

REPORT

Project CAM6

Report No 2 August 1997

ISO Guide to the Acquisition and Presentation of Design Data for Plastics

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SUMMARY

This discussion paper records the data needed to design with plastics using computer methods. These design methods include both selection of optimum mould geometry and processing conditions for the fabrication of a component as well as prediction of performance under service loads. The paper has been prepared to support a proposal in ISO TC61 for the preparation of a standard Guide to the measurement and presentation of the required data.

The contents of the paper have been identified after consultation with plastics materials suppliers and developers of design software. This paper is a first draft for the proposed Guide and further discussion will need to take place during the development of the final document. Issues that particularly need to be addressed are:

- clarification of the range of plastics and reinforced plastics that are covered by the document;
- guidance as to which materials models used by finite element analyses are valid for plastics and under what circumstances simplifying approximations are valid;
- guidance on procedures for the analysis of test data to generate the parameters identified in certain models.

Comments on this draft are welcome.

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ISSN 1361-4061

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
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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 flow of the polymer melt during the manufacture of a component.

In order to design effectively with plastics, comprehensive data are generally needed which take into account the effects on properties of time, temperature, rate and environment. A number of international standards has been developed that specify how certain data for plastics should be measured and presented. These are:

ISO 10350-1 Plastics - Acquisition and presentation of comparable single-point data. Part 1 - Moulding materials.

ISO 10350-2 Plastics - Acquisition and presentation of comparable single-point data. Part 2 - Long-fibre reinforced plastics.

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 11403-3 Plastics - Acquisition and presentation of comparable multipoint data. Part 3 - Environmental influences on properties.

The intention of these standards is to enable data on different materials from different sources to be readily compared and thereby to aid the process of materials selection. A substantial quantity of data is specified by these standards and, although not the prime purpose of the standards, some of these data are suitable for design. However, additional data are needed.

The purpose of this standard Guide is to complement 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 also recommended for determining these data. For some properties, ISO test methods or specimens are not yet available. Reference is then made to suitable procedures for data acquisition that may become standardised at a later stage.

It is intended that this Guide should 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 of data is needed in order to present information in the form required by the design analysis. Some procedures for data analysis are also described in this Guide.

1 SCOPE

This ISO Guide addresses the acquisition and presentation of design data for plastics. It covers data needed for the analysis of 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

To be included later

3 DEFINITIONS

To be included later

4 DATA NEEDED FOR DESIGN

The design data identified here are grouped under two headings:

1. Data for analysis of mechanical performance.
2. Data for processing analysis.

4.1 DESIGN FOR MECHANICAL PERFORMANCE

4.1.1 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 for which 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 - since plastics are viscoelastic, 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 and strain 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 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.

4.1.2 Design data for mechanical performance

The data required for design for mechanical performance consist of data for carrying out stress analysis and data for estimating materials failure. The data required for stress analysis depend, in part, on the service conditions relevant to the application, 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.

In addition, there is a further important case involving:

- Simpler conditions, not dependent on time, frequency or rate, either due to the nature of service conditions or of materials behaviour. This may also be assumed in an initial approximate stress analysis for the other three cases using 'effective' materials properties relevant to a given time, frequency or rate, eg a 'long-time' creep modulus.

These four cases are shown in Table 1, together with the relevant types of materials behaviour and models which may need to be included in the stress analysis (see below).

**Table 1. Typical service conditions, materials behaviour
and model types**

Service Conditions	Crucial Parameter	Relevant Types of Materials Behaviour	Model Types (see below)
Simpler Conditions		Elastic Elastic-plastic	A, B C
Sustained Loading	Time	Viscoelastic or Viscoplastic	D1, E1, C1
Cyclic Loading	Frequency		D2, E2, C2
High-Rate Loading	(Strain) Rate		D3, E3, C3

As already noted, the stress analysis will also need to consider isotropic or anisotropic properties, linear or nonlinear 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 therefore to focus on the most important cases. This is discussed now under the model types indicated in the last column of Table 1.

- [A] Linear elasticity is the simplest and most commonly used materials model, at least for a first analysis.

- [B] Nonlinear elasticity is available in many CAE codes, for example for hyperelastic behaviour. It is most useful for elastomeric materials, and is not considered further in this draft.

- [C] Elastic-plastic models for metals are available in most CAE codes and are able to handle nonlinear 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 (for example the Drucker-Prager models) is considered here. (Models C1, C2 and C3 are defined under [F] below).

- [D] Linear viscoelasticity is limited to small-strain behaviour, but can be used in three different forms (D1, D2, D3) depending on whether time, frequency or rate is the crucial service parameter.

- [E] Nonlinear 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) (not discussed further in this draft.
- [F] Models exist in CAE codes for treatment of materials behaviour which combines the effects of elasticity, plasticity and also time, frequency or rate. These include viscoplasticity models and also modifications to plasticity models (see [C] above) in time-dependent, frequency-dependent or rate-dependent forms. These latter types of model (C1, C2 and C3) are indicated in Table 1, but only C3 is considered in this draft.

Further consideration of the above models leads to identification of the data which are required for design for mechanical performance. These data requirements are summarised in Table 2a for isotropic materials and in Table 2b for a simple form of anisotropy. This form of anisotropy is applicable to situations, such as thin plates and shells, where stresses are confined to a single plane of anisotropy in the material. Through-thickness properties are then not needed for the analysis of stresses and strains within this plane. It should be recalled that certain types of model have been excluded from these tables.

Table 2c indicates the data required for characterising materials failure.

The symbols used in each of these tables are explained in section 4.1.3.

Table 2a. Data required for stress analysis (isotropic material)

Behaviour	Model Type	Properties	Variables
Linear elastic	A	E, ν	T
Nonlinear (Elastic-plastic)	C	E, ν σ_T λ, ν_p, ψ	T ϵ_p, T ϵ_p, T
Linear Viscoelastic	D1 D2 D3	D, E_s E', E'' or G', G'' E, ν	t, T f, T $\dot{\epsilon}, T$
Nonlinear Viscoelastic	E1	D E_s	t, σ, T t, ϵ, T
Rate-dependent, Elastic-plastic	C3	E, ν σ_T λ, ν_p, ψ	$\dot{\epsilon}, T$ $\epsilon_p, \dot{\epsilon}_p, T$ $\epsilon_p, \dot{\epsilon}_p, T$

Table 2b. Data required for stress analysis (anisotropic material)

Behaviour	Model Type	Properties	Variables
Linear elastic	A	E_ℓ, E_t, ν, G_ℓ	T
Nonlinear (Elastic-plastic)	C	E_ℓ, E_t, ν, G_ℓ σ_{T1}, σ_{T2} σ_{S1}, σ_{S2}	T ϵ_p, T γ_p, T
Linear Viscoelastic	D1 D3	D_ℓ, D_t E_ℓ, E_t, ν, G_ℓ	t, T $\dot{\epsilon}, T$
Nonlinear Viscoelastic	E1	D_ℓ, D_t	t, σ, T
Rate-dependent, Elastic-plastic	C3	E_ℓ, E_t, ν, G_ℓ σ_{T1}, σ_{T2} σ_{S1}, σ_{S2}	$\dot{\epsilon}, T$ $\epsilon_p, \dot{\epsilon}_p, T$ $\gamma_p, \dot{\gamma}_p, T$

Table 2c. Data required for characterising material failure

Service Conditions	Model type	Properties	Variables
Simple conditions	A	σ_T	T
	C	σ_u, ϵ_u	
		$\sigma_{ul}, \epsilon_{ul}, \sigma_{ut}, \epsilon_{ut}$	
Sustained loading	D_1, E_1	σ_c	t, ch, T
		σ_{cl}, σ_{ct}	
Cyclic loading	D_2, E_2	σ_f	N, R, T
		σ_{fl}, σ_{ft}	
High-rate loading	C_3	σ_u, ϵ_u	$\dot{\epsilon}, T$
		$\sigma_{ul}, \epsilon_{ul}, \sigma_{ut}, \epsilon_{ut}$	

4.1.3 Explanation of the symbols in tables 2a, 2b and 2c

4.1.3.1 Test Variables

ϵ true tensile strain

Note. Use of the true strain in place of the engineering strain is necessary when engineering strain values exceed about 0.05. Below a strain of 0.05, there is no significant difference between these quantities.

$\dot{\epsilon}$ true tensile strain rate

ϵ_p plastic component of the true 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

4.1.3.2 Material Properties (see tables 2a and 2b)

E	tensile modulus obtained from a test at constant strain rate
$E_{\parallel}$, $E_{\perp}$	tensile moduli along and transverse to, respectively, the direction of preferred fibre or molecular orientation in an anisotropic material
$G_{\parallel}$	shear modulus of an anisotropic material for stress application along the direction of preferred orientation
D	tensile creep compliance
E_s	tensile stress relaxation modulus
$D_{\parallel}$, $D_{\perp}$	tensile creep compliances along and transverse to, respectively, the direction of preferred orientation in an anisotropic material
E' , E''	tensile storage and loss moduli, respectively
G' , G''	shear storage and loss moduli, respectively
σ_T	true tensile yield stress

Note. In elastic-plastic materials models, non-linear behaviour is considered to be caused by plastic deformation. σ_T then varies with strain and the lowest value marks the onset of curvature on the tensile stress/strain curve.

λ hydrostatic stress sensitivity parameter

Note. This parameter is used in the yield criterion 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.

A realistic yield criterion for plastics is

$$\sigma_T = \frac{\sqrt{3}(\lambda+1)}{2\lambda} J_2^{\frac{1}{2}} + \frac{(\lambda-1)}{2\lambda} J_1$$

where J_1 and J_2 are stress invariants and are functions of the components of stress. For those materials for which $\lambda=1$, the above equation reduces to the von Mises yield criterion

σ_{T1}, σ_{T2} tensile yield stresses for loading along and transverse to, respectively, the direction of preferred orientation in an anisotropic material

σ_{S1}, σ_{S2} shear yield stresses for loading along and transverse to, respectively, the direction of preferred orientation in an anisotropic material

ν Poissons ratio

ν_p plastic component of the lateral contraction 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

Note. In general, ν_p will vary with plastic strain ϵ_p .

ψ the flow parameter

$$\tan \psi = \frac{3(1-2\nu_p)}{2(1+\nu_p)}$$

Note. This equation assumes there is no significant variation of ν_p with ϵ_p .

4.1.3.3 Failure properties (see table 2c)

σ_u tensile strength obtained from a test at constant specimen deformation rate

σ_{ul}, σ_{ut} tensile strengths for loading along and transverse to, respectively, the direction of preferred orientation in an anisotropic material

ϵ_u	strain at break obtained from a tensile test at constant specimen deformation rate
$\sigma_{ul}, \epsilon_{ut}$	strains at break for loading along and transverse to, respectively, the direction of preferred orientation in an anisotropic material
σ_c	tensile creep rupture strength
σ_{cl}, σ_{ct}	creep rupture strengths for loading along and transverse to, respectively, the direction of preferred orientation in an anisotropic material
σ_f	tensile fatigue strength
σ_{fl}, σ_{ft}	tensile fatigue strengths for loading along and transverse to, respectively, the direction of preferred orientation in an anisotropic material

4.2 DESIGN FOR PROCESSING

4.2.1 Processing simulation

Among the various plastics processing methods, injection moulding is the most dominant method in practice. As such, the CAE methods for simulation of the injection moulding process are more advanced in terms of number of CAE programs available and their sophistication. The main objective of these methods is to simulate the part-filling and post-filling steps in order to assess the manufacturability of the part. More recently, the focus has been shifted to the development of CAE tools for simulation of other processing methods such as extrusion, blow moulding and thermoforming.

4.2.2 Data for processing simulation

4.2.2.1 Data for simulation of injection moulding

The two main types of analysis involved in injection moulding simulation are:

1. Mold filling, packing and cooling analysis, carried out to optimise the processing conditions or to evaluate design alternatives such as number of gates, proper gate size, its location, etc.

2. Shrinkage and warpage analysis to predict tolerances and dimensional stability of the manufactured part.

The material properties needed for these simulations are listed in Tables 3a, 3b and 3c. The 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 the replacement of melt viscosity data by flowability.

Table 3a. Data needed for injection moulding simulation - Mold filling, packing and cooling analysis of thermoplastics and thermoplastic elastomers

Property	Variables
Melt Viscosity	T $\dot{\gamma}$ P
(Melt Density)	
Specific volume-Temperature data	P
Thermal Conductivity	T
Specific Heat	T
Solidification Temperature	P Cooling Rate
Ejection Temperature	
Crystallisation Temperature	P Cooling Rate
Heat of Crystallisation	Cooling Rate

Table 3b. Data needed for injection moulding simulation - Mold filling, packing and cooling analysis of reactive materials including thermosets

Property	Variables
Flowability (Reactive Viscosity)	T $\dot{\gamma}$ Conversion
Cure Kinetics	T Heating rate Conversion
Isothermal Induction (Gel) time	T
Polymer density	
Thermal Conductivity - unreacted	
Thermal Conductivity - reacted	
Specific Heat	T
Heat of Reaction	T
Gelation Conversion	T

Table 3c. Data needed for injection moulding simulation - Additional data for shrinkage & warpage analysis

Property	Variables
Moulding Shrinkage - parallel	h Processing parameters
Moulding Shrinkage - normal	h Processing parameters
Crystallinity	Cooling rate
Crystallisation Kinetics	T Cooling rate
Tensile Modulus - parallel	
Tensile Modulus - normal	
Poisson's Ratio, ν_{12}	
Poisson's Ratio, ν_{23}	
Shear Modulus	
Coefficient of Linear Thermal Expansion - parallel	T
Coefficient of Linear Thermal Expansion - normal	T

P - pressure h - thickness

4.2.2.2 Data for simulation of extrusion

The simulation of extrusion generally includes consideration of the melting of the polymer and the cooling of the extruded shape. The material properties needed for simulation of extrusion are listed in Table 4.

Table 4. Material properties needed for simulation of extrusion

Property	Variables
Melting Temperature	
Glass Transition Temperature	
Enthalpy of Fusion	
Coefficient of Friction	Contact material
Thermal Conductivity	T
Specific Heat	T
Melt Viscosity	T $\dot{\gamma}$ P
Uniaxial Extensional Viscosity	T t $\dot{\epsilon}$
Crystallisation Temperature	Cooling rate
Enthalpy of Crystallisation	Cooling rate
Crystallisation Kinetics	T Cooling rate

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

The material properties needed for these simulations are listed in Table 5.

Table 5. Material properties needed for simulation of blow moulding, blown film extrusion and thermoforming

Property	Variables
Biaxial Extensional Viscosity	T t $\dot{\epsilon}$
First Normal Stress Difference	T $\dot{\gamma}$
Thermal Conductivity	T
Specific Heat	T
Enthalpy of Crystallisation	Cooling rate
Crystallisation Temperature	P Cooling rate
Crystallisation Kinetics	T Cooling rate

5 MEASUREMENT OF DESIGN DATA

In this section, preferred test methods are identified for the measurement of the design data recorded in Tables 2 to 5. Standard test specimens and test conditions to be used for the acquisition of data are also recommended for each of the properties. Section 5.1 deals with data needed for design for mechanical performance and section 5.2 with data needed for processing analysis.

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

5.1 DATA ACQUISITION FOR DESIGN FOR MECHANICAL PERFORMANCE

Table 6 shows recommendations for determining the mechanical property data listed in tables 2a, 2b and 2c.

5.2 DATA ACQUISITION FOR DESIGN FOR PROCESSING

Table 7 shows recommendations for determining the data needed for process analysis listed in tables 3 to 5.

Table 6. Preferred test methods for the acquisition of data needed for design for mechanical performance (*incomplete - to be expanded in subsequent drafts*)

Property	Test method	Test specimen	Recommended test conditions	Comments
E	ISO 527-2	ISO 3167	ISO 11403-1	Strain rates to be identified
E_v , E_v	ISO 527-2	Cut from ISO 294-5	ISO 11403-1	Measurement of strain unspecified
G_I	ISO 6721-7	Cut from ISO 294-3 or 5	T - as ISO 11403; $f = 0.5$ Hz	Alternative method uses tensile test to measure E_{45}
D	ISO 899-1	ISO 3167	ISO 11403-1	
D_v , D_t	ISO 899-1	Cut from ISO 294-5	ISO 11403-1	Measurement of strain unspecified
E_s	Not available			
E' , E''	ISO 6721-4 or 5	Cut from ISO 294-3 or 5	T - as ISO 11403 $f = 0.05, 0.5, 5, 50$ Hz	Accuracy uncertain
G' , G''	ISO 6721-7	Cut from ISO 294-3 or 5	As above	
ν	ISO 527-2	ISO 3167		Measurement of lateral strain unspecified
ν_p				
σ_T	ISO 527-2	ISO 3167	ISO 11403-1	Strain rates to be identified
σ_{T1} , σ_{T2}	ISO 527-2	Cut from ISO 294-5	ISO 11403-1	Strain measurement unspecified. Strain rates to be identified.
σ_{S1} , σ_{S2}	Method available for composites			Probably low priority
λ	Shear or compression test			Probably low priority
σ_{uv} , ϵ_u	ISO 527-2	ISO 3167	ISO 11403-1	Strain rates to be identified
σ_{ulv} , σ_{uv} , ϵ_{ulv} , ϵ_{ut}	ISO 527-2	Cut from ISO 294-5	ISO 11403-1	
σ_c	ISO 6252		ISO 11403-3	
σ_{cl} , σ_{ct}	ISO 6252	Cut from ISO 294-5		
σ_f				

Table 7. Preferred test methods for the acquisition of data needed for design (incomplete)

Property	Test method	Test specimen	Recommended test conditions	Comments
Melt Viscosity	ISO 11443	Raw material	see 11403-2	How to measure the pressure dependence is not clear
Uniaxial Extensional Viscosity	Not available	Raw material	3 temperatures in the processing region	Strain rates and time to be defined
Biaxial Extensional Viscosity	Not available	Raw material	3 temperatures in the processing region	Strain rates and time to be defined
Melt Density		Injection molded specimen	Centre of processing temperature range	obtained from pVT data
pVT data	NWIP in preparation	Injection molded specimen	Isobaric cooling 2.5 °C/min 20, 40, 80, 120, 160 and 200 MPa and at 1 MPa by extrapolation	
Thermal Conductivity	NWIP in preparation	Raw material	Cooling from maximum recommended temperature to 23 °C	Transient line source method
Specific Heat	ISO 11357-4	Raw material	Cooling scan @ 10 °C/min	see 11403-2
Solidification Temperature				Needs further defining
Melting Temperature	ISO 11357-3	Raw material	Heating scan @ 10 °C/min	ISO 10350-1
Crystallisation Temperature	ISO 11357-3	Raw material	Cooling scan @ 10 °C/min	see 11403-2
Enthalpy of Fusion	ISO 11357-3	Raw material	Heating scan @ 10 °C/min	see 11403-2
Enthalpy of Crystallisation	ISO 12357-3	Raw material	Cooling scan @ 10 °C/min	see 11403-2
Crystallisation Kinetics	ISO 11357-5	Raw material	Isothermal runs at different cooling rates at crystallisation temperature	Other temperatures to be defined
Coefficient of Linear Thermal Expansion	ISO 11359-2	Central portion of ISO 3167 specimen	see 11403-2	
Flowability (thermosets)				

Property	Test method	Test specimen	Recommended test conditions	Comments
Cure Kinetics (thermosets)	ISO 11357-5	Uncured material	Isothermal runs at 3 temperatures in the processing range	
Isothermal Induction (Gel) Time	ISO 11357-5			
Polymer Density				
Heat of Reaction	ISO 11357-3	Uncured material	Heating scan @ 10 °C/min	
Gelation Conversion				Needs further defining
Moulding Shrinkage - thermoplastics	ISO 294-4	60 mm x 60 mm plate	1 mm and 2 mm thickness 20, 40, 60, 80 and 100 MPa	Melt temperature and mould temperature as defined in material standard
Moulding Shrinkage - thermosets	ISO 2577		1 mm and 2 mm thickness 20, 40, 60, 80 and 100 MPa	Resin temperature and mould temperature as defined in material standard
First Normal Stress Difference	Based on ISO 6721-10	Raw material	Same conditions as in ISO 11403-2	Test method needs to be developed

