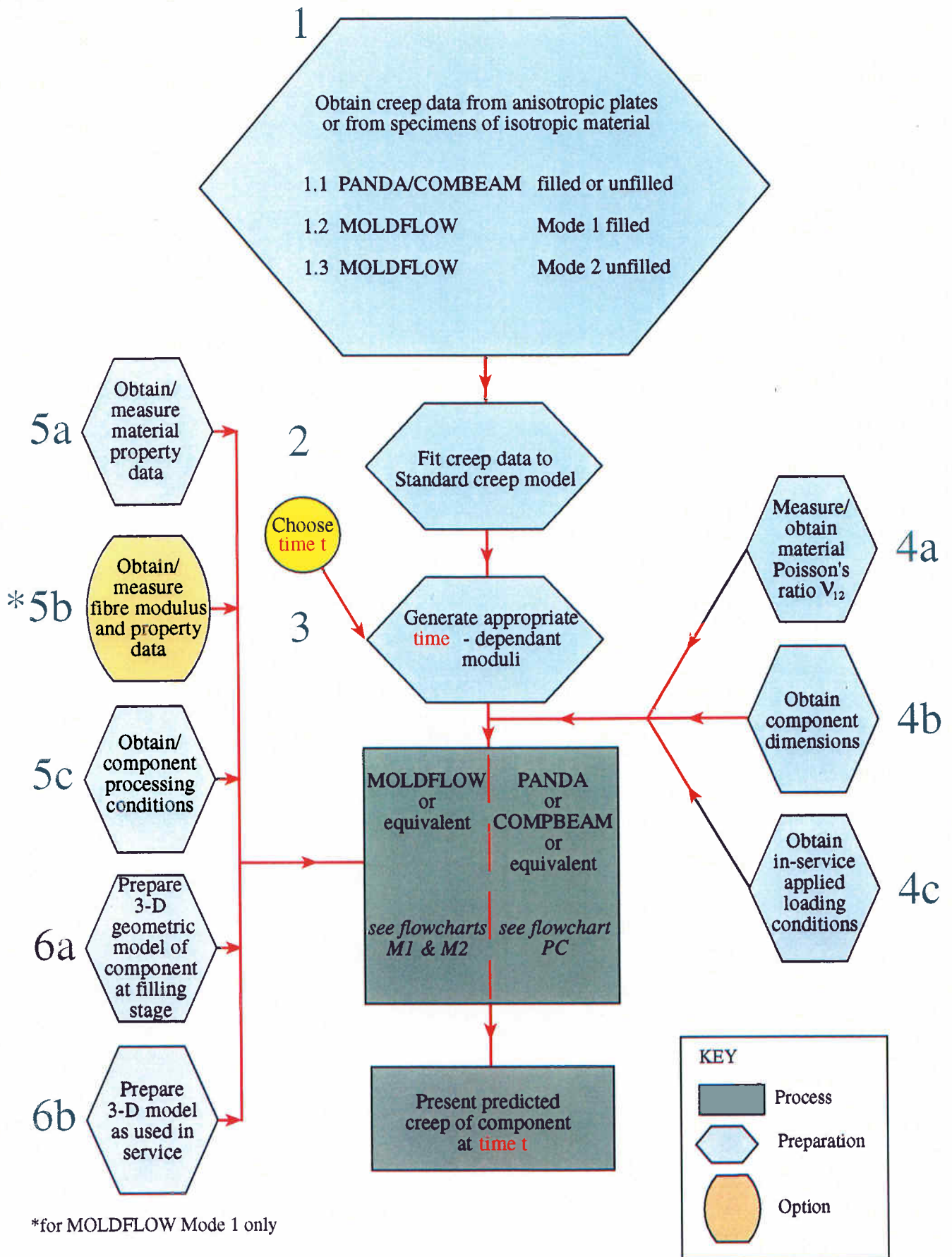
A flow chart is given for each of these options (flowchart PC for PANDA/COMPBEAM, flowchart M1 for MOLDFLOW mode 1 and flowchart M2 for MOLDFLOW mode 2). However, before the software is used the appropriate input data is required. The stages of data preparation that are necessary are shown in flowchart D.

Thus to use the protocol the user should start with flowchart 1, then follow flowchart D and then one of the three flowcharts PC, M1 or M2. Details relating to the flowcharts are given in section 3.

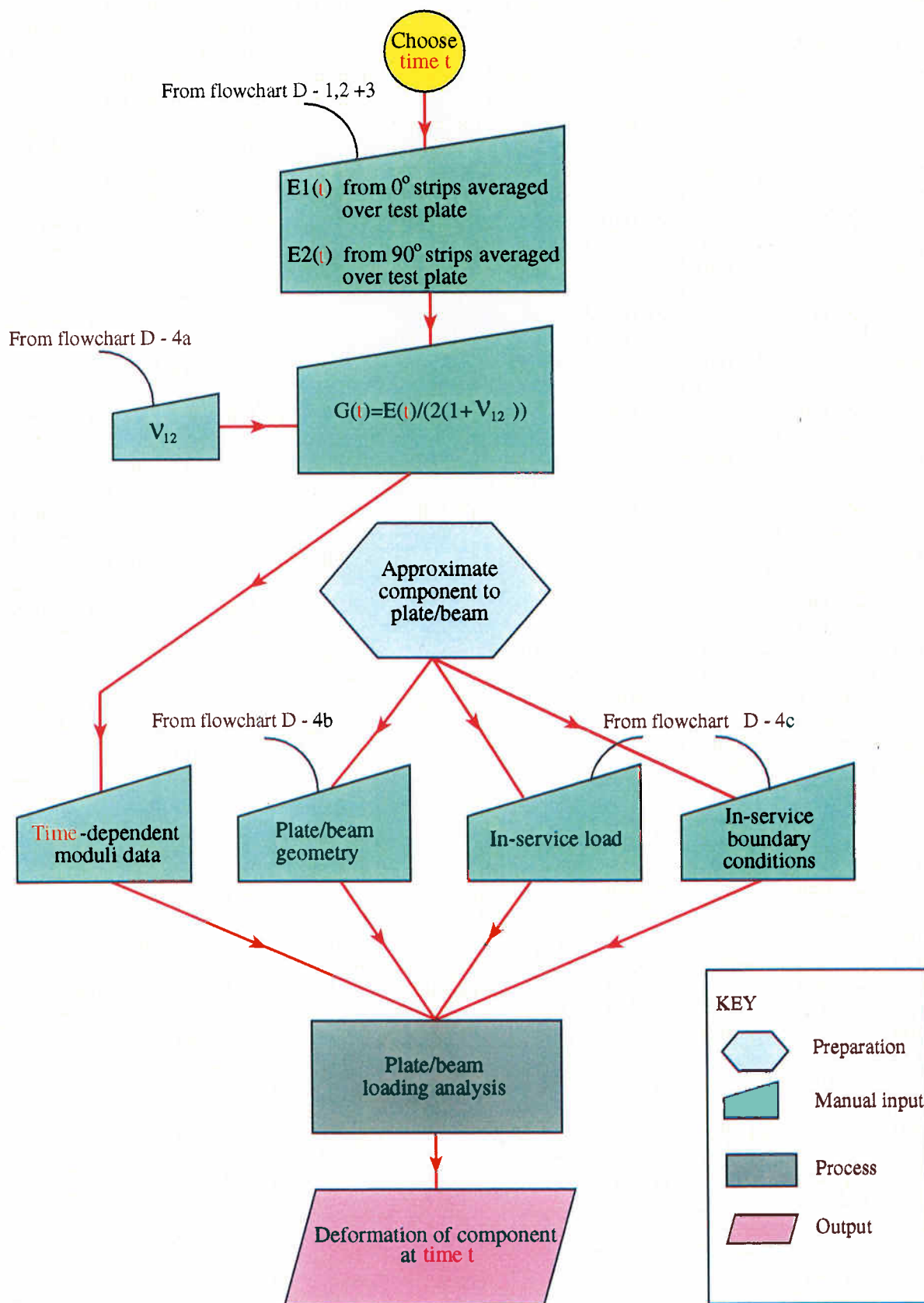
Section 4 gives examples of the use of the protocol in four simple cases. Section 5 provides a formal analysis of uncertainties arising from the mathematics behind the software. Finally, section 6 defines the symbols used in this document.

Choice of Software Package

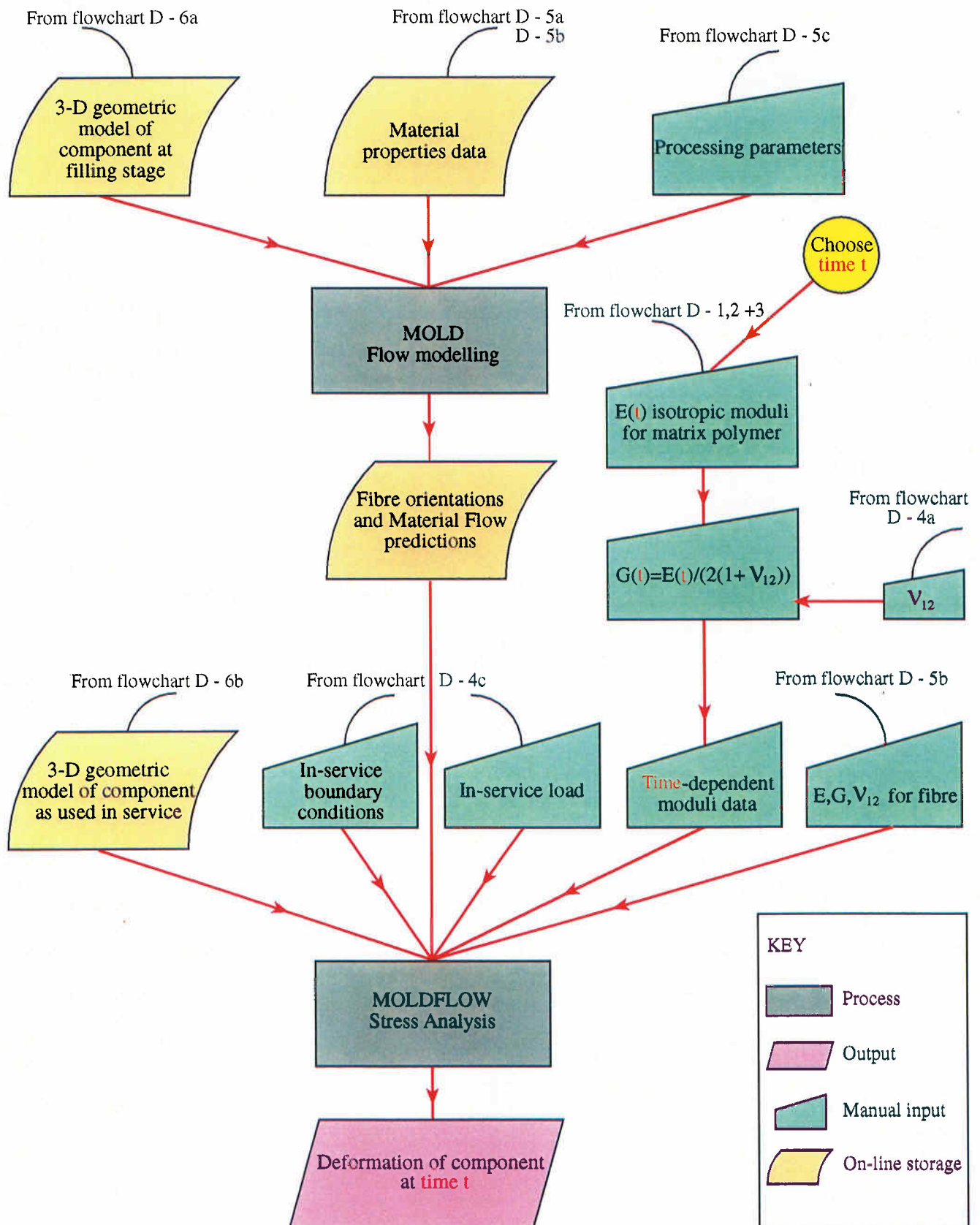
Stages of Data Preparation



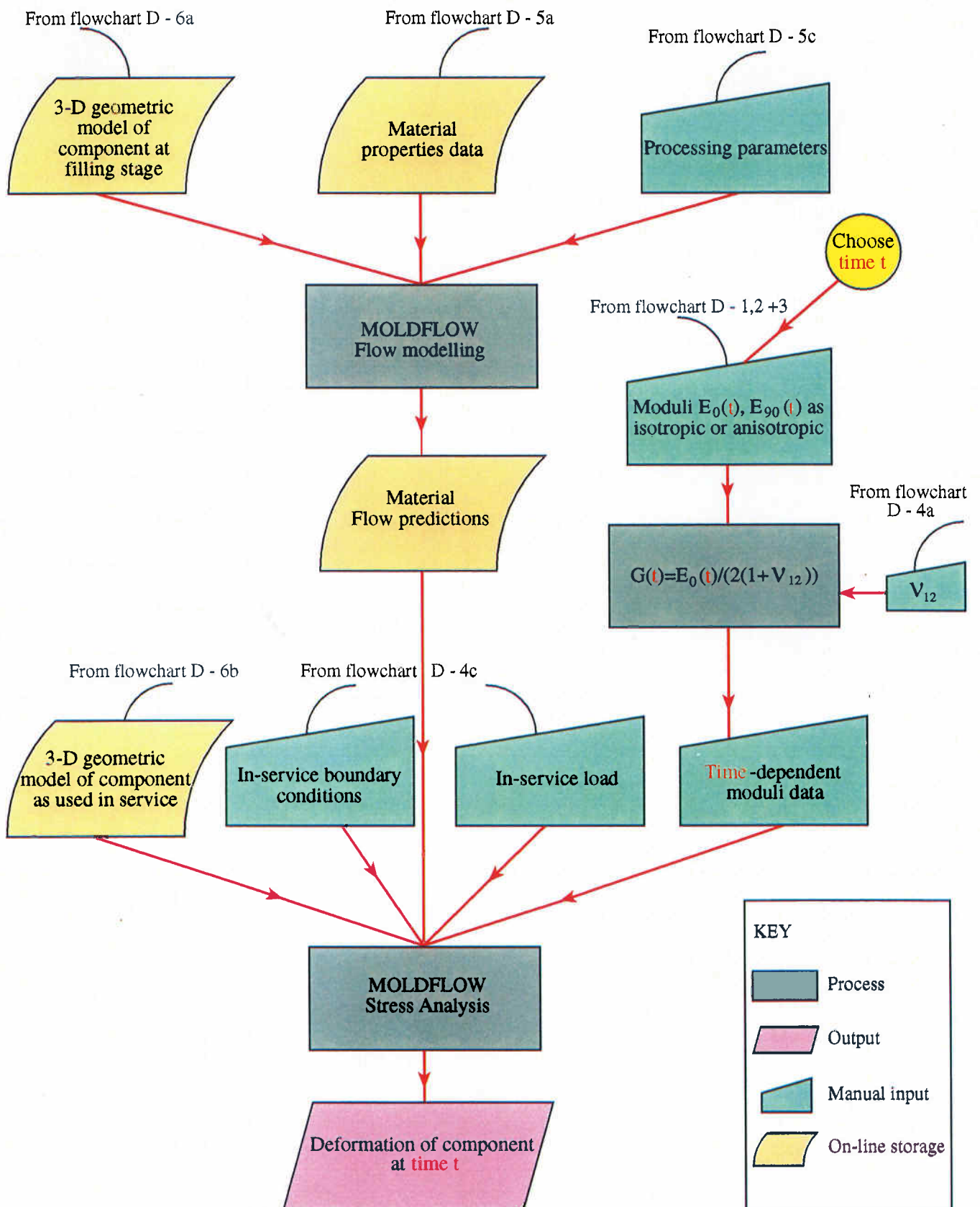
PANDA/COMPBEAM



MOLDFLOW Mode 1 (fibre filled)



MOLDFLOW Mode 2



3 PROTOCOL DETAILS

3.1 CHOICE OF SOFTWARE PACKAGE (FLOWCHART 1)

The first step is to decide which software and hardware to use for the component of interest. Flowchart 1 presents the questions that need to be answered to make this decision. The two paragraphs below give some basic information about the software packages used to date.

The PANDA software is currently available in a non-windows version running under MSDOS to purchasers of the NPL Design Guide for Plastics Panels [1] at £70. The package requires 250K on the hard disk. COMPBEAM is the equivalent package for beam analysis. A windows version of each of these packages will become available during 1996.

MOLDFLOW is available for machines operating under UNIX version 4.05 to 5.3. Minimum specification is 16 Meg RAM with 100 Mbytes swap space. Versions of MOLDFLOW suitable for use with the PC486 or Pentium are available but will be slower because these machines are not multi-tasking. The MOLDFLOW MF/FLOW package is currently priced at around £25,000 and the MF/STRESS package at around £14,000 [2].

Note that PANDA is restricted to plate-like components and COMPBEAM is restricted to beam-like components. Both these packages assume uniform properties. MOLDFLOW can cope with non-uniform properties and a much wider range of components (including beam and plate-like components).

3.2 STAGES OF DATA PREPARATION (FLOWCHART D)

Data preparation is the main part of the protocol as far as the user is concerned. It consists of six main stages, as follows:

- | | |
|---------|--|
| STAGE 1 | Acquisition of creep data from material specimens |
| STAGE 2 | Fitting of creep data to standard model |
| STAGE 3 | Generation of appropriate time-dependent creep moduli |
| STAGE 4 | Acquisition of other material data, dimensions of component and in-service loading conditions |
| STAGE 5 | For users of MOLDFLOW - acquisition of component processing conditions and static material property data (including fibre data for mode 1) |
| STAGE 6 | For users of MOLDFLOW - preparation of 3-D geometric model of the component |

Users of PANDA/COMPBEAM need only carry out Stages 1 to 4. These stages are shown in purple on the flowchart D. Detailed requirements of each of these stages are shown below.

STAGE 1 *Acquisition of creep data from material specimens*

The user will first need to decide if the component material can be regarded as isotropic or anisotropic. PANDA/COMPBEAM and MOLDFLOW mode 2 (unreinforced) can handle isotropic or anisotropic creep data. It is recommended that anisotropic creep data is acquired unless anisotropy is known to be insignificant in the component of interest.

For MOLDFLOW Mode 1 (fibre reinforced) the user must acquire isotropic creep data for the matrix polymer material. The fibre is assumed not to creep. The software calculates the fibre orientation distribution from a knowledge of the processing conditions.

Anisotropic creep moduli $E_\theta(t) = \sigma/\epsilon(t)$, should be obtained from measurements of the time-dependent tensile strain $\epsilon(t)$ on strips subjected to a constant stress σ . The strips are cut at angles $\theta = 0^\circ$ and $\theta = 90^\circ$, respectively, to the flow-direction (and at different locations) from injection-moulded square plates having uniform molecular or fibre orientation [3,4]. The creep measurements should conform to existing standards [5] and care should be taken to ensure that the storage time (age) of the specimens, the creep duration, stress level and temperature are relevant to the component service conditions. Creep data may also be obtained from materials databases or from measurements on isotropic strips if anisotropy is known to be insignificant.

STAGE 2 *Fitting of creep data to standard model*

Low stress short term creep data can be accurately modelled by the stretched-exponential function

$$E_\theta(t) = E_\theta(0) \exp\{-(t/t_0)^\gamma\}$$

where $E_\theta(t)$ is the creep modulus at angle θ (the angle to the flow direction at which the strips were machined), t_0 is a constant (the mean retardation time) and γ is the creep index. Commercial data fitting packages can be used to fit the measured values of $E_\theta(t)$ against time t to obtain values for the parameters $E_\theta(0)$, t_0 , and γ [6]. More comprehensive models are also available to cover high stress, intermittent loading [10] and temperature dependence [11].

STAGE 3 *Generation of appropriate time-dependent creep moduli*

For PANDA/COMPBEAM the component material is assumed to be anisotropic and the user must provide moduli $E_1(t)=E_0(t)$ and $E_2(t)=E_{90}(t)$ for all times of interest (t). For fibre reinforced or unreinforced materials the values of the parameters $E_\theta(0)$, t_0 and γ used to generate $E_1(t)$, $E_2(t)$ for PANDA or COMPBEAM should each be averaged from at least 3 strip positions in the test plate. However, if it can be assumed that the properties of an unreinforced material are essentially independent of position in the plate, parameters derived from just two strips cut at angles 0° and 90° respectively to the flow direction can be used. For a component of a material known to be isotropic, moduli data should be provided with $E_1(t)=E_2(t)$.

The user must also provide the shear modulus of the material $G_{12}(t)$, eg from the relation $G_{12}(t)=E_1(t)/(2(1+\nu_{12}))$, where ν_{12} is the Poissons Ratio.

For MOLDFLOW Mode 1 (fibre reinforced) the matrix of the component material is assumed to be isotropic and the user must provide isotropic modulus data $E(t)$ for the matrix polymer for all times of interest (t). This data may also be obtained by averaging values of $E_0(t)$ and $E_{90}(t)$ determined on strips from the anisotropic plates of unreinforced polymer. The shear modulus of the matrix material $G_{12}(t)$ may be provided from the relation:

$$G_{12}(t)=E(t)/(2(1+\nu_{12})).$$

For MOLDFLOW Mode 2 (unreinforced) the component material can be provided as anisotropic or isotropic and the material moduli $E_0(t)$, $E_{90}(t)$ must be provided as a function of time (t) as outlined above for PANDA or COMPBEAM. $G_{12}(t)$ is determined by the software from the relation $G_{12}(t)=E_0(t)/(2(1+\nu_{12}))$.

STAGE 4 *Acquisition of other material data, dimensions of component and in-service loading conditions*

There are three parts (a, b and c) to this stage which are described below:

STAGE 4A *Acquisition of material Poisson's ratio*

For PANDA or COMPBEAM, Poisson's ratio ν_{12} , is required for the component material.

For MOLDFLOW Mode 1 (fibre reinforced), Poisson's ratio ν_{12} , of the matrix polymer and the Poisson's ratio ν_f for the fibre are required.

For MOLDFLOW Mode 2 (unreinforced) the Poisson's ratio ν_{12} of the component material is required.

The user must either measure Poisson's ratio ν_{12} for the component material or use a reliable materials database. Measurements should conform to existing standards [8]. Poisson's ratio is assumed to remain constant with time.

STAGE 4B *Acquisition of component dimensions*

The dimensions of the component must be specified or measured in the case of an existing component. These dimensions will be required to model the component as a plate for PANDA or as a beam for COMPBEAM or to provide the basis of the 3-D geometric model for MOLDFLOW.

STAGE 4C *Acquisition of in-service loading conditions*

PANDA defines the load on the plate as acting either at a point, along a line or uniformly over the whole plate. COMPBEAM offers specific flexural loading such as 3 or 4 point bend and cantilever and a general multi-point loading condition. A stepped beam or lever arm in flexure or torsion and cantilever in torsion can also be analysed. Plate edge conditions in PANDA and beam end conditions in COMPBEAM can be defined as simply supported, clamped or free, with the proviso that PANDA cannot handle two adjacent free edges.

MOLDFLOW finite element stress analysis can handle nearly every type of loading and surface edge condition. The user should consult the MOLDFLOW User Manual MF/STRESS for full details [2].

STAGE 5 *Acquisition of component processing conditions and static material property data*

There are three parts (a, b and c) to this stage which are described below:

STAGE 5A *Acquisition of polymer property data*

For both filled and unfilled polymers MOLDFLOW requires some basic data on the polymer properties. These are required to carry out a flow analysis. The results of this flow analysis are later used in the stress analysis to calculate the component deformation or creep. This flow analysis allows anisotropy and stresses due to shrinkage to be taken into account in the creep calculation. The data that are required are:

- viscosity as a function of shear rate and temperature
- pressure/volume/temperature relationships
- conductivity
- specific heat
- melt density

These data are held on the MOLDFLOW database for many common polymer grades. The user can also enter his own data.

STAGE 5B *Acquisition of fibre data*

For fibre reinforced materials the user must provide the following fibre property data to use the MOLDFLOW approach:

- mean glass fibre length
- mean glass fibre diameter
- mean % volume glass fibres in component material
- Young's modulus of the fibre E_f
- Poisson's ratio of the fibre ν_f
- Shear modulus G_f for the fibre.

G_f is often determined from the relation $G_f = E_f / (2(1 + \nu_f))$. The other data can be provided by the supplier or obtained from the MOLDFLOW or other database. The dimensions of the glass fibres may need to be measured. Reference [3] gives an example of an appropriate measurement method using optical micrograph techniques. The fibre length and diameter should be checked from samples taken from the component since the aspect ratio can alter during the moulding process. The % volume of glass fibres can be measured using digital image analysis [9]. Thermal, physical and mechanical properties data for MOLDFLOW flow modelling are held in MOLDFLOW's materials database, or can be provided by the supplier or by a test house.

STAGE 5C *Acquisition of component processing conditions*

As explained above, the Flow Modelling stage of MOLDFLOW can be regarded as a stage of data preparation. It is used to model the flow of material into the mould and to predict the fibre orientation and material flow distribution throughout the moulded component: it produces a file of predicted property data which is used as input for the MOLDFLOW Stress analysis stage. The following processing conditions will need to be provided by the user at the FLOW Modelling Stage of MOLDFLOW [2] :-

- mould temperature
- melt temperature
- injection time
- pack pressure
- pack time
- cool time

These should be obtained from the component manufacturer or designer.

STAGE 6 *Preparation of 3-d geometric model for flow modelling*

The MOLDFLOW geometric model needs to accurately describe the geometry of the component. The model can be defined by a number of surfaces. In setting up these surfaces it is necessary to consider the stress analysis to be carried out using MOLDFLOW as loading and boundary conditions can only be applied to an individual surface [3]. There may be slight differences between the geometric model used to predict flow and that used to predict creep. For example, the gate and runner system do not need to be included in the prediction of creep of the component as they will be removed after manufacture.

3.3 PREDICTION OF CREEP OF COMPONENTS

Once all the relevant data has been acquired (flowchart D has been completed) and the appropriate software and hardware chosen (flowchart 1 has been completed) all that remains is to enter the data and run the program. To do this one of three flow charts should be followed depending on choices made earlier. The options are:

- PANDA/COMPBEAM for simple beam or plate-like components *flowchart PC*
- MOLDFLOW mode 1 for any fibre reinforced component *flowchart M1*
- MOLDFLOW mode 2 for any unreinforced component. *flowchart M2*

This section shows how the programmes use the data to predict creep of components.

3.3.1 Simple plate or beam-like components

For plate or beam-like components the user is referred to Flowchart PC. The data as specified in the previous section is entered into PANDA (for plate-like components) or COMPBEAM (for beam-like components). The programme is then run to give predicted deflections at any time of interest, under the service conditions of the component.

3.3.2 Complex fibre reinforced components

For fibre reinforced components that cannot be approximated to a simple plate or beam a finite element package such as MOLDFLOW should be used. Flowchart M1 shows the details of the modelling. Input data requirements are specified in the previous section and summarised in flowchart D. MOLDFLOW first models the filling and packing stages to obtain fibre orientation distributions throughout the component. The STRESS module of MOLDFLOW is then used to predict the deformation of the component under the load applied in service, after any period of time (t) of interest.

3.3.3 Complex un-reinforced components

For unreinforced components that cannot be approximated to a simple plate or beam a finite element package such as MOLDFLOW should be used. Flowchart M2 shows the details of the modelling. Input data requirements are specified in the previous section (see also flow chart D). As with fibre reinforced components, MOLDFLOW predicts the filling and packing stages, however in this case it is the anisotropic *polymer* orientations that are carried over into the stress analysis. Data on the anisotropic creep properties are then used to predict the deformation of the component under the loading conditions in service, after any period of time (t) of interest.

4 EXAMPLES OF USE OF THE PROTOCOL

In order to provide examples of the use of the protocol four materials were injection moulded to produce square plates 150 x 150 x 2.7 mm, see Figure 1. This square plate was selected because it provides a high degree of anisotropy and can be modelled by both PANDA and MOLDFLOW. The materials were selected to cover both unreinforced and fibre reinforced materials, see Table 1 below. The processing conditions (Table 2 below) were selected to cover the normal processing range for these materials.

Material	v_{12}	Glass fibre length (mm)	Glass fibre diameter (mm)	% volume glass fibres
PBT/Glass	0.44	0.334	.0090	10.8
PP/Glass	0.46	0.4880	.0125	13.2
PBT	0.45			
PP	0.47			
Glass	0.2			

Table 1 Material structural data used in MOLDFLOW and PANDA(v_{12} only)

Specimen	FILLING			PACKING		
	Mould temperature (°C)	Melt temperature (°C)	Injection time(s)	Pack pressure (MPa)	Pack time(s)	Cool time(s)
PBT/Glass	58	270	4.36	59	6	30
PP/Glass	60	250	1.01	55	15	30
PBT	58	270	4.03	38	12	30
PP	60	250	3.9	44	25	25

Table 2 Processing data used in MOLDFLOW for the Flow Modelling of filled and unfilled plates

The plates were simply supported and flexed by line loading as shown in Figure 2, and the centre-point deformation measured as a function of time. Full details of the experimental procedures and materials can be found in [4].

The protocol was then followed to predict the deformations using PANDA and MOLDFLOW in both modes (reinforced and unreinforced). The results of this exercise are shown in Figures 3 to 6 and summarised in Table 3 below.

Plate	Moldflow at 10 sec	Panda at 10 sec	Moldflow at 10 ³ sec	Panda at 10 ³ sec	Maximum ² deflection
PP/glass 0°	+32% ¹	+26%	+28%	+23%	
PP/glass 90°	-5%	+12%	-20%	-4%	80%
PBT/glass 0°	+23%	+20%	+24%	+24%	
PBT/glass 90°	-2%	+8%	+4%	+30%	17%
PP 0°	-17%	-16%	-4%	-1%	75%
PP 90°	-13%	-10%	+11%	+2%	
PBT 0°	+12%	+7%	+15%	+10%	24%
PBT 90°	+4%	+3%	+17%	+15%	
Mean	13½%	11½%	15%	13½%	50%

Notes:

1. +32% means Moldflow is predicting a 32% higher deflection (lower modulus) than experiment.
2. The maximum deflection observed during creep, expressed as a % of the initial deflection.
3. These results are taken from the report CMMT(A4).

Table 3 Comparison of MOLDFLOW and PANDA predictions with experiment

The results were discussed at an industrial advisory group meeting held at the NPL on January 18th 1996 and the following conclusions were drawn:

- Using the protocol is about 4 times better than ignoring creep altogether.
- The two models (PANDA and MOLDFLOW) agree well (to about 5%).
- Most of the discrepancy (of the order of 10 to 15% on average) between predictions and experiment is not due to failure to predict creep but rather to discrepancies in *initial* deformation values between the models and experimental measurements.

5 UNCERTAINTIES

This section gives a brief formal analysis of the theoretical uncertainties involved with the protocol.

Taking into account all known sources of error the uncertainty in measuring the time dependent moduli $E_0(t)$ of strips has been estimated to be less than 2%.

A 2% increase in moduli $E_0(t)$ produces about 2% decrease in predicted deflection.

A 5% increase in Poisson's ratio produces a less than 2% decrease in predicted deflection.

For fibre reinforced materials the programs rely on the Tandon-Weng [12] model to relate bulk material modulus to fibre and matrix moduli. Use of this model allows the implications of uncertainties in the properties of the fibres on the mechanical properties of the composite to be calculated. An example of the effect of a 10% variation in fibre length (c) and volume fraction (v_f) on modulus, as predicted by Tandon-Weng, is shown in the table below.

**The Effect of Variations in Fibre Properties on Moduli
of Glass Fibre Reinforced Polypropylene**

	E1 (GPa)	E2 (GPa)	G ₁₂ (GPa)	v ₁₂
V_f = 0.20 c = .132	6.854	2.037	.6349	.4101 base case
V _f = 0.20 c = .1188	6.278	1.984	.6182	.4122
V _f = 0.20 c = .1452	7.438	2.091	.6515	.4080
V _f = 0.18 c = .132	6.477	2.031	.6349	.4114
V _f = 0.22 c = .132	7.191	2.043	.6344	.4089

$E_f = 72$ GPa, $V_f = 0.2$, $v_{m12} = 0.43$, $E_m = 1.4$ GPa

It would be unreasonable to expect an uncertainty in the fibre length of less than 10% because of degradation during processing and the difficulty of measuring fibre lengths in components. Thus the resulting uncertainty in E1 (modulus parallel to the fibre) can be quite large. Uncertainties in moduli resulting from uncertainties in volume fraction are expected to be much less as volume fraction is much easier to control and measure.

6 DEFINITIONS

List of symbols used in this protocol are defined below:

$E_{\theta}(t)$	anisotropic creep moduli at time (t)
$\epsilon(t)$	time dependent tensile strain
σ	tensile stress
θ	angle at which strips are cut from plates relative to principal flow direction
t_o	mean retardation time
γ	creep index
ν_{12}	Poisson's ratio of component material
$G_{12}(t)$	shear modulus for component material at time (t)
$E1(t)$	Young's modulus for the material of an anisotropic plate or beam along the principal flow direction at time (t). PANDA/COMPBEAM [1].
$E2(t)$	Young's modulus for the material of an anisotropic plate or beam normal to the principal flow direction at time (t). PANDA/COMPBEAM [1].
ν_f	Poisson's ratio of fibre
G_f	shear modulus of fibre
E_f	Young's modulus of fibre
E_m	Young's modulus of matrix (assumed isotropic)
V_f	fibre volume fraction
c	fibre length

7 REFERENCES

1. Johnson A.F. and Sims G.D., Design Procedures for Plastics Panels, NPL Publication, Teddington 1987.
2. MOLDFLOW User Manuals MF/FLOW MF/STRESS Release 3. Moldflow (Europe) Ltd, Orpington, Kent, BR6 0JA. September 1994.
3. Rides, M., Chakravorty, S., McDermott, J.R. and Read, B.E., Characterisation and modelling of injection moulded plates. Part 2, Modelling and comparison of measurements. NPL Report DMM(C)29, November 1994.
4. Woolf, A. and Read, B.E., Prediction of creep behaviour of plastic components. NPL Report DMM(C)48, September 1994.
5. ISO 899-1 Plastics - Determination of creep behaviour- Part 1: Tensile creep.
6. Read, B.E., Generation of tensile creep data on thermoplastic specimens cut from injection-moulded anisotropic plates. NPL Report DMM(C)32, November 1994.
7. Pearce, A. and Sims, G.D. Short term flexural creep data of oriented, injection-moulded thermoplastic plates, Part 1: edge gated, unfilled and glass-fibre reinforced polypropylene and poly(butylene terephthalate), NPL Report DMM(C)30, November 1994.
8. ISO 527-1:1993 Plastics - Determination of Tensile Properties.
9. Chakravorty, S., Rides, M. and Brown, C.S., Characterisation and modelling of injection moulded plates. Part 1: Characterisation, NPL Report DMM(C)28, November 1994.
10. Tomlins, P.E., Creep Measurement of Plastics, NPL Best Practice in Materials Measurement 002, 1996.
11. Tomlins, P.E., Read B.E. and Dean G.D., The effect of temperature on creep and physical ageing of poly(vinyl chloride), POLYMER, Vol 35., No. 20, 1994.
12. Tandon, G.P. and Weng, G.T., Polymer Composites, 327-333, 1984.

8 ACKNOWLEDGEMENT

The development of this Protocol formed part of a research programme carried out as part of the "Materials Measurement Programme", a programme of underpinning research financed by the United Kingdom Department of Trade and Industry. The authors also acknowledge valuable discussions with B E Read, D H Ferriss and A Pearce of NPL.

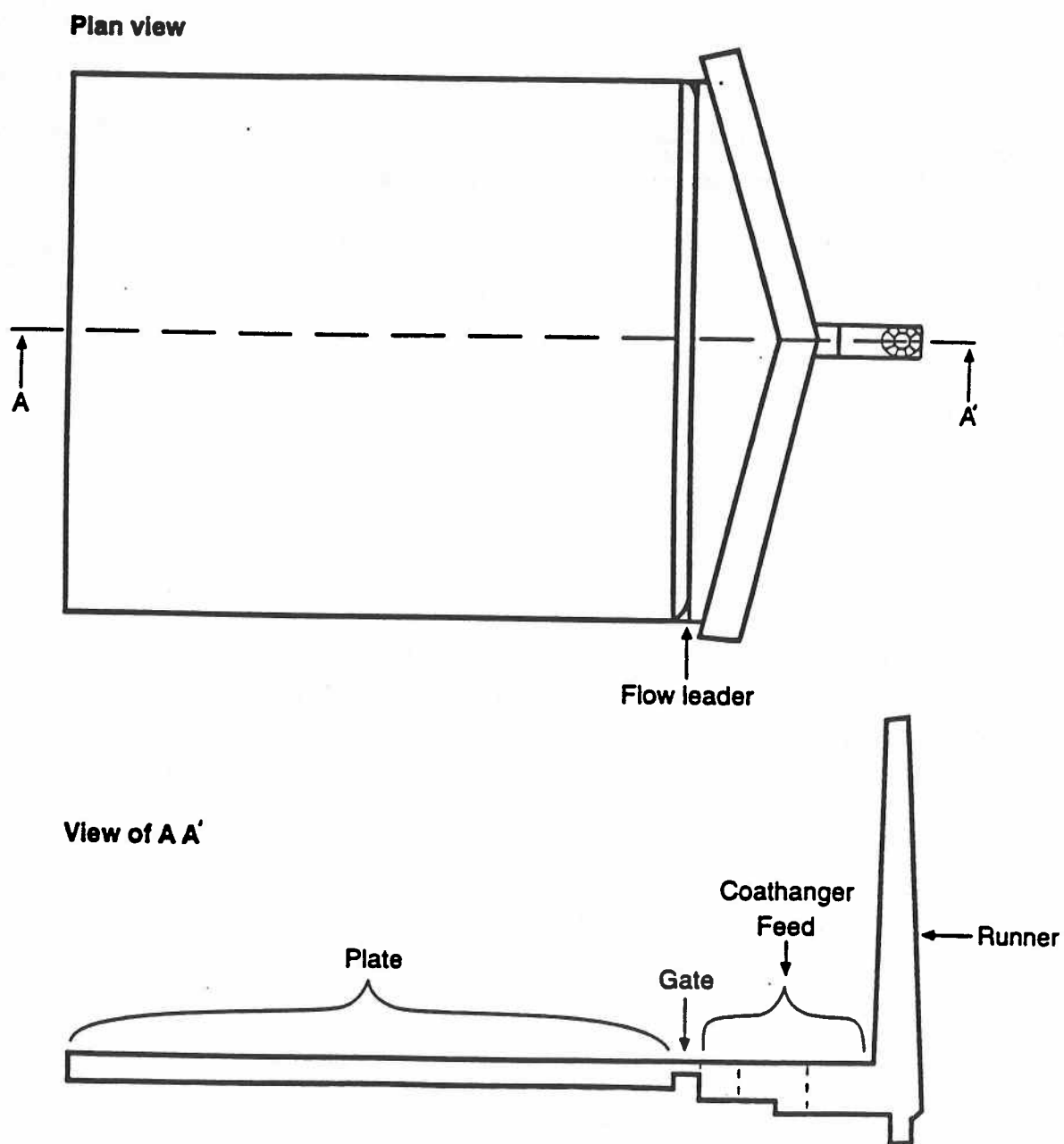


Figure 1 Plate geometry plan and cross-sectional view.

Figure 2a Two distributed line loading conditions used in PANDA and MOLDFLOW

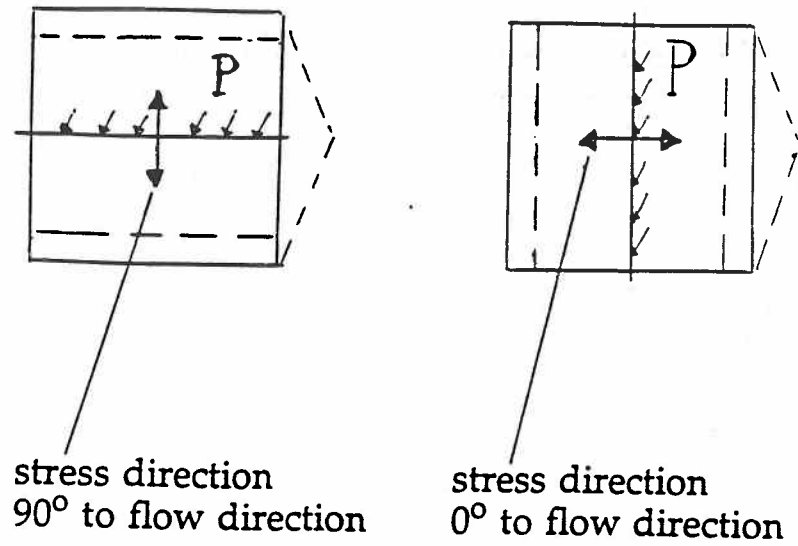
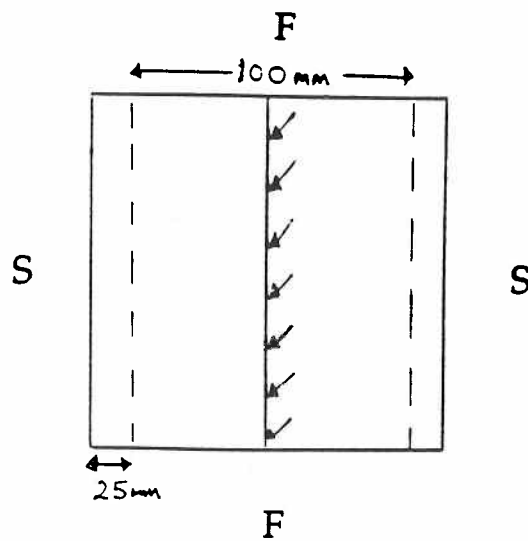


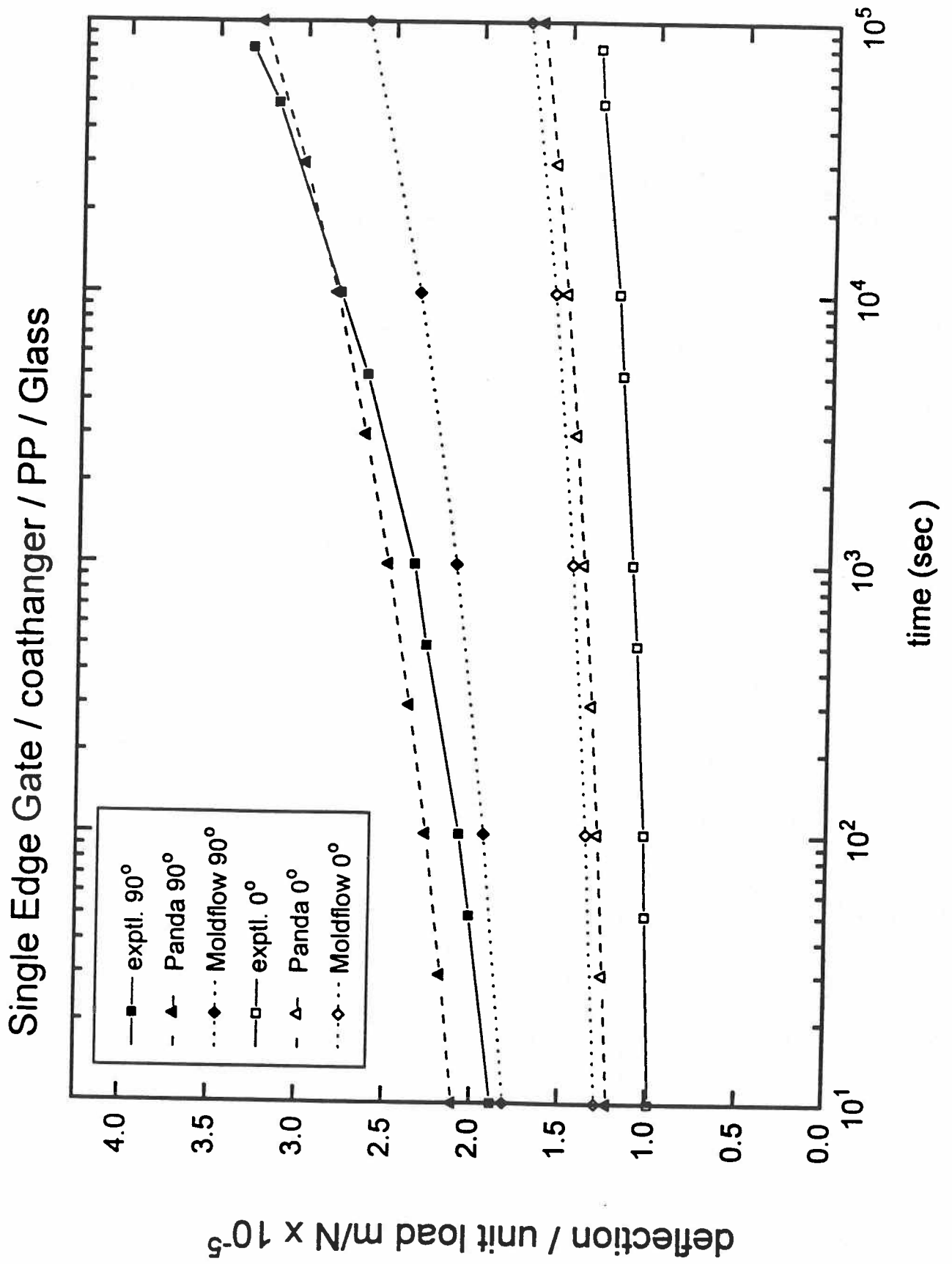
Figure 2b Plate boundary conditions used in PANDA and MOLDFLOW



S denotes edge simply supported

F denotes edge free

Figure 3



Single Edge Gate / coathanger / PBT / Glass

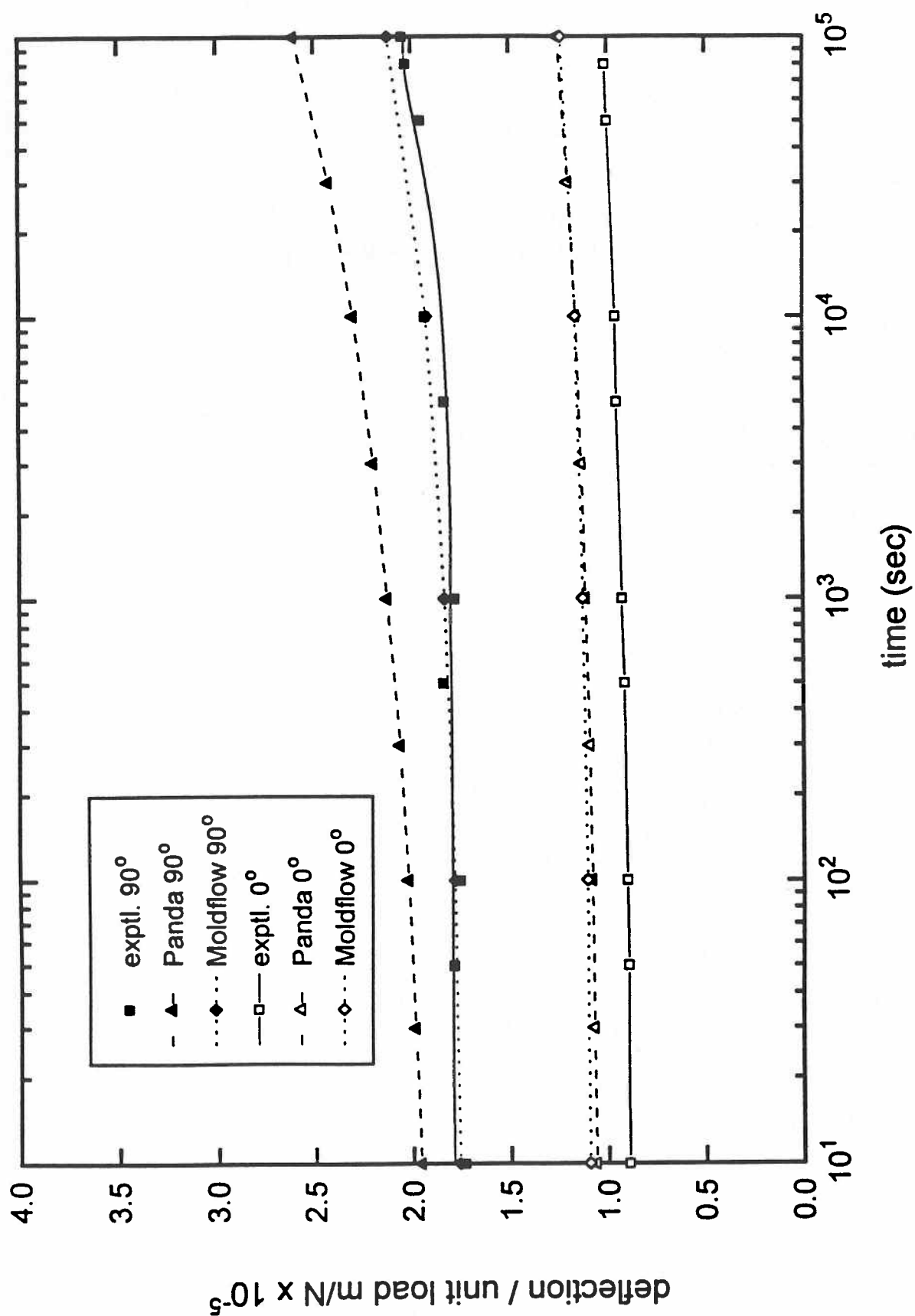


Figure 4

Single Edge Gate / coathanger / PP / unfilled

Figure 5

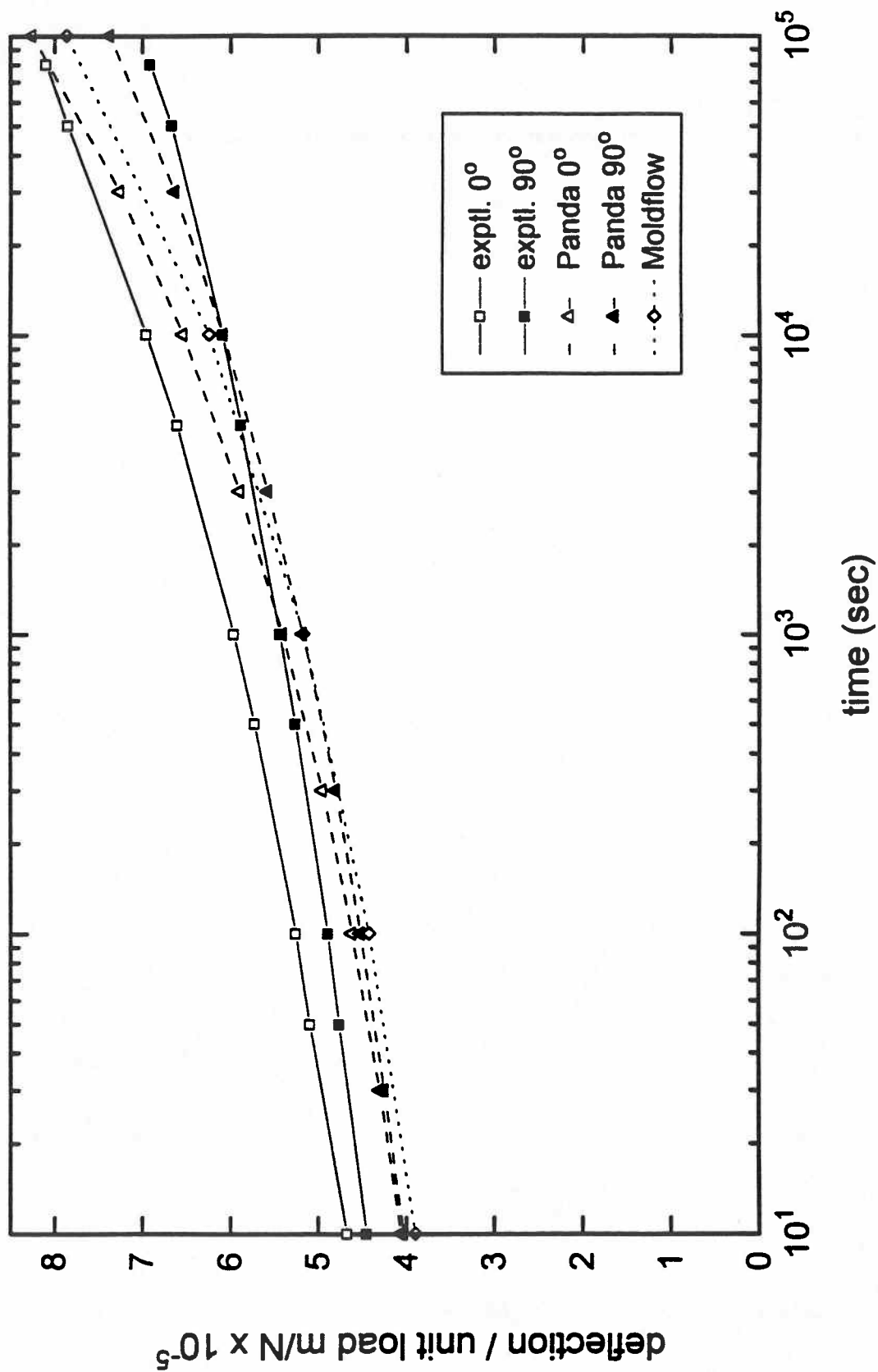


Figure 6

Single Edge Gate / coathanger / PBT unfilled

