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Plastics — Guide to the acquisition and presentation of design data

*Plastiques — Lignes directrices pour l'acquisition et la présentation de
caractéristiques de conception*



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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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Introduction

Plastics and composites are increasingly being used in load-bearing applications where they compete with traditional materials such as steels and aluminium. In these applications, it is important to achieve a confident knowledge of the safe operating limits of the component through competent design. Computer methods for design are available, and are continually being improved, that enable predictions to be made of the performance of plastics under a variety of situations. These situations include mechanical performance under service loads and environments as well as a flow of the polymer melt during the manufacture of a component.

In order to design effectively with plastics in load-bearing applications, comprehensive data are generally needed which take into account the effects of time, temperature, rate and environment on properties. A number of International Standards have been developed that specify how certain data for plastics should be measured and presented. These are ISO 10350-1 and ISO 10350-2, and ISO 11403-1, ISO 11403-2 and ISO 11403-3.

The purpose of these standards is to enable comparable data to be measured on different materials from different sources to aid the process of materials selection. A substantial quantity of data is specified by these standards and, although not the primary purpose of the standards, some of these data are suitable for design. However, additional or alternative data will also be needed for many applications.

The purpose of this guide is to augment existing data presentation standards by identifying data that are needed specifically for design with plastics. The selection of these data is guided by the requirements of available computer methods for design. Preferred test methods, test specimens and test conditions are recommended in section 5 for determining these data. For some properties, ISO test methods or specimens are not yet available. Reference is then made in the Notes to Tables 6 and 7 to suitable procedures for data acquisition that may become standardised at a later stage.

It is intended that this guide assist the development of databases that will interface with computer methods for design so that the property data required by these methods can be readily accessed. For certain properties, some analysis and interpretation of data is needed in order to present information in the form required by the design analysis. Some procedures for data analysis are described in the annexes.

Plastics — Guide to the acquisition and presentation of design data

1 Scope

This International Standard gives guidelines for the acquisition and presentation of data that can be used for design with plastics. Emphasis is given to the acquisition of data needed by computerised methods for design. It includes data needed for the analysis of the flow of polymer melts during the manufacture of a component as well as data needed for the prediction of mechanical performance of the component in service. The data requirements cover design with unfilled plastics as well as filled, short-fibre reinforced and continuous-fibre reinforced materials.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 294-3, *Plastics — Injection moulding of test specimens of thermoplastics materials — Part 3: Small plates*

ISO 294-5, *Plastics — Injection moulding of test specimens of thermoplastics materials — Part 5: Preparation of standard specimens for investigating anisotropy*

ISO 527-2, *Plastics — Determination of tensile properties — Part 2: Test conditions for moulding and extrusion plastics*

ISO 527-4, *Plastics — Determination of tensile properties — Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites*

ISO 527-5, *Plastics — Determination of tensile properties — Part 5: Test conditions for unidirectional fibre-reinforced plastic composites*

ISO 899-1, *Plastics — Determination of creep behaviour — Part 1: Tensile creep*

ISO 1183, *Plastics — Methods for determining the density and relative density of non-cellular plastics*

ISO 2577, *Plastics — Thermosetting moulding materials — Determination of shrinkage*

ISO 3167, *Plastics — Multipurpose test specimens*

ISO 6252, *Plastics — Determination of environmental stress cracking (ESC) — Constant-tensile-stress method*

ISO 6603-2, *Plastics — Determination of puncture impact behaviour of rigid plastics — Part 2: Instrumented impact test*

ISO 6721-2, *Plastics — Determination of dynamic mechanical properties — Part 2: Torsion-pendulum method*

ISO 6721-3, *Plastics — Determination of dynamic mechanical properties — Part 3: Flexural vibration — Resonance-curve method*

ISO 6721-4, *Plastics — Determination of dynamic mechanical properties — Part 4: Tensile vibration — Non-resonance method*

ISO 6721-5, *Plastics — Determination of dynamic mechanical properties — Part 5: Flexural vibration — Non-resonance method*

ISO 6721-7, *Plastics — Determination of dynamic mechanical properties — Part 7: Torsional vibration — Non-resonance method*

ISO 6721-8, *Plastics — Determination of dynamic mechanical properties — Part 8: Longitudinal and shear vibration — Wave propagation method*

ISO 6721-10, *Plastics — Determination of dynamic mechanical properties — Part 10: Complex shear viscosity using a parallel-plate oscillatory rheometer*

ISO 10350-1, *Plastics — Acquisition and presentation of comparable single-point data — Part 1: Moulding materials*

ISO 11357-2, *Plastics — Differential scanning calorimetry (DSC) — Part 2: Determination of glass transition temperature*

ISO 11357-3, *Plastics — Differential scanning calorimetry (DSC) — Part 3: Determination of temperature and enthalpy of melting and crystallization*

ISO 11357-4¹⁾, *Plastics — Differential scanning calorimetry (DSC) — Part 4: Determination of specific heat capacity*

ISO 11357-5, *Plastics — Differential scanning calorimetry (DSC) — Part 5: Determination of characteristic reaction-curve temperatures and times, enthalpy of reaction and degrees of conversion*

ISO 11357-7, *Plastics — Differential scanning calorimetry (DSC) — Part 7: Determination of crystallization kinetics*

ISO 11359-2, *Plastics — Thermomechanical analysis (TMA) — Part 2: Determination of coefficient of linear thermal expansion and glass transition temperature*

ISO 11403-1, *Plastics — Acquisition and presentation of comparable multipoint data — Part 1: Mechanical properties*

ISO 11403-2, *Plastics — Acquisition and presentation of comparable multipoint data — Part 2: Thermal and processing properties*

ISO 11443, *Plastics — Determination of the fluidity of plastics using capillary and slit-die rheometers*

ISO 15310, *Fibre-reinforced plastic composites — Determination of the in-plane shear modulus by the plate twist method*

ISO 17744, *Plastics — Determination of specific volume as a function of temperature and pressure (pVT diagram) — Piston apparatus method*

1) To be published.

3 Symbols

3.1 Test variables

ε tensile strain

NOTE Use of the true strain $\log_e (1 + \varepsilon)$ in place of the engineering strain is necessary when engineering strain values exceed about 0,1. Below a strain of 0,1, there is no significant difference between these quantities.

$\dot{\varepsilon}$ tensile strain rate

ε^p plastic component of the tensile strain

NOTE This is used in elastic–plastic models for describing non-linear behaviour.

γ shear strain

$\dot{\gamma}$ shear strain rate

γ^p plastic component of the shear strain

t time

σ stress

T temperature

f frequency

ch chemical environment

N number of cycles to failure in a fatigue test

R ratio of minimum to maximum stresses in a fatigue test

$\dot{T}$ rate of change of temperature

p pressure

p_{CH} cavity pressure at hold

t_H hold time

h specimen thickness

v_s slip velocity

3.2 Material properties for stress analysis (see Tables 2 and 3)

E tensile modulus obtained from a test at constant strain rate

E_p, E_n tensile moduli along and transverse to, respectively, the direction of preferred fibre or molecular orientation in a transversely isotropic material

G_p shear modulus of a transversely isotropic material for stress application in the direction of preferred orientation

D tensile creep compliance

E_R	tensile stress relaxation modulus
D_p, D_n	tensile creep compliances along and transverse to, respectively, the direction of preferred orientation in a transversely isotropic material
E', E''	tensile storage and loss moduli, respectively
G', G''	shear storage and loss moduli, respectively
σ_T	true tensile yield stress (see Note 4 to Table 12)
λ	hydrostatic stress sensitivity parameter (see Note 6 to Table 12)
σ_{Tp}, σ_{Tn}	tensile yield stresses for loading along and transverse to, respectively, the direction of preferred orientation in a transversely isotropic material (see Notes 4 and 9 to Table 12)
σ_{Sp}, σ_{Sn}	shear yield stresses for loading along and transverse to, respectively, the direction of preferred orientation in a transversely isotropic material (see Note 9 to Table 12)
ν	Poisson's ratio
ν^e	elastic component of the Poisson's ratio
ν^p	plastic component of the Poisson's ratio equal to minus the ratio of the plastic component of the lateral strain to the plastic component of the axial strain in a specimen under a tensile stress (see Note 5 to Table 12)
ν_{pn}	Poisson's ratio for an anisotropic material determined with the uniaxial stress applied along the direction of preferred orientation
ψ	flow parameter
α	coefficient of linear thermal expansion
α_p, α_n	coefficients of linear thermal expansion parallel and normal to the direction of preferred orientation in a transversely isotropic material
c_p	specific heat

3.3 Failure properties (see Table 4)

σ_u	tensile strength obtained from a test at constant specimen deformation rate
σ_{up}, σ_{un}	tensile strengths for loading along and transverse to, respectively, the direction of preferred orientation in a transversely isotropic material
ε_u	strain at break obtained from a tensile test at constant specimen deformation rate
$\varepsilon_{up}, \varepsilon_{un}$	strains at break for loading along and transverse to, respectively, the direction of preferred orientation in a transversely isotropic material
σ_c	tensile creep rupture strength
σ_{cp}, σ_{cn}	creep rupture strengths for loading along and transverse to, respectively, the direction of preferred orientation in a transversely isotropic material
σ_f	tensile fatigue strength

σ_{fp} , σ_{fn} tensile fatigue strengths for loading along and transverse to, respectively, the direction of preferred orientation in a transversely isotropic material

3.4 Material properties for processing simulation (see Tables 3, 4 and 5)

η	melt viscosity
η_{eu}	uniaxial extensional viscosity
η_{eb}	biaxial extensional viscosity
$\eta_{reactive}$	viscosity of the reactive system
N_1	first normal stress difference
ρ_B	bulk density
ρ_m	melt density
ρ_s	density of the solid
$\rho_{reacted}$	density of reacted system
k	thermal conductivity
k_m	thermal conductivity of the polymer melt
c_p	specific heat
c_{pm}	specific heat of the polymer melt
T_s	solidification temperature, a reference temperature defined by the mould filling simulation software
T_{ej}	ejection temperature, a reference temperature defined by the mould filling simulation software
v	specific volume
ΔH_r	heat of reaction
t_{ind}	isothermal induction time
α_{gel}	gelation conversion
$\dot{R}$	reaction rate
μ_b , μ_s	dynamic coefficients of friction between plastic and metal used for the barrel or screw respectively
T_m	melting temperature
T_g	glass transition temperature
T_c	crystallisation temperature
ΔH_f	enthalpy of melting
ΔH_c	enthalpy of crystallization
X	degree of crystallinity

$\dot{X}$	rate of crystallization
S_{Mp}	moulding shrinkage parallel to the direction of preferred orientation
S_{Mn}	moulding shrinkage normal to the direction of preferred orientation
ν_{pn}	Poisson's ratio for a transversely isotropic material determined with the uniaxial stress applied along the direction of preferred orientation
ν_{np}	Poisson's ratio for a transversely isotropic material determined with the applied stress along a direction normal to the direction of preferred orientation and the lateral strain measured in the preferred orientation direction
G_p	shear modulus of a transversely isotropic material for stress application in the direction of preferred orientation
α_p	coefficient of linear thermal expansion parallel to the direction of preferred orientation in an anisotropic material
α_n	coefficient of linear thermal expansion normal to the direction of preferred orientation in an anisotropic material

4 Data needed for design

4.1 General

The design data identified here are grouped under two headings:

- Data for analysis of thermomechanical performance (section 4.2)
- Data for processing analysis (section 4.3)

4.2 Design for thermomechanical performance

4.2.1 The design process

The process of design for the mechanical performance of a component involves two operations. The first is an analysis of the stress and strain distributions in the component under service load. The second is a comparison of the maximum levels of stress, strain or displacement predicted by the analysis with maximum allowable values based on failure criteria for the material or operating conditions of the component. These operations are then repeated in order to select component dimensions and geometry whilst ensuring that safe limits are not exceeded. The data requirements for these two operations are different.

The data requirements for stress analysis are determined by the constitutive law that relates stress and strain under the appropriate service loading conditions. Choice of a valid constitutive relationship will depend upon the following factors.

- Mechanical behaviour, whether the material is isotropic or anisotropic or shows glassy or rubber-like behaviour.
- The level of induced strain. If this is small, then linear viscoelastic or linear elastic behaviour may be considered but, at higher strains, relationships between stress and strain will be non-linear.
- The history of the applied load or displacement and the temperature. Since plastics are viscoelastic, properties depend on time, frequency and strain rate and so their response to short-term loads such as impact will be very different from that under sustained load.

A finite element analysis (FEA) is a versatile method for calculating stress, strain and temperature distributions in a component of complex geometry. For this reason, the data requirements identified here for performing a stress analysis have been guided by available materials models that are suitable for plastics. An accurate calculation relies on the use of a materials model for the analysis which employs a realistic constitutive relationship.

The satisfactory operating limits of a component may be specific to the component or the plastics material from which it is made. Safe operating limits for the material are generally expressed in terms of ultimate values of stress or strain and will depend on many factors such as the temperature, the humidity, processing conditions, the presence of an aggressive environment and the history of the applied load. Where failure is caused by crack growth, additional property data may be needed.

4.2.2 Design data for thermomechanical performance

Data required for design for thermomechanical performance consist of data for carrying out a stress analysis and data for estimating material failure. In principle, these data requirements depend on the detailed materials characteristics exhibited by the material, and on the service conditions relevant to the application. However, in practice, the designer may adopt various simplifications by approximating materials behaviour or service conditions in order to make the design analysis technically tractable and financially viable. This influences data requirements and the practical use of data.

From the designer's point of view, the simplest form of materials behaviour is that of an isotropic, linear, temperature-insensitive, elastic material. However, as stated in section 4.2.1, plastics may exhibit aspects of anisotropy, nonlinearly, temperature-dependence, viscoelasticity or plasticity. Where a particular aspect is relevant to a design problem, the designer may decide to avoid a more complex analysis by assuming a simpler form of behaviour and compensate for this by use of "effective" material properties. Examples include use of a secant or tangent modulus to represent nonlinearity in a linear analysis, use of a long-time creep modulus to represent viscoelasticity in an elastic analysis, and use of "average" or "representative" property values to replace anisotropy and temperature-sensitivity. However, although a simpler (approximate) form of representation may be used, data for the more complex form of behaviour will generally be required in order to select appropriate "effective" properties.

Definition of the design problem involves specification of component geometry (shape, size, etc.) and service conditions (e.g. loads and other constraints). Although FEA packages can handle complex circumstances, the designer may idealise component geometry and may approximate service conditions in order to simplify the design calculations (e.g. by creating a "statically determinate" situation for which stresses and strains can be calculated separately, only the latter calculation requiring material properties). Similarly, the designer may use an approximate design calculation (e.g. assuming "pseudo-elasticity"). These idealisations and assumptions introduce inaccuracies into the design predictions which are not attributable to the quality of the design data, although appropriate data selection is required.

A crucial aspect of design analysis is the selection of suitable materials models. This selection determines consequent requirements for materials design data, and depends, in particular, on the nature of the service loads, for example:

- sustained loading, involving effects such as creep or stress relaxation, for which time under load is the important parameter;
- cyclic loading, for example in damped vibrations, for which frequency is the important parameter;
- high-rate loading, for example due to impact, for which strain rate is the important parameter.

Table 1 — Typical service conditions, materials behaviour and model types

Service conditions	Crucial parameter	Relevant types of materials behaviour	Model type(s) (see below)
Simpler conditions	—	Elastic	A, B
		Elastic–plastic	C
Sustained loading	Time	Viscoelastic or viscoplastic	C1, D1, E1
Cyclic loading	Frequency		C2, D2, E2
High-rate loading	Strain rate		C3, D3, E3
Model type:			
a) Linear elasticity is the simplest and most commonly used materials model, at least for a first analysis. b) A hypoelastic model enables approximate solutions to be obtained under strain levels where behaviour is non-linear. Hyperelastic models are available for elastomeric materials and are not considered in this International Standard. c) Elastic–plastic models for metals are available in most FEA packages and are able to handle non-linear and three-dimensional stress conditions. Those based on von Mises yielding may have restricted suitability for plastics, and a more general form of the yield criterion with sensitivity to hydrostatic stress (the linear Drucker–Prager model) is considered here. Some versions of elastic–plastic models combine the effects of elasticity, plasticity and also time, frequency or rate. These latter types of model (C1, C2 and C3) are indicated in this table, but only C3 is considered in this International Standard. d) Linear viscoelasticity is limited to small-strain behaviour, but data can be used in the three different forms (D1, D2, D3) depending on whether time, frequency or rate is the crucial service parameter. e) Non-linear viscoelasticity models for general service conditions are not available in a useable form, but models exist for use under special conditions. These include a creep form (E1) based on isochronous curves, a finite-linear form (E2) for large amplitude vibrations and a rate-dependent form (E3): the last two are not discussed further in this International Standard.			

As already noted, the stress analysis will also need to consider isotropic or anisotropic properties, linear or non-linear behaviour and the effects of temperature. It is therefore evident that there are many sets of conditions under which materials properties may be needed in principle, and it is necessary to focus on the most important cases. This is discussed now with reference to the model types indicated in Table 1.

Further consideration of these types leads to identification of the data required for design for thermomechanical performance. These data are summarised in Table 2 for isotropic materials. Anisotropic materials require additional data that describe the variation of properties with direction in the material. The simplest situation arises with the loading of parts in the form of a plate or panel where stresses are confined to a plane and stresses through the thickness direction are neglected. This is assumed in Table 3. Criteria for determining when material rupture will take place under multiaxial stress states and arbitrary loading histories have not been established for plastics. Ultimate values obtained from tensile tests under specific loading histories are indicated in Table 4. The symbols used in these tables are explained in Section 3.

When material behaviour is actually isotropic linear elastic, the data shown in Table 2 for model A are all that is required. When the behaviour is more complex, but an isotropic linear elastic analysis is performed, *data relevant to the other models may be needed in order to select appropriate "effective" properties*. For example, data for models D and E give effective properties to represent viscoelastic effects, data for models C and E can be used to select effective properties to handle nonlinearly, and data from Table 3 can be used to select effective properties to take account of the effects of anisotropy. When the design analysis takes these factors into account in full, then data for models C, D and E, and from Table 3, are required in their own right (but see Note to Table 3).

Table 2 — Data required for stress analysis (isotropic material)

Behaviour	Model type	Properties	Variable(s)
Linear elastic	A	E, ν	T
Non-linear elastic	B	$E, \nu,$ σ	T ε, T
Non-linear (elastic-plastic)	C	E, ν^e σ_T λ, ν^p, ψ	T ε^p, T ε^p, T
Linear viscoelastic	D1 D2 D3	D, E_R, ν E', E'' (or G', G''), ν ρ E, ν	t, T f, T T $\dot{\varepsilon}, T$
Non-linear viscoelastic	E1	D, ν E_R, ν	t, σ, T t, ε, T
Rate-dependent, elastic-plastic	C3	E, ν^e σ_T λ, ν^p, ψ	$\dot{\varepsilon}, T$ $\varepsilon^p, \dot{\varepsilon}^p, T$ $\varepsilon^p, \dot{\varepsilon}^p, T$

Table 3 — Data required for stress analysis (anisotropic material)

Behaviour	Model Type	Properties	Variables
Linear elastic	A	E_p, E_n, ν_{pn}, G_p	T
Non-linear (Elastic-plastic)	C	E_p, E_n, ν_{pn}, G_p $\varepsilon_{Tp}, \sigma_{Tn}$ σ_{Sp}, σ_{Sn}	T ε^p, T ε^p, T
Linear Viscoelastic	D1	D_p, D_n	t, T
Non-linear Viscoelastic	E1	D_p, D_n	t, σ, T
Rate-dependent, Elastic-plastic	C3	E_p, E_n, ν_{pn}, G_p σ_{Tp}, σ_{Tn} σ_{Sp}, σ_{Sn}	$\dot{\varepsilon}, T$ $\varepsilon^p, \dot{\varepsilon}^p, T$ $\varepsilon^p, \dot{\gamma}^p, T$
NOTE The above models and data requirements for anisotropic materials are clearly more complicated than those for isotropic materials and, except for the linear elastic case, are likely to be used very rarely except for the purpose of selecting effective properties.			

Under certain circumstances, property data will be required additional to those identified in Tables 2 and 3. If the analysis involves changes in temperature during loading, then the thermal expansion coefficient α (α_p and α_n for anisotropic materials) will be needed. If the loading generates high accelerations such that inertial forces are significant, then the density ρ of the material must be known. In situations where it is necessary to predict the effects of internal heating of the plastic material arising from large strain and high strain-rate loading, then data on the specific heat c_p will also be needed.

Furthermore, materials whose properties are sensitive to the concentration of absorbed water will need to have data supplied for material that has been conditioned at the relevant humidity for the application.

Table 4 — Ultimate values for stress and strain obtained from tensile tests with different loading histories

Service Conditions	Model type	Properties		Variables
		Isotropic	Anisotropic	
Simple conditions Constant elongation rate	A, B, C	σ_u, ε_u	$\sigma_{up}, \varepsilon_{up}, \sigma_{un}, \varepsilon_{un}$	T
Sustained loading	D1, E1	σ_c	σ_{cp}, σ_{cn}	t, ch, T
Cyclic loading	D2	σ_f	σ_{fp}, σ_{fn}	N, R, T
High-rate loading	C3	σ_u, ε_u	$\sigma_{up}, \varepsilon_{up}, \sigma_{un}, \varepsilon_{un}$	$\dot{\varepsilon}, T$

It should be noted that the failure properties of plastics are sensitive to long-term changes in the molecular or crystalline structure of the material brought about by various ageing processes. The most notable of these are physical ageing (relaxation of free volume), thermal ageing, brought about by exposure to elevated temperatures, and ultraviolet degradation caused by exposure to sunlight.

4.3 Design for processing analysis

4.3.1 Processing simulation

Among the various processing methods available for fabrication of plastics into useful parts, injection moulding is the most prevalent method in practice. As such, the CAE (computer aided engineering) tools for simulation of the injection moulding process are more advanced in terms of the number of programs available and their sophistication. Recently, more emphasis has been given to the development of CAE tools for simulation of other processing methods such as extrusion, blow moulding, and thermoforming.

4.3.2 Data for simulation of injection moulding

Simulation programs for injection moulding are available from a number of sources. In general, most of these programs provide a two-dimensional analysis incorporating temperature distribution through the third dimension. Enhancements to allow full three-dimensional simulation have only recently been introduced. Both of these simulation programs are rather complex in nature requiring rigorous definition of part geometry and utilising various viscosity models to describe the flow behaviour of polymer melts, and some expertise is required to use these programs. To overcome the need for such rigorous analysis, several simulation programs for simple two-dimensional simulation are currently on the market.

The main objective of these methods is to simulate the part-filling and post-filling steps in order to assess and optimize the manufacturability of the part. The three main types of analysis involved in injection moulding simulation are

- simple mould filling analysis to determine the ability to fill the mould cavity and to assess the pressure requirements,
- advanced mould filling, packing and cooling analysis, carried out to optimize the processing conditions or to evaluate part and mould design alternatives such as number of gates, proper gate size, its location, etc., and
- shrinkage and warpage analysis to satisfy tolerances and predict dimensional stability of the manufactured part.

The material properties needed for simple mould filling simulation are listed in Table 5.

Table 5 — Data needed for injection moulding simulation — Simple mould filling analysis of thermoplastics and thermoplastic elastomers

Property	Variables
η	$T, \dot{\gamma}$
ρ_m	—
k_m, c_{pm}	—
T_s, T_{ej}	—

Depending on the software package, reference is also made to the “no flow temperature” or the “transition temperature” in place of the solidification temperature T_s . The need for T_{ej} also depends on the software package. The material properties required for advanced filling, packing and cooling analysis are shown in Tables 6 and 7. The material property requirements are essentially the same for thermoplastics and thermoplastic elastomers. The main differences in the case of reactive materials, such as thermosets, are the inclusion of reaction kinetics data and use of reactive polymer viscosity data in place of melt viscosity data.

Table 6 — Data needed for injection moulding simulation — Advanced mould filling, packing and cooling analysis of thermoplastics and thermoplastic elastomers

Property	Variable(s)
η	$T, \dot{\gamma}, p$
v	$p, T, \dot{T}$
k, c_p	T
T_s	$p, \dot{T}$
T_{ej}	—

When relevant data are not available, the pressure dependence of viscosity and the temperature dependence of thermal conductivity and specific heat are not included in the analysis.

Table 7 — Data needed for moulding simulation — Mould filling, packing and cooling analysis of reactive materials including thermosets

Property	Variable(s)
η_{reactive}	$T, t, \dot{\gamma}$
ρ_{reacted}	—
k, c_p	T
$\Delta H_r, \dot{R}$	$T, \dot{T}$
α_{gel}	—

The material properties required for shrinkage and warpage analysis are shown in Table 8.

Table 8 — Data needed for injection moulding simulation — Additional data for shrinkage & warpage analysis

Property	Variable(s)
S_{Mp}, S_{Mn}	h, p_{CH}
X (semicrystalline materials)	T
$\dot{X}$ (semicrystalline materials)	$T, \dot{T}$
E_p, E_n	T
ν_{pn}, ν_{np}, G_p	—
α_p, α_n	T

4.3.3 Data for simulation of extrusion

The simulation of extrusion generally includes consideration of the solids transport, the melting of the polymer in the barrel, flow of the melt in the die and the cooling of the extruded shape. Available CAE packages employ different viscosity models to describe the flow behaviour of the polymer melt (see Annex B) and make various simplifying assumptions. The simplifying assumptions typically relate to neglecting contributions from extensional flow, thereby avoiding the need for data on uniaxial extensional viscosity and the first normal stress difference.

The material properties needed for simulation of extrusion processes incorporating these analyses are listed in Table 9.

Table 9 — Material properties needed for simulation of extrusion

Type of analysis	Property	Variable(s)
Solids transport and melting of the polymer	$T_m, \Delta H_f$ (semicrystalline materials)	—
	T_g (amorphous materials)	—
	ρ_m, ρ_s	—
	μ_b, μ_s	p, T, ν_s
	ρ_B	p
	k, c_p	T
Flow of melt in the die	ρ_m	
	k_m, c_{pm}	T
	η, N_1	$T, \dot{\gamma}$
	η_{eu}	$T, t, \dot{\epsilon}$
Cooling of the extrudate	$T_c, \Delta H_c$ (semicrystalline materials)	$\dot{T}$
	$\dot{X}$	$T, \dot{T}$

In practice, the temperature dependence of k and c_p is often ignored if the associated loss of accuracy is considered acceptable.

4.3.4 Data for simulation of blow moulding, blown film extrusion and thermoforming

Injection blow moulding and thermoforming processes involve deformation of a profile or a sheet in a softened state, while extrusion blow moulding and blown film extrusion processes involve deformation in the melt state. The material properties needed for these simulations are listed in Tables 10 and 11.

Table 10 — Material properties needed for simulation of injection blow moulding and thermoforming

Type of Analysis	Property	Variables
Reheating the preform or sheet	k, c_p	T
Deformation of softened material	k, c_p	T
	N_1	$T, \dot{\gamma}$
	η_{eb}	$T, t, \dot{\epsilon}$
Solidification of the formed shape	T_s (amorphous materials)	$\dot{T}, p$
	$T_c, \Delta H_c$ (semicrystalline materials)	$\dot{T}$
	$\dot{X}$	$T, \dot{T}$

Table 11 — Material properties needed for simulation of extrusion blow moulding, and blown film extrusion

Type of Analysis	Property	Variables
Melting of polymer in the barrel	$T_m, \Delta H_f$ (semicrystalline materials)	
	T_g (amorphous materials)	
	ρ_m	
	μ_b, μ_s	p, T, v_s
	ρ_B	p
	k, c_p	T
Flow of melt in the die	ρ_m	
	k, c_p	T
	η, N_1	$T, \dot{\gamma}$
	η_{eu}, η_{eb}	$T, t, \dot{\epsilon}$
Cooling of the extrudate	$T_c, \Delta H_c$ (semicrystalline materials)	$\dot{T}$
	$\dot{X}$	$T, \dot{T}$

5 Determination of design data

5.1 General

In this section, preferred test methods are identified for determining the properties shown in Tables 2 to 11. Standard test specimens and test conditions to be used for the acquisition of data are also recommended for each of the properties. Section 5.2 deals with data needed for design for mechanical performance and 5.3 with data needed for processing analysis.

For those properties for which ISO standards are not available for the measurement of data, reference is made, through the use of notes to the tables, to apparatus and specimens which have been used successfully. These methods may be subjects for future standards development.

5.2 Data acquisition for design for mechanical performance

Table 12 shows test methods recommended for determining the mechanical property data listed in Tables 2, 3 and 4.

The methods that are based on International Standards employ standard test specimens that are prepared under well-specified conditions. It should be noted that the material structure in these specimens will, in general, be different from that in the component to be designed. The influence that these structural differences will have on property values will depend upon the property, the processing method and conditions and the geometry of the component. Procedures for increasing the relevance of test specimen data for design are not yet recognised.

NOTE Working groups in ISO TC 61 are considering suitable mould designs for preparing additional standard test specimens in the form of a plate by injection moulding (ISO 294-5).

By testing specimens cut from the plate along and transverse to the direction of melt flow into the mould, it may be possible to obtain upper and lower bounds to properties arising from molecular or fibre orientation. Selection of appropriate property values within these bounds will require knowledge of the flow conditions in critical regions of the component.

Estimates of the anisotropy in tensile modulus of short-fibre reinforced plastics may also be obtained from flow simulation packages that calculate fibre orientation functions throughout a moulded product. A knowledge of fibre and matrix properties is required as well as certain other parameters. An important feature of this approach to the characterisation of elastic behaviour is that information is generated on the variation of properties through the thickness of the moulding. However, as with any predictive method, there will, in general, be some uncertainty in the accuracy of derived properties or performance values.

The precision with which specific test data can be used for design will also be restricted by batch-to-batch variations in material properties. The precision of data for design can then be increased by the statistical analysis of data from different batches.

Despite these limitations in test specimen data, the test methods in Table 12 are highly relevant for the acquisition of design data.

5.3 Data acquisition for design for processing

Table 13 shows recommendations for determining the data needed for processing simulations listed in Tables 5 to 11.

Table 12 — Preferred test methods for acquisition of data needed for design for mechanical performance

Property	Test method	Test specimen	Recommended test conditions	See Note
E	ISO 527-2	ISO 3167	ISO 11403-1	1
ν	ISO 527-2	ISO 3167	—	2
E_p, E_n, ν_{pn}	ISO 527-2	Cut from ISO 294-5	ISO 11403-1	3
	ISO 527-4 or -6	See relevant part of ISO 527		
G_p	ISO 6721-7	Cut from ISO 294-3 or 5	ISO 11403-1	
	ISO 15310	150 mm square plate	Temperatures in ISO 11403-1	
σ_T	ISO 527-2	Waisted tensile specimen	ISO 11403-1	4
ν_p	ISO 527-2	ISO 3167	—	5
λ	Shear or compression test	—	—	6
D	ISO 899-1	ISO 3167	ISO 11403-1	
D_p, D_n	ISO 899-1	Cut from ISO 294-5	ISO 11403-1	3
E_s	No International Standard	—	—	7
E', E''	ISO 6721-4 or -5	Cut from ISO 294-3 or ISO 294-5	T ISO 11403 f 0,05, 0,5, 5, 50 Hz	8
G', G''	ISO 6721-7	Cut from ISO 294-3 or ISO 294-5	As above	8
σ_{T1}, σ_{T2}	ISO 527-2	Cut from ISO 294-5	ISO 11403-1	9, 4 and 3
σ_{S1}, σ_{S2}	No International Standard	—	—	10, 9
σ_u, ϵ_u	ISO 527-2	Waisted tensile specimen	ISO 11403-1	
$\sigma_{up}, \sigma_{un}, \epsilon_{up}, \epsilon_{un}$	ISO 527-2	Cut from ISO 294-5	ISO 11403-1	3
σ_c	ISO 6252	ISO 3167		
σ_{cp}, σ_{cn}	ISO 6252	Cut from ISO 294-5		3
σ_f	—	—	—	—

NOTE 1 ISO 11403-1 specifies the temperature values to be used if it is considered beneficial to present modulus values at standard temperatures so that data from different sources can be compared. Modulus values will increase with increasing strain rate and the rate-dependence will vary with temperature being greater the closer the temperature is to the centre of a relaxation region. The determination of the variation of modulus with rate is routine for strain rates in the range 1×10^{-5} to $1 \times 10^{-1} \text{ s}^{-1}$. At higher rates, the measurement of strain is generally not possible using conventional extensometers (but see Note 4). Data acquisition at high rates is possible through correlations with measurements at lower temperature or with high frequency dynamic mechanical data.

For long-term loading applications (time under load greater than 0,5 h), creep modulus values should be used derived from tensile creep tests.

NOTE 2 The measurement of lateral strain for the determination of Poisson's ratio is not described in ISO standards. A transducer is needed for measuring the change in the width of the specimen under a uniaxial tensile stress. Lateral extensometers are available for this purpose. The Poisson's ratio varies with temperature and strain rate, and, as with modulus, the changes are most pronounced in a relaxation region. Poisson's ratio also varies with strain (see Note 5).

NOTE 3 Specimens of suitable geometry are cut from moulded sheet with specimen axes along and transverse to the direction of preferred orientation. For materials that can be injection moulded, properties will depend upon the processing conditions, the mould geometry and, possibly, the location in the mould. ISO 294-5 is concerned with standardising the dimensions and geometry of a mould in which plate specimens can be prepared having a high degree of anisotropy in properties. The optimum mould thickness for achieving high anisotropy is around 1 mm. The optimum length and width of the plate is then about 80 mm so that specimens having the geometry of the half-scaled, multipurpose test specimen (ISO 527-2 type 1BA) can be prepared by machining. Using this specimen geometry, failure properties can also be determined. Note also that if data only for strains well below failure are required, then measurements may be made on parallel-sided specimens cut from the standard 60 mm square plate (ISO 294-3) although, by virtue of the shorter specimen length, the accuracy of results is likely to be lower.

Table 12 (continued)

NOTE 4 In elastic-plastic materials models, non-linear behaviour is considered to be caused by plastic deformation. The lowest value of σ_T coincides with the onset of curvature (non-linearity) in the tensile stress/strain curve. The value of σ_T then varies with plastic strain and data are derived from measurements of stress/strain curves (see section A.4). Stress/strain data are generally needed over ranges of temperature and strain rate (see section A.5). Data at high strain rates are needed for the prediction of impact performance but the measurement of strain in high-speed tests has not been described in any standard. Strain values can be derived from measurement of cross-head displacement if corrections are applied for the machine compliance and the non-uniform strain in the specimen. For high-speed tests, use of a small tensile specimen is recommended.

There is also scope for obtaining data at high rates by extrapolation of measurements at moderate rates. Validated procedures for this are not yet available.

For long-term loading applications (time under load > 0,5 h), σ_T values should be obtained from isochronous stress/strain curves derived from tensile creep tests.

NOTE 5 The plastic component of Poisson's ratio ν_p is derived from simultaneous measurements of longitudinal and transverse strain in tensile tests taken to large strains where behaviour is non-linear. It is used to determine the flow parameter for elastic-plastic models. The transverse strain measurements are also used to derive true stress values from measurements of nominal (engineering) stress. Equations (A.8), (A.9), (A.7) and (A.6) relate relevant parameters.

NOTE 6 The quantity λ is used in the yield criterion in certain elastic-plastic materials models and is a measure of the influence of the hydrostatic component of stress on yield behaviour. It is equal to the ratio of yield stresses in uniaxial compression and uniaxial tension. It can be derived from measurements of compression or shear stress/strain curves in conjunction with tensile stress/strain data. The acquisition of data under compression requires elaborate apparatus to prevent buckling of the specimen. The use of this test with shorter thicker specimens to avoid buckling gives rise to lateral stresses in the specimen. The ISO standard ISO 604 is thus not adequate for this purpose. Shear stress/strain data can be obtained from tests on notched bars (Iosipescu) or notched plates (Arcan) loaded in simple shear. Shear strains can be measured in fibre-reinforced specimens using strain gauges, but a purpose-built extensometer is recommended for unreinforced plastics.

A proposed yield criterion for plastics (see section A.4) is

$$\sigma_T = \frac{\sqrt{3}(\lambda + 1)}{2\lambda} J_{2D}^{1/2} + \frac{(\lambda - 1)}{2\lambda} J_1$$

where J_1 and J_{2D} are stress invariants and are functions of the components of stress.

λ is then given by

$$\lambda = \frac{\sigma_C}{\sigma_T} = \frac{\sqrt{3}\sigma_S}{(2\sigma_T - \sqrt{3}\sigma_S)}$$

where

σ_C and σ_S are yield stresses in compression and shear at the same equivalent plastic strain as the tensile yield stress σ_T .

For those materials for which $\lambda = 1$, the above Equation reduces to the von Mises yield criterion.

NOTE 7 No ISO standard specifies the measurement of stress relaxation modulus. The specimen and extensometry are the same as those used to acquire creep data. A constant displacement is applied to the specimen and the reduction in load with time is recorded. The stress relaxation function $E_R(t)$ is given by the ratio of the time-dependent stress to the constant strain. The stress relaxation modulus at a particular time is approximately equal to the inverse of the creep compliance at the same time for times and temperatures remote from a relaxation region. More generally, the transformation of creep data to stress relaxation data requires a knowledge of the whole creep function.

NOTE 8 There are a number of commercial instruments that measure dynamic properties. These commonly employ small specimens so that a temperature scan can be completed relatively quickly. A small specimen can lead to significant errors in derived modulus values. The various parts of ISO 6721 should be consulted for information on sources of error in these tests and guidance on the application of corrections.

NOTE 9 These properties as a function of strain are only needed for the application of elastic-plastic models to anisotropic materials.

NOTE 10 Although no International Standard exists, the Iosipescu or Arcan test methods have been used to obtain stress/strain curves in shear for a variety of materials. For fibre reinforced plastics, strain gauges have been used to determine shear strains. For unreinforced plastics, the use of a purpose-built extensometer is recommended.

Table 13 — Preferred test methods for the acquisition of data needed for design for processing

Property	Variables	Test method	Test specimen	Recommended test conditions
η (thermoplastics)	$T, \dot{\gamma}, p$	ISO 11443	Raw material	See ISO 11403-2 and Note 1
η_{reactive} (thermosets)	$T, t, \dot{\gamma}$	See Notes 2 and 3	Raw material	—
η_{eu}	$T, t, \dot{\epsilon}$	See Note 4	Raw material	—
η_{eb}	$T, t, \dot{\epsilon}$	See Note 5	Raw material	—
N_1	$T, \dot{\gamma}$	See Note 6	Raw material	—
ρ_m	—	See Note 7	Raw material	—
ν	$p, T, \dot{T}$	ISO 17744	Injection-moulded specimen	See Notes 8 and 9
k	T	See Note 10	Raw material	—
c_p	T	ISO 11357-4	Raw material	Cooling scan at 10 °C/min (see ISO 11403-2)
T_s	$\dot{T}, p$	ISO 11357-3 see Note 11	Raw material	Cooling scans at 10 °C/min, 50 °C/min, 100 °C/min and 200 °C/min (see Note 12)
T_{ej}	—	ISO 11357-3	Raw material	Cooling scan at 10 °C/min (see Note 12)
T_m	—	ISO 11357-3	Raw material	Heating scan at 10 °C/min
T_g	—	ISO 11357-2	Raw material	Cooling scan at 10 °C/min
T_c	$\dot{T}$	ISO 11357-3	Raw material	Cooling scans at 10 °C/min, 50 °C/min, 100 °C/min and 200 °C/min
ΔH_f	—	ISO 11357-3	Raw material	Heating scan at 10 °C/min
ΔH_c	$\dot{T}$	ISO 11357-3	Raw material	Cooling scans at 10 °C/min, 50 °C/min, 100 °C/min and 200 °C/min
X	T	ISO 11357-7	Raw material	Cooling scan at 10 °C/min
$\dot{X}$	$T, \dot{T}$	ISO 11357-7	Raw material	—
$\dot{R}$ (thermosets)	$T, \dot{T}$	ISO 11357-5	Uncured material	—
ΔH_r (thermosets)	$T, \dot{T}$	ISO 11357-5	Uncured material	—
α_{gel} (thermosets)	—	ISO 11357-5	Uncured material	Heating scan at 10 °C/min (see Note 13)
ρ_{reacted}	—	ISO 1183	cured material	—
α_p and α_n	T	ISO 11359-2	specimens cut from ISO 294-3 plate	See ISO 11403-2
S_{Mp} and S_{Mn} (thermoplastics)	h, p_{ch}	ISO 294-4	60 mm × 60 mm plate (ISO 294-3)	1, 1.5 and 2 mm thickness; cavity pressures of 25, 50 and 100 MPa
S_{Mp} and S_{Mn} (thermosets)	h, p_{ch}	ISO 2577	60 mm × 60 mm plate (See ISO 294-3)	1, 1.5 and 2 mm thickness; cavity pressures of 25, 50 and 100 MPa
E_p and E_n	T	ISO 527-2	specimens cut from ISO 294-5 plate	At 23 °C; 1 mm/min; 0,05 – 0,25 % strain range
ν_{pn} and ν_{np}	—	ISO 527-2	specimens cut from ISO 294-5 plate	At 23 °C; 1 mm/min; 0,1 – 0,5 % strain range (see Note 14)

Table 13 (continued)

Property	Variables	Test method	Test specimen	Recommended test conditions
G_p (moulding materials)	—	ISO 6721-2 OR ISO 6721-7	ISO 3167 or cut from ISO 294-5	See ISO 11403-1
G_p (fibre-reinforced plastics)	—	ISO 15310	150 mm square plate	—
μ_b, μ_s	p, T, v_s	See Note 15	—	—
ρ_B	p	See Note 16	—	—

NOTE 1 The pressure dependence of viscosity is relevant for moulding thin wall parts. However, the determination of the pressure dependence of viscosity is not addressed in any of the test standards for viscosity measurement. In most analyses, the pressure dependence of viscosity is therefore neglected.

NOTE 2 For the determination of viscosity of a reactive system, a slit die rheometer based on ISO 11443 is recommended. Alternatively, a parallel plate viscometer based on ISO 6721-10 may be used.

NOTE 3 To determine the dependence of viscosity on shear rate for a reactive system, a dynamic mechanical rheometer is recommended.

NOTE 4 No test standard existed at time of publication for measuring the uniaxial extensional viscosity of polymer melts. However, measurements can be made using Meissner's apparatus, the Göttfert Rheoten extensional rheometer or the Rosand Precision Ltd, Version 7 unit²⁾. It is recommended that uniaxial extensional viscosity be measured at 3 temperatures in the processing region.

NOTE 5 No test standard exists today for measuring the biaxial extensional viscosity of polymer melts, although development of new apparatus based on the use of film inflation has been reported by IKV. Alternatively, Meissner's apparatus has also been used for measuring biaxial extensional viscosity. It is recommended that biaxial extensional viscosity be measured at 3 temperatures in the processing region.

NOTE 6 For the determination of first normal stress difference at a limited range of shear rate, a parallel plate viscometer method based on ISO 6721-10 is recommended. The data need to be measured at the same conditions as in ISO 11403-2.

NOTE 7 Melt density can be obtained by the ratio of MFR and MVR, but more accurately from pVT data. It is recommended that melt density be measured at a temperature corresponding to the centre of the processing temperature range.

NOTE 8 It is recommended that measurements be made at a cooling rate of 2,5 °C/min at 40, 80, 120, 160 and 200 MPa with an estimation at 1 MPa.

NOTE 9 In the case of semicrystalline resins, the effect of cooling rate is apparent by shifts in both the crystallization temperature and the specific volume (or density). The corresponding shifts can be predicted by compensating for changes in crystallization temperature and degree of crystallinity estimated from DSC scans at fast cooling rates.

NOTE 10 For the determination of thermal conductivity, the transient line source method with cooling from the maximum recommended processing temperature to 23 °C is recommended.

NOTE 11 Pressure DSC can be used for the determination of the pressure dependence of solidification temperature but is currently not described by any test method standard.

NOTE 12 The solidification and ejection temperatures are reference temperatures which are obtained from the DSC scans as defined by the mould filling simulation software. The measurement of values as a function of pressure is currently not common practice (see Note 11).

NOTE 13 The gelation conversion is calculated using the Kamal model from the DSC characterisation of uncured material at several heating rates, in combination with slit die rheometer data using the Macasko model. α_{gel} is the conversion at which viscosity is infinite.

NOTE 14 Poisson's ratio ν_{pn} is measured in the linear portion of the stress-strain curve. Poisson's ratio ν_{np} can be calculated using $\nu_{np} = \nu_{pn} E_n/E_p$.

NOTE 15 No test standard currently exists to determine the dynamic coefficient of friction. Very often, the roughness of the barrel and screw surfaces are taken into consideration in assigning values for these parameters. For μ_b a common practice is to assign a value of 0.3 for a smooth barrel, 0.45 for a rough barrel and 1.0 for a grooved barrel. Similarly for μ_s , a value of 0.25 is assigned for a smooth screw surface and 0.35 for a corroded screw surface.

NOTE 16 No test standard currently exists to determine the bulk density of moulding materials. It may be possible to adapt the method ISO 61 intended for determination of the apparent density of moulding materials in powder form.

2) These are examples of products available commercially. This information is given for the convenience of users of this International Standard and does not constitute an endorsement by ISO of these products.

Annex A (informative)

Illustrations of the application of finite element analyses to plastics components

A.1 Component geometry and loading arrangement

In this annex, the application of finite element methods is illustrated by calculations of stress and strain distributions in plastics components subjected to different loading situations. A range of types of material behaviour is considered. The aim is to show how the parameters required by various materials models used in FEA analysis can be derived from experimental data. Descriptions here are necessarily brief and reference should be made to technical literature and FEA user manuals for more detailed information.

The applications considered are shown in Table A.1.

Table A.1 — Applications of finite element analyses considered in this section

Section	Behaviour	Loading	Model type
A.2	Linear elastic	Static	A
A.3	Non-linear elastic	Static	B
A.4	Non-linear (elastic plastic)	Static	C
A.5	Non-linear (rate-dependent plasticity)	Impact	C3
A.6	Non-linear viscoelastic (time-dependent plasticity)	Creep	E1 or (C1)
A.7	Linear viscoelastic	Dynamic	D2
A.8	Anisotropic linear elastic	Static	A

In sections A.2 to A.6, the application of different materials models is considered to a single component geometry and loading arrangement. The component is a circular plate that is simply supported on a ring close to its circumference and loaded at its centre as shown in Figure A.1. The selected dimensions correspond closely with those used for puncture impact tests described in ISO 6603-2. Note that a specimen thickness of 3 mm has been chosen in place of the 2 mm thickness recommended in that International Standard. The element mesh for the specimen is shown in Figure A.2, where it can be seen that the loading device and the support are defined by a linear mesh which assumes that these parts are infinitely rigid compared with the plate.

A.2 Application of a linear elastic materials model

With this model, stress and strain components are considered to be linearly related at all levels of strain. However, geometric non-linearity, which allows for changes in the geometry of the plate brought about by large central displacements, is taken into account in the analysis. According to Table 2, the data requirements for this model are the tensile modulus E and Poisson's ratio ν . As indicated in Table 12, these can be determined from a tensile test following the procedure described in ISO 527-2. Any dependence of properties on the rate of loading or the time under load is not taken into consideration in the analysis but associated errors can be minimised by using data measured at strain rates or loading times appropriate to the application.

Results from a tensile test on a propylene copolymer are shown in Figure A.3 measured at a constant deformation rate of 10 mm/min. This corresponds to an elastic strain rate of $2 \times 10^{-3} \text{ s}^{-1}$. Values for the tensile modulus of 1,6 GPa and for Poisson's ratio of 0,39 are obtained from the data in the strain range up to 0,01, which marks the limit of linear behaviour. Using these values, a finite element analysis has been used to obtain the variation of the force applied by the hemispherical contact with the central deflection of the plate. This is shown in Figure A.4 where it is compared with results derived from a non-linear analysis (see section A.4). Figure A.5 shows the distribution of the tensile component of strain in the radial direction at a central deflection of 4 mm. In certain regions of the plate, the strain magnitude is above the limit for linear behaviour and this is consistent with the observed departure of the predicted curve in Figure A.4 from the curve based on a model for non-linear behaviour.

Clearly the linear elastic analysis could be used to give closer agreement with the non-linear analysis at the higher deflections if an effective value for Young's modulus were chosen from the slope of the secant to the tensile stress/strain curve at an appropriate higher strain. A procedure for selecting the appropriate strain is, however, not clear, and the accuracy in predictions at the smaller central deflections would be reduced.

A.3 Application of a non-linear elastic materials model

Errors in the linear elastic analysis become progressively more significant at deflections where strain levels in the plate exceed the limit for linear behaviour. More accuracy in predictions can then be achieved using a hypoelastic model that allows for some non-linearity in the stress/strain curve in Figure A.3. The data requirements for this model are shown in Table A.2.

Table A.2 — Data requirements for a hypoelastic model derived from the data on the propylene copolymer shown in Figure A.3

ε	E_T	ν_T	I_1	I_2	I_3
-0,06	0,075	0,459	$-1,570 \times 10^{-2}$	$2,168 \times 10^{-3}$	$-2,944 \times 10^{-5}$
-0,04	0,252	0,457	$-6,032 \times 10^{-3}$	$1,070 \times 10^{-3}$	$-1,154 \times 10^{-5}$
-0,02	0,818	0,455	$-2,768 \times 10^{-3}$	$2,704 \times 10^{-4}$	$-1,485 \times 10^{-6}$
-0,01	1,200	0,433	$-1,754 \times 10^{-3}$	$6,546 \times 10^{-5}$	$-1,700 \times 10^{-7}$
0	1,600	0,390	0,0	0,0	0,0
0,01	1,200	0,433	$1,754 \times 10^{-3}$	$6,546 \times 10^{-5}$	$1,700 \times 10^{-7}$
0,02	0,818	0,455	$2,768 \times 10^{-3}$	$2,704 \times 10^{-4}$	$1,485 \times 10^{-6}$
0,04	0,252	0,327	$6,032 \times 10^{-3}$	$1,070 \times 10^{-3}$	$1,154 \times 10^{-5}$
0,06	0,075	0,221	$1,570 \times 10^{-2}$	$2,168 \times 10^{-3}$	$2,944 \times 10^{-5}$
0,08	0,013	0,176	$2,880 \times 10^{-2}$	$3,441 \times 10^{-3}$	$5,243 \times 10^{-5}$
0,1	0,003	0,157	$4,216 \times 10^{-2}$	$4,948 \times 10^{-3}$	$8,364 \times 10^{-5}$
0,2	0,001	0,122	$1,163 \times 10^{-1}$	$1,499 \times 10^{-2}$	$3,501 \times 10^{-4}$

E_T are values for the tangent tensile modulus obtained as a function of tensile strain ε and are equal to the gradient of the stress/strain curve at the strain ε , ν_T are values for the tangent Poisson's ratio and are equal to the gradient of the plot of lateral strain against longitudinal strain at the strain ε , and I_1 , I_2 and I_3 are strain invariants and are related to the tensile strain ε as follows:

$$\begin{aligned}
 I_1 &= (1 - 2\nu)\varepsilon \\
 I_2 &= \nu\varepsilon^2(2 - \nu)
 \end{aligned}
 \tag{A.1}$$