CENTRE FOR WINDOW AND CLADDING TECHNOLOGY

The Performance of Gaskets in Window and Cladding Systems

A 'State of the Art' Review

Dr Richard Harris

Centre for Window and Cladding Technology 1996

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This research report was written by the Centre for Window and Cladding Technology (CWCT) as a review of current issues and technology relating to the design and performance of gaskets in window and cladding systems.

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1 INTRODUCTION

Gaskets are used to limit the passage of fluids though a joint. However, there are additional functions that a gasket performs, and a more complete list might be:

- control the passage of fluids (air and water) through the joint
- retain one component within another
- transmit forces across the joint
- allow relative movement of the joint surfaces
- accommodate variations due to manufacturing tolerances

Some of these properties are assessed by testing, although in an indirect manner. For example weather-tightness testing of a door or window necessarily tests the performance of the various gaskets, but cannot identify the contribution of each gasket other than by noting where leakage has occurred. Also, by applying a pressure difference across the component, either for weather-tightness testing or as part of a wind-loading assessment, it is possible to identify whether the gaskets perform properly under typical load conditions. However, although a wind-loading test may be both preceded and followed by air- and water-tightness tests (to check that components such as gaskets have not failed, or been caused to cease working by deformation of the mounting and contact surfaces), such tests are never carried out on components that have been in service for long periods of time, and the component and gasket designer have no information about long term joint performance.

This research report was prepared by the Centre for Window and Cladding Technology (CWCT) as a review of current issues and technology relating to the design and performance of gaskets in window and cladding systems. The CWCT has reviewed all aspects of gasket performance and use, and has undertaken formal interviews and informal discussions with gasket producers and users, a survey of existing literature, and a simple experimental study of the mechanical behaviour of some typical gaskets. This report is relevant to anyone involved in the design and specification of joints and gaskets.

1.1 Performance of gaskets in window and cladding systems

The original intention of the research project was to study the performance of gaskets from a 'materials and shapes' point of view - i.e. what are the best materials and shapes to use for gaskets. It soon became apparent however that the design, manufacture and installation processes, both for the gasket and the joint, are prone to the problems that occur as a lack of communication between the various parties involved in the processes - in particular the joint is often an interface between two components from different suppliers and the responsibility for the joint falls onto an unprepared third party. Improving the level of knowledge about gasket materials and shapes is therefore unlikely to have any impact unless the communication process is improved.

This report therefore examines all issues related to the performance, design and use of gaskets.

1.2 Scope

In the scope of construction systems a gasket can be defined as

"a pre-formed element used to seal a joint against the passage of water or air"

This definition is only intended to exclude those types of joint seal which are applied to the joint in a liquid state and allowed to cure or harden in the joint. Generally the gasket is manufactured from one (or several in some cases) of many different kinds of synthetic rubber or plastic, and the gasket is usually formed by a process of extrusion or moulding.

The term 'gasket' is actually very loose, and may be applied to any pre-formed joint-sealing element. However, some types of gasket are identified according to the function that they have. Thus, a 'glazing gasket' is used between a glazing frame and the glazing, the term 'weather-strip' applies to a gasket which is primarily intended to deter water from entering a joint, and the term 'draught-strip' is applied where the primary purpose is to limit the passage of air through a joint.

In this report where the term 'gasket' is used it refers to all types of pre-formed seal. Where the terms 'weather-strip' and 'draught-strip' are used it is generally to avoid confusion where there may be two or more seals in a joint.

The remainder of this report is divided into 6 chapters. Chapter 2 provides a glossary of the more general terms used in this report. Chapter 3 considers the joint, and examines how the performance of the joint can be improved before a seal is introduced. Chapter 4 looks at the engineering properties of gasket materials in comparison with other materials, and Chapter 5 examines the performance of gaskets themselves. Chapter 6 discusses issues relating to installation and replacement of gaskets, and Chapter 7 discusses communication issues.

2 GLOSSARY

The definitions below apply to this report, and most are in general use. Figures are used to illustrate the definitions where appropriate:

2.1 Joints

2.1.1 General terms

Figures 2.1.1(a) to (e) give examples of the following terms:

2.1.1.1 Joint

A joint is formed by the close proximity of the surfaces of two adjacent components. A joint generally passes from one exposed surface of the building facade to the other, although it might be defined as passing from one exposed surface to some significant cavity within the facade.

2.1.1.2 Fixed joint

A fixed joint is a permanent joint in which the seal will be broken only if one of the joint components (or the seal) needs to be replaced.

2.1.1.3 Opening joint

A joint is an opening joint if one or both of the components is fitted with hinges, rails or some other device which allows the component to be moved easily, thereby breaking the seal on a frequent basis.

2.1.1.4 Open joint

An open joint is one where the joint surfaces are permanently separated by a clear gap, without any form of added sealing device. However, an open joint may be shielded in some way or shaped to prevent direct passage of fluids through the joint.

2.1.1.5 Wet-sealed joint

A wet-sealed joint is one in which the sealing function is performed by a sealant applied in a liquid state and allowed to cure or harden in place.

2.1.1.6 Dry-sealed joint

A dry-sealed joint is one in which the sealing function is performed by some device, generally called a gasket, which is pre-formed and installed in a solid state. However, sealant tapes, in which a sealant is applied first to a removable substrate and later transferred to the joint as a strip of material, may be considered as gaskets, because the sealant is applied to the joint in a hardened form. Similarly a sealant-impregnated foam may be considered to be a gasket.

2.1.1.7 Self-sealed joint

A self-sealed joint is one in which the contact pressure between the joint surfaces is expected to cause sufficient deformation of the surfaces to create a seal. The joint between a glazing bead and a glazing frame is a typical self-sealed joint. In the absence of sufficient sealing pressure it may be necessary to introduce a seal (usually a wet-applied small joint sealant) - an example is the joint between a glazing frame and a sub-sill.

2.1.1.8 Mounting surface

The mounting surface is any surface of the joint onto which a seal is retained, typically by means of a mechanical fixing, a push-fit or an adhesive system. In some cases both surfaces of a joint might be mounting surfaces if two components are intended not to be separated - an example is the double-adhesive-backed security glazing tape sometimes used to fix a glazing unit into a window frame.

2.1.1.9 Contact surface

The contact surface is any surface of the joint with which a seal makes contact but does not adhere.

2.1.1.10 Rain-screen

A rain-screen is a device used to discourage water from entering a joint by shielding the entrance to the joint.

2.1.1.11 Baffle

A baffle is a device used within a joint to prevent the direct passage of water through the joint. The baffled joint has gaps which allow the movement of air through the joint but intercept any drops of water which enter the joint.

2.1.1.12 Drip

A drip is a feature, usually a step or a recess, intended to separate a flow of water from a surface. A drip is usually used on the underside of an overhanging component to prevent water from running into an otherwise sheltered joint.

2.2 Gaskets

2.2.1 General terms

Figure 2.2.1 illustrates the following terms:

2.2.1.1 Gasket

A gasket is any pre-formed seal, principally intended to seal a joint against the passage of air, water or both.

2.2.1.2 *Weather-strip*

A weather-strip is a seal whose primary function is to prevent water from entering a joint. The weather-strip is often visible on the exposed side of the joint and may be intended to act as a rain-screen, rather than eliminate all water penetration into the joint.

2.2.1.3 *Draught-strip*

A draught-strip is a seal whose primary function is to prevent the passage of air through the joint.

2.2.1.4 *Glazing gasket*

A glazing gasket is a gasket that is used in a fixed joint between a glazing frame and the glazing. The term infill gasket may also be used, where panels other than glazing are involved.

2.2.1.5 *Picture-frame or frame gasket*

A picture-frame gasket or frame gasket is a continuous gasket with integral corners (formed either by welding or injection moulding) which is used around the perimeter of sealed-in glazing or infill panels.

2.2.1.6 *Ladder gasket*

A ladder gasket is a continuous gasket which has the appearance of a ladder, used where several panels are to be sealed in place in a continuous run.

2.2.2 Gasket shapes

Examples of the following terms are shown in Figure 2.2.2:

2.2.2.1 *Profile*

The profile is the shape of the gasket, in cross-section.

2.2.2.2 *Push-in gasket*

A push-in gasket is designed to be fitted into a groove in the mounting surface, prior to the formation of the joint. It should be possible to remove a push-in gasket by pulling it from the groove.

2.2.2.3 *Slide-in gasket*

A slide-in gasket is designed to slide into a groove on the mounting surface, but must be installed from the end of the groove. A slide-in gasket can usually only be removed by sliding it out from the end of the groove.

2.2.2.4 *Drive-in or wedge gasket*

A drive-in or wedge gasket is designed to be forced into the gap between the mounting surface and contact surface, usually as the last stage in sealing the joint. A drive-in gasket can usually be removed by pulling it from the joint, although it may be manufactured with a rigid strip which makes this difficult.

2.2.2.5 *Channel gasket*

A channel gasket wraps around the edge of a component, usually an infill panel or glazing unit, which then pushes into a channel in another component. A channel gasket cannot be replaced without disassembling the joint.

2.2.2.6 *Lock-strip gasket*

A lock-strip gasket has a removable strip which allows the gasket to be opened up for installation, the strip being replaced to lock the gasket into place.

2.2.2.7 *Fir-tree or E-gasket*

A fir-tree or E-gasket has a number of protruding arms which meet the contact surface at an angle and accommodate movement by deflection of the arms (working as a cantilever). The profile of such a gasket looks like a letter 'E', or resembles the branches of a fir-tree. The number of contact arms is variable, and the arms do not all need to point in the same direction, nor do they need to be of the same length. Double-sided fir-tree gaskets may be used to seal joints between cladding panels.

2.2.2.8 *Crescent gasket*

A crescent gasket has a crescent-shaped profile. Wedge gaskets are predominately of this shape, although wedge gaskets may also have a fir-tree profile. Wedge gaskets are usually used for the retention of glazing or infill components.

2.2.2.9 *Flipper or V-gasket*

A flipper gasket has a single angled contact arm, which works as a cantilever. This type of gasket is usually used for draught-stripping or weather-stripping.

2.2.2.10 *Tubular O- and P-gaskets*

A tubular gasket works by compression of a thin-walled tube. The tube need not have a regular shape. These gaskets are generally used as weather-stripping. The tube may be filled with a flexible foam material, and may have protrusions to stabilise the compression behaviour of the tube so that it does not deflect to one side.

2.2.2.11 *Sheathed gasket*

A sheathed gasket has a core of one material, usually a foam, coated with an outer layer of some more durable material. A strip of rigid material may be included in the gasket foot to give a more positive retention in the mounting surface. This type of gasket is used for draught-stripping or weather-stripping.

2.2.2.12 *Pile or brush gasket*

A pile or brush gasket has a large number of durable fibres set into a rigid base. This type of gasket usually has a flexible plastic strip or strips running along the length of the gasket between the fibres to provide an air-seal. Pile gaskets are commonly used in sliding joints to provide a draught-stripping function with low sliding friction.

2.2.2.13 *Anti-stretch device*

An anti-stretch device (either a strip of some plastic material or a non-elastic cable running through the gasket) may be incorporated in a gasket to prevent the gasket from being stretched during installation. The device may be a coloured rigid strip running along a gasket which also identifies the gasket size, protects the gasket from abrasion during installation and discourages removal of the gasket.

2.2.2.14 *Tear-off strip*

The tear-off strip is a part of the gasket which can be removed to change the size of joint gap into which the gasket will fit. This device is often used on wedge gaskets, and removal of the tear-off strip allows the gasket to be forced into a narrower joint.

2.2.2.15 *Foot, dart or arrowhead*

The foot is a part of the gasket which is shaped to fit into a slot on the mounting surface. The foot may also be called a dart or an arrowhead, which relate to its shape.

2.2.2.16 *Race*

The race is the groove on the mounting surface into which a gasket foot is located.

2.2.2.17 *Locating groove*

The locating groove is found on the back of wedge gaskets, and is designed to fit over a nib or protrusion on the mounting surface.

2.2.2.18 *Nib*

The nib is a protrusion on the mounting surface which presses into the groove on the back of a wedge gasket.

2.2.3 Gasket materials

Polymer science is a major discipline in its own right, and the following definitions are very simplistic. The reader should be aware that distinctions between different materials are often blurred by the infinite variety of compounds, blends and alloys that are possible, and that it is rarely possible to define the behaviour of a given material in simple terms.

2.2.3.1 Polymer

A polymer is a high molecular weight compound made by joining together low molecular weight building blocks called monomers. Several different monomers may be combined to form a single polymer, and the monomers may be connected in linear chains or branched chains, and in an ordered or random pattern. Each polymer chain may contain several thousand monomer units, and different polymers may be alloyed together and/or further processed to produce a synthetic rubber.

2.2.3.2 Rubber or Elastomer

A rubber or elastomer is a polymer material existing in a highly elastic state. Generally to be called a rubber or elastomer a material should be capable of being stretched rapidly to high extensions and then snap back to its original shape and size when released (i.e. it should retain elastic behaviour at very high strains, often 500% or more). Note that a polymer may only appear to be rubbery or elastomeric in a particular range of temperature or blend, and that the behaviour may not be perfectly elastic and may be time-dependent.

2.2.3.3 Thermoset elastomer

In a thermoset elastomer the molecular structure of the processed polymer is fixed and cannot be reprocessed even if heat and pressure are applied. Such materials cannot be recycled.

2.2.3.4 Vulcanisation

The term vulcanisation is applied to the process by which the individual chains in a polymer mass are caused to form atomic bonds (usually called cross-links) which join the chains together. A thermoset elastomer generally contains such cross-links. A number of processes may be used to initiate vulcanisation, including the application of heat, pressure or radiation, often with special chemicals added to encourage vulcanisation to occur.

2.2.3.5 Thermoplastic elastomer

In a thermoplastic elastomer re-processing can occur with the application of sufficient heat and pressure. A thermoplastic elastomer usually has a molecular structure in which regions of flexible material (which exhibit rubber-like behaviour) are interspersed by regions of glassy material (which act as cross-links). The regions of rubber-like and glass-like material may be parts of the same polymer chain.

2.2.3.6 Cellular rubbers

Cellular rubbers have gas-filled pockets within the material which are formed during the production process. The cells may not be of uniform size and shape, and are not necessarily air-filled.

2.2.3.7 Closed-cell rubbers

A closed-cell rubber is a cellular material in which the gas-filled pockets are separate from one another. Closed-cell rubbers are generally air- and water-tight.

2.2.3.8 Open-cell rubbers

An open-cell rubber is a cellular material in which adjacent cells open onto one-another. Such rubbers are not air-tight, and may absorb water unless treated with suitable water-repellent chemicals.

2.2.4 Manufacturing and installation processes

2.2.4.1 Extrusion

Extrusion is a process by which materials are forced, at high temperature and pressure, through a die at a steady rate. The result is a continuous length of material with a uniform cross-section. However, the profile of a rubber extrusion may differ from the profile of the die as a result of material expansion (die swell) in the short interval between extrusion and cooling of the rubber.

2.2.4.2 Shot moulding and injection moulding

Shot moulding and injection moulding are names given to the process by which an amount of molten material is forced, under high pressure, into a mould. This process may be used to form complex joins between two lengths of pre-extruded gasket. In shot moulding a measured amount of material (the shot) is added to the injector and then forced into the mould; in injection moulding a continuous reservoir of molten material is used.

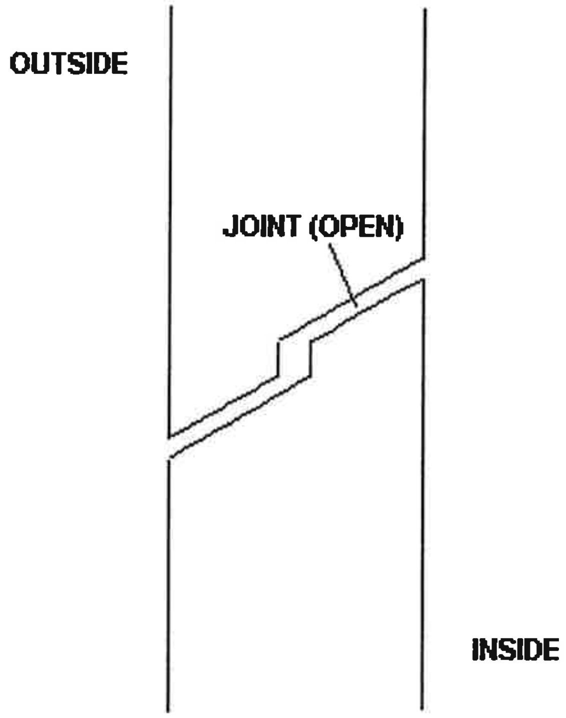
2.2.4.3 Co-extrusion

Co-extrusion is a process by which two or more materials are extruded together. This process may be used to extrude a thermoplastic gasket directly onto a PVC-U glazing bead, to extrude two different blends of the same polymer together, to extrude two different colours of material together, or to extrude a polymer material onto some other type of material.

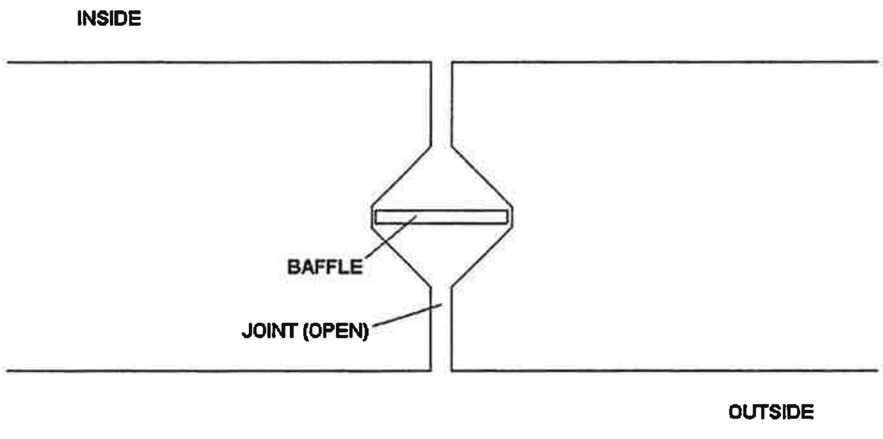
2.3 Closure

The list of terms given above is not intended to be exhaustive, but should include the more significant terms. Additional terms may be introduced in the remainder of this document, and they will be explained where appropriate.

Figure 2.1.1 **Examples of glossary terms relating to joints in general**

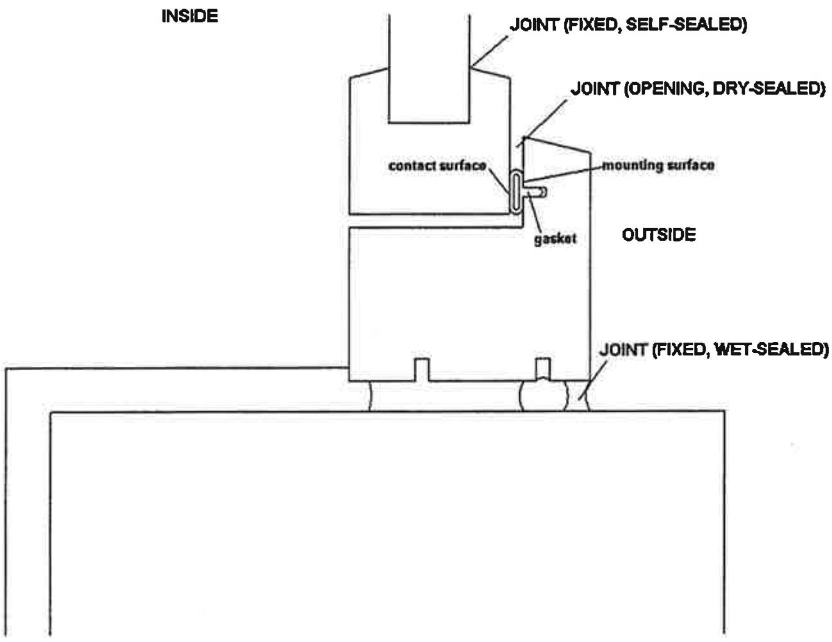


a) a vertical section (elevation) through pre-cast concrete cladding panels

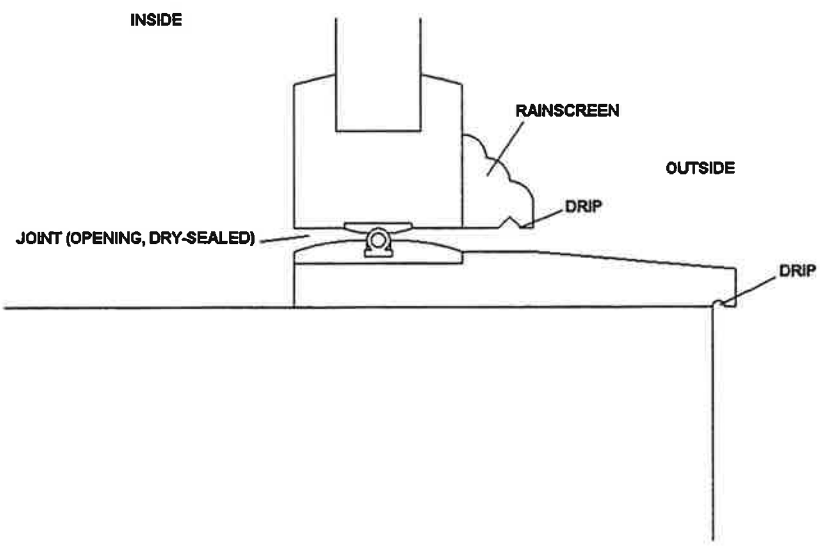


b) a horizontal section (plan) through pre-cast concrete cladding panels

Figure 2.1.1 **Examples of glossary terms relating to joints in general**

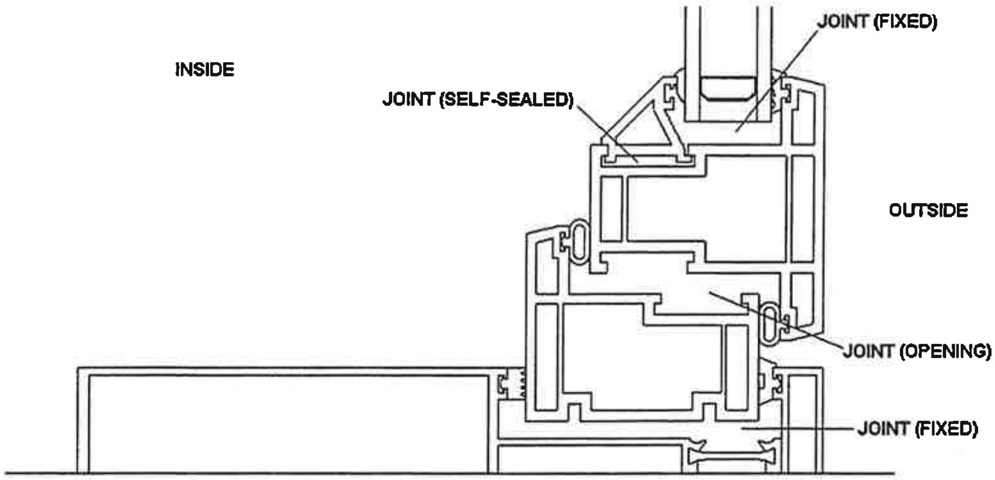


c) a horizontal section (plan) through a door jamb (inward opening)



d) a vertical section (elevation) through a door sill

Figure 2.1.1 Examples of glossary terms relating to joints in general



e) a horizontal section (plan) through a curtain walling frame (mullion with glazed-in outward-opening PVC-U window)

Figure 2.2.1 Examples of glossary terms relating to gaskets in general

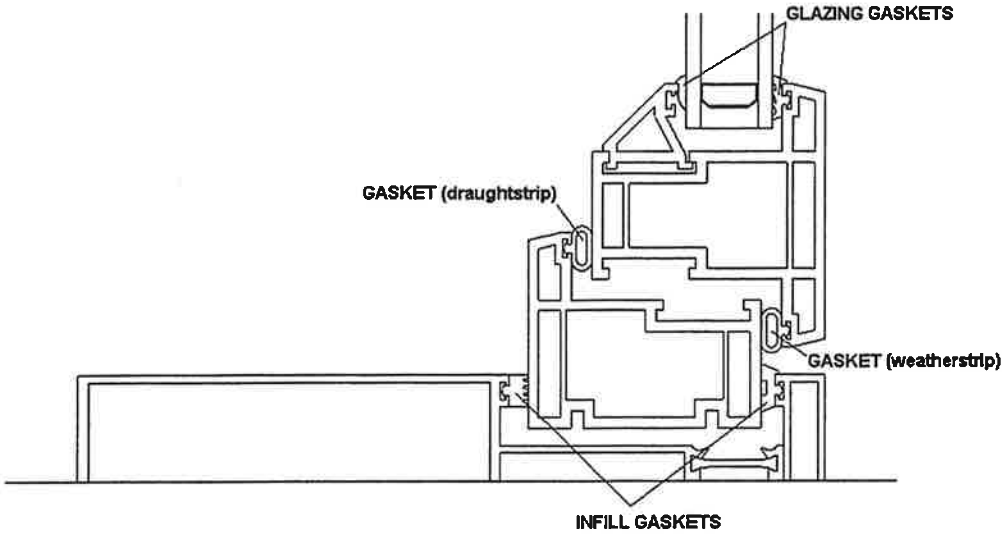
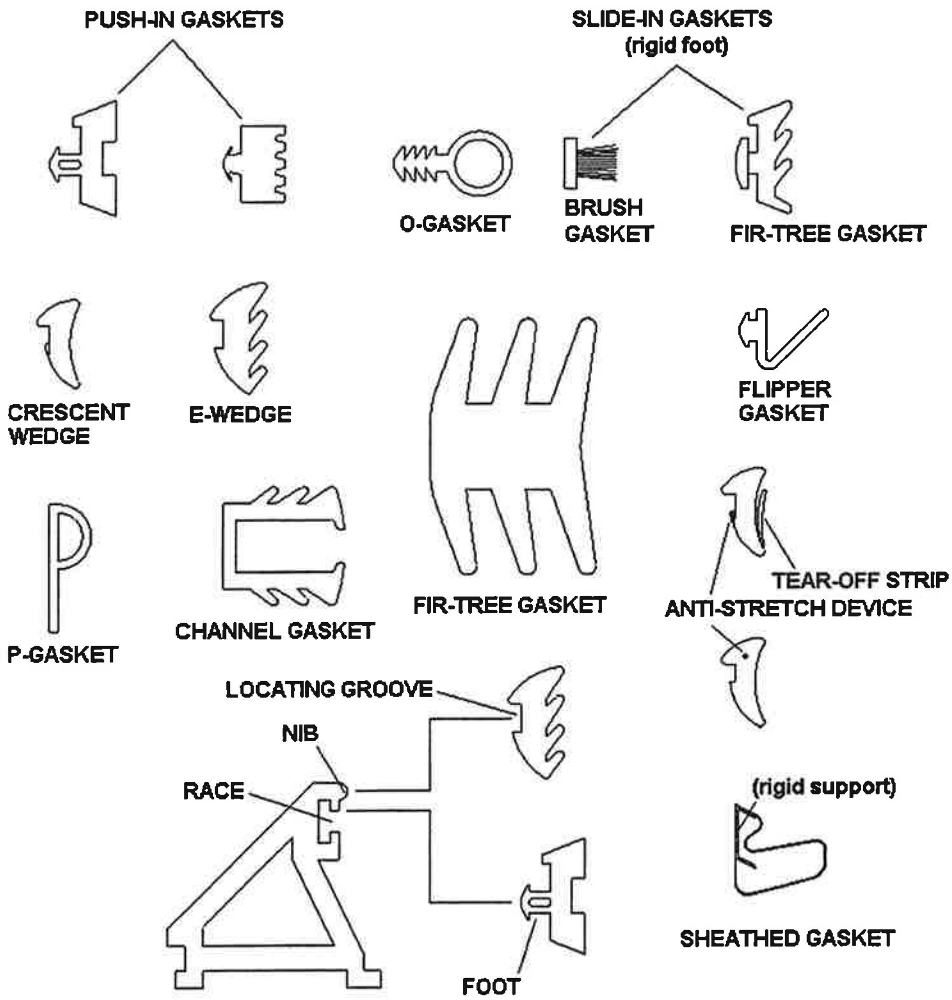


Figure 2.2.2 Examples of glossary terms relating to gasket shapes



3 THE JOINT (and the physics of fluid flow)

The act of producing a building facade comprises the design and selection of a large number of dissimilar components which must then be joined together through a large variety of different interfaces to form a whole which (if it has been done properly) performs to the design specification. However, the performance of the whole is not so much a sum of the parts, but rather a product of the holes between the parts, and the performance of the facade is often only as good as the weakest interface. The sealed joint is one of the most difficult interfaces to get right.

3.1 The need for a gasket

An important question, and yet one that is not always asked, is:

"do I need a gasket?"

Although this might seem like an unusual question there is often an impulse to put some kind of seal into every joint, on the basis that a joint with a seal must be better than a joint without a seal. However, the designer should also ask the questions:

"will the seal improve the joint performance?"

"will the chosen type of seal be the most cost-effective?"

"what will happen when the seal fails?"

When failure of a joint seal occurs then there are three further points to consider:

"which fluids can pass through the joint (air or water) and how will they affect the performance and durability of other components?"

"will the failure reduce the performance of the jointed system in any other way?"

and

"how easily can the seal be replaced?"

These points are very important, particularly the issue of what will happen when the seal fails - seals in an exposed position may have an arduous life, and if they were required in the first place they clearly must be replaced if they start to show signs of failure. Types of seal which can be readily replaced are obviously preferable, particularly where there are health and safety issues related to the need to gain access to the failed seal and replace it.

The optimum joint design must be one in which the number of seals is minimised and the seals are of a type that can be easily repaired or replaced. This chapter discusses joints and the physics of air and water movement through joints, and identifies the ways in which joints can be designed to reduce the need for additional sealing.

3.2 Joint leakage

Air and water leakage through a joint in a facade may lead to several problems, ranging from occupant discomfort in draughts, to damage to property by contact with water, or even damage to structural elements of the building envelope. The diffusion of water vapour through a joint may be a significant benefit in terms of reducing the risk of condensation within the facade, or may be a significant factor in causing condensation within the facade, depending on where the joint is.

The main issues are:

3.2.1 Air leakage

Although some air movement is required through the facade, for ventilation purposes, a modern view is that the air movement should be controlled. Uncontrolled air 'leakage' is generally the result of poor joint design, and may cause discomfort, result in poor energy efficiency, and lead to a failure of performance in pressure-moderated or pressure-equalised systems.

3.2.1.1 Discomfort

The presence of significant air movements may lead to occupier discomfort in two ways - either the occupier of a room is in the direct line of the moving air and feels cold as a result (the draught air is generally below body temperature even without allowing for 'wind chill'), or some other lightweight item is in the direct path of the air jet and moves as a result (papers blowing off a desk, curtains billowing over a window or slatted blinds vibrating). The joint and gasket designers should aim to eliminate jets of air moving through a joint.

Draughts are discussed in CIRIA SP87A (1992), which gives a simple chart relating acceptable air velocity (in terms of occupant comfort) to air temperature. The acceptable velocity ranges from about 0.1 m/s for air at 17°C, to about 0.5 m/s for air at 30°C. For the laminar flow of air through a uniform gap between two parallel plane surfaces the mean air velocity is related to the pressure differential across the joint by

$$v = \frac{t^2}{12\mu}\frac{\Delta p}{l}$$

- v is the mean velocity, in m/s
- t is the width of the gap between the surfaces, in m
- μ is the dynamic viscosity of the air, (about 1.8×10^{-5} Ns/m^2)
- Δp is the air pressure differential across the joint, in Pa
- l is the length of the joint, in m

For a gap 0.1 mm wide and 50 mm long a mean air velocity of 0.1 m/s only requires a pressure difference of 108 Pa. This is the static pressure difference that will occur if a wind of 13 m/s blows against the outside surface of the building. Although this wind velocity may appear to be high it is classed on the Beaufort scale as a fresh to strong breeze. A larger joint width will obviously give a higher air velocity for the same pressure differential.

It should be noted that the air flow-rate through a 1 metre length of this joint is

$$Q = Av = 10^{-5} \quad \text{m}^3\text{/s}$$

or

$$q = 3600Av = 0.036 \quad \text{m}^3\text{/h per metre of joint}$$

The requirements of BS 6375 Part 1 (1989) state that for a 108 Pa pressure differential the acceptable rate of air leakage through a window with an opening light is 2.1 m^3/h per metre of opening joint - significantly greater than for the example above.

3.2.1.2 Energy efficiency

Regardless of the direction of air movement through the facade there is a loss of energy from the building because either the air entering the building has to be conditioned to the interior conditions, or the air leaving the building has already been conditioned. If the flow-rate of air passing through the facade is known then the rate of energy loss due to mass transfer is at least

$$E = \rho C_P Q(T_i - T_e)$$

- E is the rate of energy loss, in W
- ρ is the air density, (about 1.23 kg/m^3)
- C_P is the air specific heat capacity, (about 1008 J/kgK)
- Q is the air leakage flow-rate, in m^3/s
- T_i is the interior air temperature, in °C
- T_e is the exterior air temperature, in °C

This equation determines the change in the internal energy of the air as a result of the temperature change. Since the heating or cooling plant is unlikely to be 100% efficient there will be an additional amount of energy required to condition the interior air, and the value given by the formula above should be divided by the overall efficiency of the heating or cooling process to determine the true energy penalty due to air leakage.

Now consider typical figures for air leakage through weather-strips. As stated above BS 6375 Part 1 (1989) allows a leakage of 2.1 m^3/h per metre of opening joint for a window with an opening light, at the 108 Pa pressure differential calculated in 3.2.1.1. If the air temperature inside the building is 20°C and the air temperature outside the building is 0°C then the rate of energy loss per metre of joint is at least

$$E = 1.23 \times 1008 \times \frac{2.1}{3600} \times 20 = 14.5 \text{ W}$$

For a casement window 900 mm wide by 1250 mm high the estimated total joint length is 4 m, which gives a total rate of energy loss of 58 Watts. If the window is a typical unit with low-emissivity glazing its overall U-value will generally be less than 2.5 W/m^{2}K (CWCT, 1995) and the rate of energy loss by heat transfer is

$$E = UA(T_i - T_e)$$

- U is the overall U-value of the window, in W/m^{2}K
- A is the overall projected area of the window, in m^2

which gives

$$E = 2.5 \times (0.9 \times 1.25) \times 20 = 56.3 \qquad \text{W}$$

The rate of energy loss by air leakage (58 W) is greater than the normal heat transfer through the window (56.3W), even without allowing for inefficiencies in the heating system.

Further energy losses occur if the moisture content of the air entering and leaving the building is different. The energy required to change the moisture content of a given flow-rate of air is

$$E = \rho h_{fg} Q(g_i - g_e)$$

- E is the energy required, in W
- ρ is the air density, (about 1.23 kg/m^3)

- h_{fg} is the latent heat of evaporation of water, (about 2450×10^3 J/kg)
- Q is the air leakage flow-rate, in m^3/s
- g_i is the interior air moisture content, in kg of water per kg of dry air
- g_e is the exterior air moisture content, in kg of water per kg of dry air

Again there may be some inefficiency associated with the conditioning process and the value given by the formula above must be divided by the overall efficiency of the humidification/de-humidification process to determine the true energy penalty.

As an example, considering the window described above, if the room air is at 40% relative humidity (at 20°C this gives $g_i=0.0058$ kg/kg) and the outside air is at 90% relative humidity (at 0°C this gives $g_e=0.0034$ kg/kg) then the energy loss per metre of joint is

$$E = 1.23 \times 2450000 \times \frac{2.1}{3600} \times (0.0058 - 0.0034) = 4.2 \ \ \text{W}$$

The rate of energy loss due to changes in moisture content is about 25% of the rate of energy loss due to changes in the air temperature alone.

It is apparent that the energy efficiency of a building will be greatly reduced if the leakage air flow-rate Q is not controlled. However, an air-tight building must have some ventilation if the occupants are to be comfortable (ventilation also helps to reduce the risk of condensation and is now a requirement of the Building Regulations Approved Document F (1995)). This apparent conflict of interest in requiring that leakage must be stopped and ventilation then introduced is not a problem if it is remembered that the aim is to provide sufficient ventilation - not a surfeit. Issues of air-tightness are also important if the building facade is in some way pressure moderated or pressure equalised:

3.2.1.3 'Pressure moderation' and 'pressure equalisation'

In some types of facade it is desirable for cavities within the facade to be opened (vented) to the exterior. The reasons for this venting may be to provide drainage routes out of the cavity for liquid water or water vapour (these are discussed in 3.2.2 and 3.2.3) or to enable the cavity air pressure to respond to (and hopefully equal) fluctuations in the exterior air pressure. This pressure moderation (which should be called pressure equalisation only if the cavity air pressure follows the exterior pressure closely) is intended to reduce the pressure difference across the opening(s) between the cavity and the exterior, thereby reducing the risk of water passing through the opening(s) as a result of an air pressure differential.

The degree of pressure moderation that can be achieved depends on two key factors - the size of the opening(s) between the cavity and the exterior, and the air-tightness of the other surfaces around the cavity:

The pressure in an air-filled cavity with a number of openings is governed by the relationship

$$\frac{V}{p}\frac{dp}{dt} = \Sigma Q$$

- V is the cavity air volume, in m^3
- p is the cavity air absolute pressure, in Pa
- t is time, in s
- Q is the air flow-rate through each cavity opening, in m^3/s

This relationship assumes that the pressure fluctuations occur isothermally (i.e. rapidly enough that the cavity air temperature does not change as a result).

For each cavity opening the air flow-rate is given by

$$Q = Av = \frac{At^2}{12\mu}\frac{\Delta p}{l}$$

for laminar flow through a uniform crack, or

$$Q = C_Q A\sqrt{\frac{2(\Delta p)}{\rho}}$$

for flow through a short opening.

- t is the width of the crack, in m
- A is the area of the crack or opening, in m^2
- μ is the air dynamic viscosity, in Ns/m^2
- Δp is the pressure difference across the crack or opening, in Pa
- l is the length of the crack, in m
- C_Q is the flow coefficient of the opening, (typically 0.6 for a square-edged opening)
- ρ is the air density, (about 1.23 kg/m^3)

It should be noted that for a product in which the normal air leakage comprises laminar flow through cracks in parallel with turbulent flow through other openings a more general relationship is used for air leakage, which is of the form

$$Q = K(\Delta p)^n$$

This relationship is assumed in BS 6375 Part 1 (1989) for windows with opening lights, where the index n is taken as 2/3.

A large opening (large A) between the outside air and the cavity air will give the best pressure moderation (perhaps pressure equalisation) if the cavity air volume V is small - the large opening means that a small pressure difference forces a large flow of air into the volume, and the small volume means that the cavity pressure will change most rapidly. For a large cavity with a small opening there is a requirement for the pressure difference across the opening to be large in order to force sufficient air into the cavity to change the cavity pressure, with the result that the cavity pressure does not closely follow the external pressure.

However, if there are significant leakage flow-paths from the cavity (into the building or into adjacent cavities, which is particularly significant near the corners of the building) then these will limit the rate at which the cavity pressure can change and so will reduce the degree of pressure equalisation. If the cavity surface includes a joint gasket at any point then that gasket must retain its integrity for the pressure moderation to be successful. It is for this reason that the CWCT (1993) requires interior gaskets on curtain wall systems to be formed as a single continuous piece (a frame gasket). Gaskets are clearly important if pressure moderated systems are to function properly.

The need for air-tightness in joints is emphasised by Perera, Turner and Scivyer (1994). Their report notes that air movement through the building envelope should be controlled, and that the elimination of draughts also improves occupant comfort. Significant guidance is given for reducing air infiltration, and the need for proper detailing at corners and connections is emphasised - the joining together of gaskets is often critical.

Air leakage through gaskets has been studied by Bassett and Beckert (1990) who examined several types of draught-strip. It is noted that New Zealand building codes allow for three levels of window air leakage, based on the air leakage per metre length of joint (tests can be performed at 50 or 150 Pa overall pressure difference and the acceptable performance is different for each) or air leakage per m^2 of window (at 150 Pa). Level 8 (the intermediate level) allows for 8 l/s of leakage per 1 m^2 of window at 150 Pa, or 2 l/s of leakage per 1 m of opening joint at 150 Pa or 1 l/s of leakage per 1 m of opening joint at 50 Pa. It is suggested that this level is relevant to draught-stripped domestic windows. To test these performance criteria several draught-strips were tested to determine compression force and air leakage at different degrees of opening (with a 50 Pa pressure difference). It was noted that the relationship between compression and force was a variable function of seal type, and that correct selection of the seal for a particular joint was paramount. It is suggested that a folded V-strip type of seal was least affected by variations in the joint width, giving a moderate operating force and low air leakage over a wide range of compression. Bassett and Beckert also provide a useful table of the ageing characteristics of draught-strip materials, identifying factors which limit life expectancy, and giving life expectancies in the ranges of "less than 2 years", "2 to 7 years" and "above 7 years", suggesting that if satisfactory performance is to be retained then the seals must be replaced.

A similar study (although more detailed) has been carried out by Höglund and Wånggren (1980). It was found that the method of mounting could affect the air-tightness for weather-strips that were mounted by means of a rubber flat stapled to a timber frame. It was also found that tubular weather-strips gave the best air-tightness (when compared on a common window) although it does not appear that the seal compression was controlled to give the same operating forces, which must have some influence on the results. Again V-strips are seen to have a good range of acceptable operation, but it is noted that any seal that is initially thicker will have a wider range of compression for which good performance is obtained (and can therefore accommodate a wider range of tolerances). Finally it is noted that parameters such as the wall-thickness of tubular seals depend on the required balance between sealing effectiveness and closing force. It is noticeable that this study accepts 25 N as an acceptable closing force for a door (based on requirements for disabled people) whereas the New Zealand study allowed a force of 50 N per metre of draught-strip (the closing force would then be at least 100 N for a typical door 2 m high).

3.2.1.4 Relationship between air-tightness and closing force

The results of Höglund and Wånggren (1980) and those of Bassett and Beckert (1990) make the link between the closing force of a window or door and the air leakage past the draught-strips - as the draught-strip is compressed further so the closing force increases but the air leakage goes down. An important study, but one which does not appear to have been done, is to compare the effectiveness of two seals in series against a joint with a single seal - the single seal will have less closing force and so can be compressed further than two seals together, and this may actually result in less air leakage through the single seal than through the double seal.

It is also useful to consider the effect of installation methods, as the folding of a seal around a corner can prevent the seal from making a proper contact with the joint surfaces - many studies of the air-tightness of draught-strips only consider a linear portion of the seal. Beech and Saunders (1983) however assessed gaskets in three different configurations, two of which included joins. The first arrangement used a length of gasket formed into a circle, with the ends bonded together with a neoprene adhesive; in the second configuration the gasket was formed into a square, and in the third arrangement a straight length of gasket was used with the ends cast into blocks of sealant. In each test both joint surfaces were of the same material, being steel for one set of tests and mortar for another. The gaskets were more air-tight when compressed more, and less air-tight with mortar joint surfaces than with steel joint surfaces. Air-leakage rates were found to be higher for a square mitre-joined assembly than for a straight section of gasket, and even higher for a square section with joins formed by lapping the gasket ends. The joins between strips of gasket are clearly significant, which has obvious implications for the installation of the gasket. It is also noted in the report by Beech and Saunders that the air leakage experienced for installed gaskets was higher than measured in the laboratory, and this too was attributed to joining (joining in the laboratory is always likely to be better controlled than on site).

BS 7386 (1990) defines a number of tests for the performance of draught-strips, including a test for the air leakage through the draught-strip. However, it is unusual to see the results of such a test reported in trade literature.

Canadian standard CAN/CSGB-51.90 (1992) also identifies a number of test methods for the performance of weather-stripping. Test method 5 relates weather-strip performance to the minimum deflection required to give an air leakage of 1.8 m^3/hour per metre of seal at 75 Pa pressure difference. The test is performed on a straight piece of the seal at a temperature of –20°C (this ensures that the seal performs under the worst weather conditions) and the results are then normalised to a temperature of 15°C. Test methods 3 and 4 measure the force-compression (force-deflection for wiper seals) characteristics of seals, using a counter-balanced apparatus similar to that shown in Figure 5.1.1, and set a maximum deflection based on a force per unit length equivalent to 5 kg per metre (49 N/m), which is a value obtained by consensus as giving a reasonable closing force - the test is again performed at –20°C. The results of tests 3, 4 and 5 are then combined, in method 6, to determine the range of deflections over which the seal functions properly. Test method 7 identifies an accelerated ageing procedure which combines high temperatures and ultraviolet light with exposure to condensation. Methods 8 and 9 relate to tests on the aged product, and methods 10 and 11 deal with tests for impact and cycling resistance of door weather-strips.

AAMA 701.2 (1974) defines various tests for the properties of pile weather-strip, although with slightly different test parameters from the Canadian standard, and examines the air leakage through a length of weather-strip when compressed to 80%, 70%, 60% and then 50% of the nominal thickness. However, with pile weather-strips the issue of closing force is not usually relevant.

DD 171 (1987) gives recommended levels for operating forces for doors. The highest recommended force required to open a door with a lever handle is 70 N, which does not give much scope for the use of hard rubber weather-stripping. It should also be noted that external doors made of materials such as timber may experience significant moisture movement, and seals which work on a wiping action may become tighter as the timber swells, prevent the door from being opened properly. Seals which become harder as they age may also cause problems, and BS 4255:Part 1 (1986) includes a test for the increase (or decrease) in hardness of a rubber material as a result of ageing.

3.2.2 Water leakage

Water leakage through a joint may occur by several different mechanisms. These are:

- Gravity flow
- Pressure flow
- Kinetic flow
- Surface tension effects
- Pumped flow
- Air-supported droplets

3.2.2.1 Gravity flow

Gravity flow is where a drop of water moves under the influence of its own weight. The physics of gravity flow demand that there is sufficient weight to overcome surface tension forces. Gravity flows can be discouraged by providing steps and upward slopes in the path of the flow, although care should be taken not to create regions where water can collect.

3.2.2.2 Pressure flow

Pressure flows occur as the result of a pressure difference across a body of water - it is usually necessary that the water form a continuous film across the joint, otherwise a sufficient air pressure differential cannot be generated to move the water. Pressure flows can be discouraged by preventing a continuous film of water from forming, and this requires that the joint is sufficiently wide that any film of water collapses under its own weight. However, if water cascades over the joint opening then a continuous film may be generated and blown into the joint by air pressure fluctuations. This can be discouraged by distancing the stream of water from the joint opening with a suitable overhang (a rain-screen with a drip).

3.2.2.3 *Kinetic flow*

Kinetic flows occur if water droplets approach the joint at a sufficiently high speed that they are carried through the joint by their own momentum. Suitable arrangements of baffles, preventing a direct passage through the joint, or a rain-screen with a drip, preventing access to the joint opening, will stop kinetic flows.

3.2.2.4 *Surface tension effects*

Water is attracted to surfaces by its surface tension. This allows a droplet of water to run along a horizontal surface, unless some step is provided in the path of the water to encourage the water to separate from the surface. A 'drip' is often used on the edge of any overhanging feature to prevent water from running back along the underside of the overhang.

Capillary flow may occur due to surface tension, but this requires a narrow joint, so that the mass of water is sufficiently small that it can move under the influence of the (low) surface tension force. If the joint is wide enough to prevent the formation of a continuous liquid film then capillary flow cannot occur. Where a film of water does occur then pressure flow may occur.

3.2.2.5 *Pumped flow*

Pumped flow occurs if a film of water is trapped between two surfaces which undergo a relative motion. Pumping is prevented if the film of water cannot form in the first place. Again the joint should be sufficiently wide that a film of water cannot form.

3.2.2.6 *Air-supported droplets*

A fast moving flow of air may carry droplets of water through a joint (this is different to kinetic flow in that the droplets may be very small and possess little momentum). This phenomenon can be prevented by slowing the air, such that the water droplets fall under gravity and can be drained away, or by stopping the flow of air by using some form of draught-strip. Alternatively the joint can be shaped such that the droplets impinge on some convenient surface from where they can be drained.

3.2.2.7 *Summary of water movement through joints*

Most water movement through a joint can be minimised by sensible joint design. The use of rain-screens, baffles, steps, drips and wide joints can limit the available mechanisms for water transport through an opening. However, the issue of air-borne water droplets passing through a joint does require that the air flow through the joint is either stopped or slowed. This may necessitate the use of a draught-strip within the joint, and this draught-strip can be placed at any position within the joint.

Herbert and Harrison (1974) examined a number of open joints with differing degrees of baffling within the joints. It was found that overlapping baffles were sufficient to prevent water penetration, and that directing water droplets into regions of low air velocity was a successful strategy for draining the water out of the joint. An important finding of this study was that there is a critical air velocity through an open joint, above which water droplets are entrained into the air flow and carried through the joint. A value of about 5 m/s at the joint opening was suggested for this critical velocity. However, water could be forced through the joint at lower velocities if a 'plug' of water formed across the opening of the joint. It is recommended by Herbert and Harrison that the joint opening should not narrow too rapidly, and that the smallest gap within a joint should be at the back of the joint, presumably to minimise air velocities near the entrance of the joint. Guidance is also given on the design of joints which rely on an overlap (a step in the joint) to reduce water penetration.

Bassett, Bishop and Brown (1991) give very good case studies of water penetration through joints, and remedial actions that were required to correct the problem. The study is a good demonstration of how easily water will find weaknesses in constructions, particularly if there is an air pressure difference encouraging water flow. The need for proper detailing at corners and junctions of seals is also emphasised.

Finally, Beech and Saunders (1983) note that water leakage through joints formed in a test building did not relate to the air leakage through the same gasket. It was stated that the water leakage depended on the 'microclimate' near the joint, and on the interaction with air-flows around the joint. Remarkably, the gasket which gave the highest levels of air infiltration gave the lowest level of water leakage, apparently because the shape of the gasket included a large chamber which drained water away and prevented the generation of a sufficient pressure difference to force the water past the last line of defence - the gasket was pressure moderated!

3.2.2.8 The need for drainage

It should be noted that any cavity within a facade may become filled with water, and so all cavities should either be linked and drained to the exterior, or drained individually. Joints around the cavity should all be carefully sealed, particularly if the cavity is intended to be pressure moderated, but care must be taken not to impede drainage routes. Components such as aluminium window frames may also be at risk from water entering joins in the frame, unless those joins are sealed and protected from distortions that would open up the join. PVC-U window frames may also be at risk from water penetration if welded corner joins fail - note that water can pass through the smallest gaps by capillary action, often wind-assisted. If water leakage occurs through a poor join in a framing system then the weather-stripping or glazing gaskets may be unreasonably blamed for the failure.

3.2.3 Water vapour diffusion

The presence of water vapour within a cavity in a facade may give rise to the formation of condensation within the facade, which may then lead to damage of the facade structure. Whilst fully sealing the facade could help to prevent the diffusion of water vapour into the facade this is a dangerous practice because the integrity of the seals cannot be guaranteed against poor workmanship or premature failure. An alternative is to ensure that one face of the facade (that which is usually exposed to the environment with the lowest moisture content) is deliberately left unsealed so that water vapour can diffuse out of the facade. This may require the use of a seal which prevents water penetration but allows water vapour to diffuse through the seal.

The obvious solution is to use a baffle. As an alternative to a rigid baffle however, open-cell polymer foams may be impregnated with non-setting sealant materials which enable them to repel water whilst allowing water vapour to diffuse through. The structure of the foam then behaves like a complex baffle. An advantage of an impregnated foam is that it can be easily compressed and pushed through a small joint opening but will then recover to near its original size and shape, thereby filling the joint. The sealant causes the foam to adhere to the joint surfaces, allowing the joint to expand (the degree of movement may limit the use of a gasket - a gasket which is still in compression at the greatest joint width could place an excessive force on the joint surfaces at the smallest joint width), but the foam can be easily removed should it need to be replaced.

3.3 Examples of joint design

The following examples illustrate how joints may be designed to reduce water penetration:

3.3.1 Rain-screen over-cladding

Figure 3.3.1 shows two typical joints in a rain-screen cladding system. The first figure shows the horizontal joint between panels, which is shaped to prevent the direct passage of water. Although water may be carried through the joint by a stream of air this is not a problem as the jet of air is directed towards the back face of the cladding, so that the water is caught and runs down the cladding panel to suitable drainage points.

The second figure shows the vertical joint between panels, where the panels are clipped over a supporting rail. In this case water may run down the support rail and behind the cladding panels, and so some form of seal is needed to close the joint between the panels and the support rail, or perhaps between the adjacent panels. Alternatively a cover could be used to hide the joint. In this example a foam seal is used at the back of the joint, which is the most protected location. Note that the seal must be air-tight if the rain-screen is pressure moderated.

CIRIA SP87F (1992) also discusses the design of joints in curtain walling and rain-screen over-cladding. Emphasis is given to providing proper drainage and the reliance of single-sealed systems on good fabrication and installation is noted.

3.3.2 Scandinavian-type casement windows

Figure 3.3.2 shows a Scandinavian-type casement window frame. The window is inward opening, and at the head of the window this means that the joint is protected by the natural overhang of the outer frame, with a drip to separate running water from the frame. The opening to the ventilator is on the underside of the top frame, and there is a significant rise for water to overcome in order to pass through the ventilator.

The joint at the sill of the window is protected by the aluminium glazing bead which has been arranged so that it overhangs the aluminium flashing on the fixed frame. There is only a single seal between the opening light and the fixed frame, and this seal is protected from contact with water and any form of radiated light or heat. Furthermore, by being positioned away from the outside environment the draught-strip is not subjected to significant temperature variations and will neither get very hot nor very cold. The draught-strip pushes into a simple groove in the frame and would be easy to replace should the need arise.

3.3.3 Roof windows

Figure 3.3.3 shows a typical design of roof window. In this case the joint is protected with an overlapping aluminium flashing, which is deep enough to prevent water penetration due to the high kinetic energy of raindrops bouncing from the roof. Again only an air-seal is required to prevent strong winds from blowing water through the joint, and this air-seal is located close to the inside of the window.

3.3.4 Summary of joint design to discourage water leakage

A joint can be designed to function with only one seal, usually an air-seal. However, a common design option in many UK windows is to locate a gasket at the external opening of a joint, either to act as a rain-screen (as in the opening light of a casement window) or to retain a component (as in the case of glazing gaskets). However, this exposed position is not conducive to the long-life of many gasket materials. The advantages of being able to use a single gasket in a joint, away from the joint opening, are best understood in conjunction with an appreciation of the behaviour of typical gasket materials. This is discussed in the following chapter.

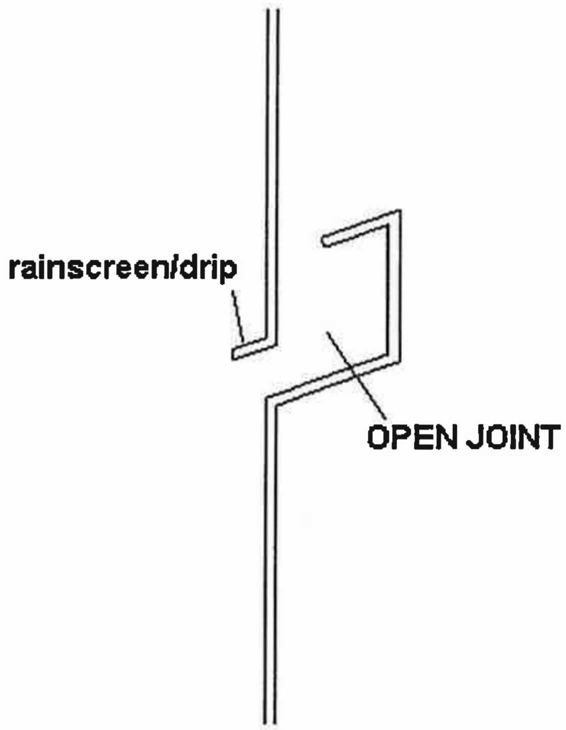
BS 6093 (1981) gives guidance relating to the design of joints, and shows how a joint may be designed to avoid water penetration with the minimum amount of sealing. Where gaskets are considered it is noted that the gasket manufacturer should be consulted early in the design stage, because the gasket interacts with the joint and it is the combination of joint and gasket that provides weather-tightness. Furthermore, the need to achieve close tolerancing is emphasised, as is the need for continuity at junctions between gaskets. The need for drainage is emphasised wherever gaskets must be joined on site and are more likely to be improperly joined, allowing some water penetration to occur. For the most part however this standard considers sealant joints. However, it is uncertain whether many joint designers even consider this standard, preferring to work on the basis of previous experience, usually 'that's the way we've always done it', without any knowledge of whether the last set of joints actually worked!

The SFTC (1986) have also published guidance on weather-sealing, and Figure 3.3.4 is taken directly from their publication. It is interesting to note the statement on the lower figure ('covered' joint) that 'the weatherseal must not be fixed here', indicating the location where UK windows almost always have a weather-strip! It is explained that putting the seal in such an exposed location will cause the seal to get wet, lose efficiency and possibly pump water into the joint. Guidance is given on the design of the joint at all locations around an opening window, and there are also recommendations for the dimensions of drips to separate water from the underside of a frame.

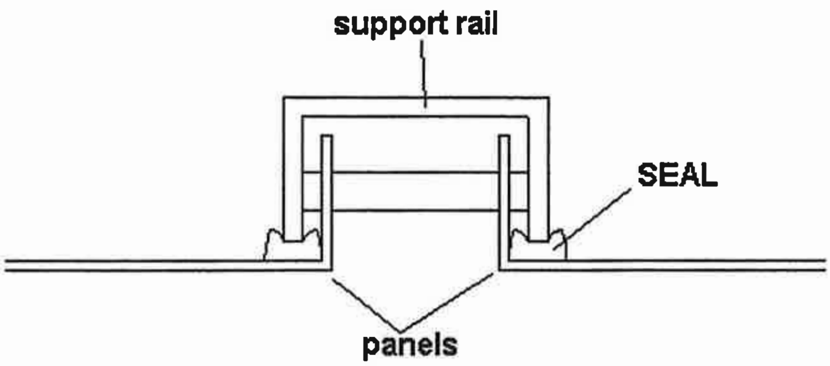
3.4 Closure

Joints can be designed to reduce, or even eliminate, the need for a seal. Designing the joint properly, even if a seal has to be introduced, can greatly reduce the problems that occur when the seal fails.

Figure 3.3.1 Joints in a rain-screen cladding system



a) a vertical section (elevation) through a panel



b) a horizontal section (plan) through a panel

Figure 3.3.2 **Joints in a Scandinavian-type window**

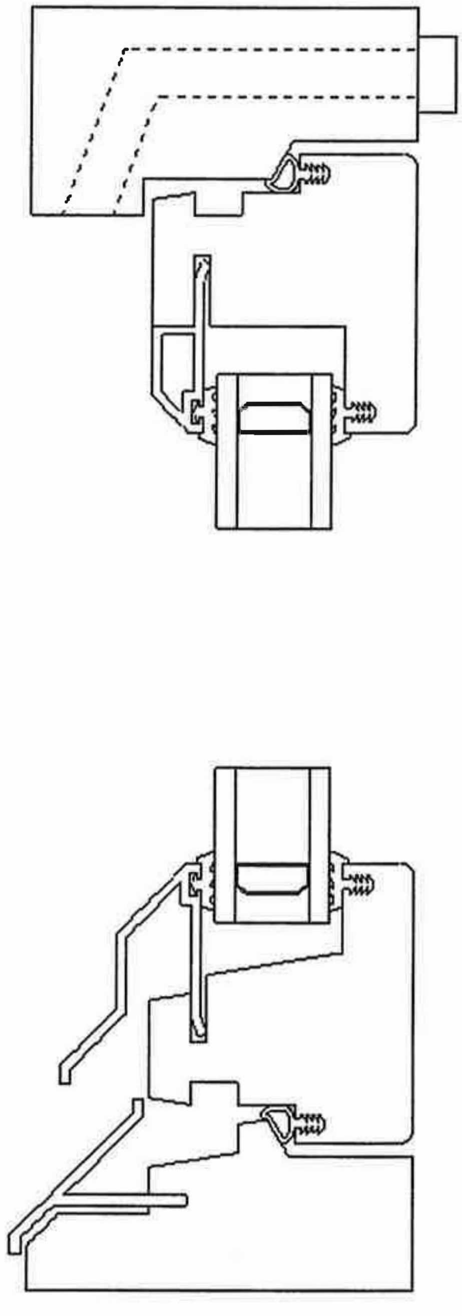


Figure 3.3.3 **Joints in a roof window**

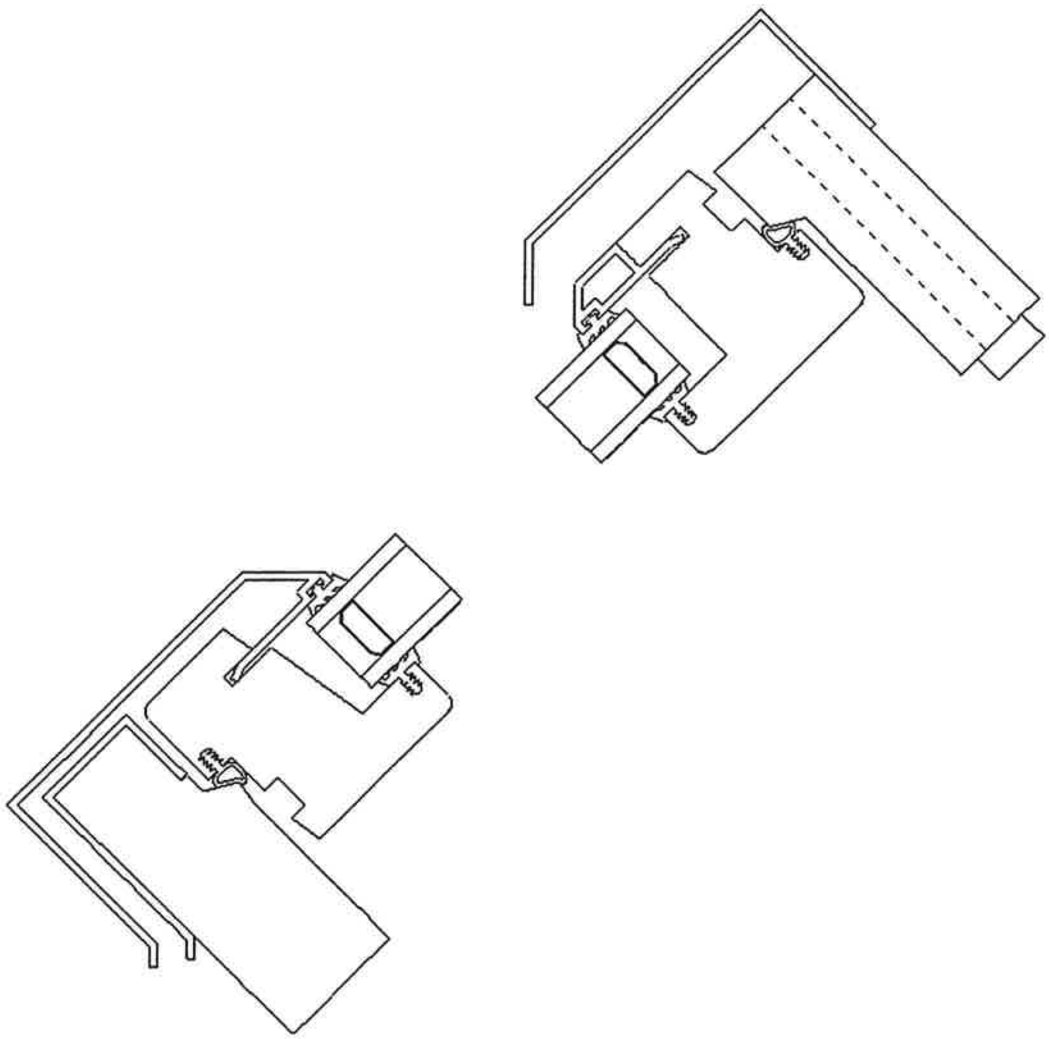
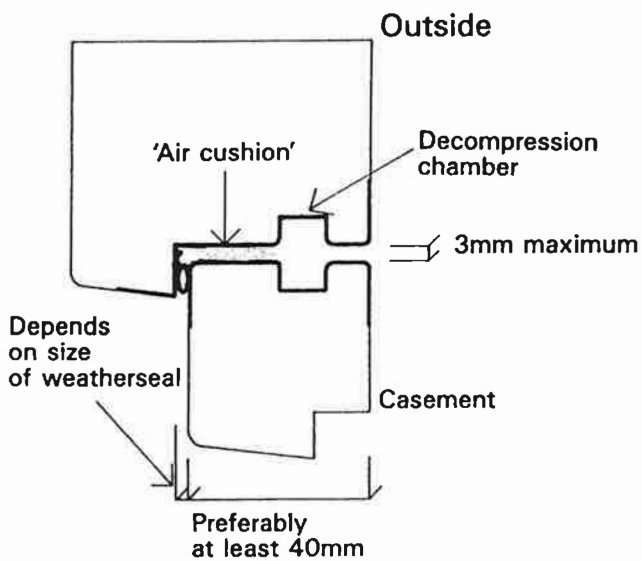
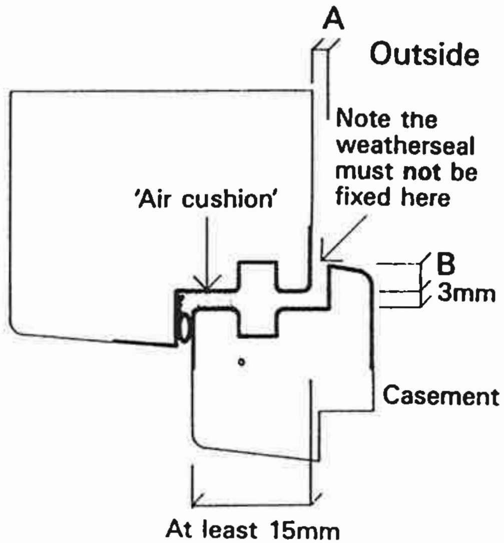


Figure 3.3.4 Joint design and seal location for windows (from SFTC (1986))



'Open' joint
(shown for vertical side joint)



'Covered' joint
(shown for vertical side joint)

4 THE PROPERTIES OF GASKET MATERIALS

The purpose of this chapter is to identify some of the key properties of the materials used for gaskets. The performance of gaskets is dependent upon some fundamental differences in the behaviour of elastomers compared to other engineering materials, but the properties of traditional engineering materials are described first:

4.1 Mechanical properties of traditional materials

Most traditional engineering materials have very similar characteristics when subjected to engineering forces; the only dissimilarities occur if a material is brittle (breaks rather than yielding) or anisotropic (has properties that depend on the direction in which the force is applied, usually due to the internal structure being oriented along an axis, for example timber which has different properties along and across the grain). The characteristics are based on small changes in size and shape (small strains) when a force is applied:

4.1.1 Traditional 'small strain' material behaviour

Most engineering materials behave the way they do because the principal forces within the material are generated by the atomic bonds that hold the material together. Normally these bonds have an optimum length, at which the repelling forces between atoms are exactly balanced by the attracting forces between atoms. When the material is strained the bonds must either lengthen or become shorter, and so the repelling or attractive force becomes greater and a stress is generated. However, the forces that are generated are very high, and only small strains can be achieved.

The behaviour of many engineering materials is expressed using simple concepts of stress and strain. Consider a uniform bar of some material suspended by one end and loaded at the other. The basic form of the stress-strain curve for a ductile material such as steel is plotted in Figure 4.1.1. This curve is characterised by 5 points, marked I through V on the figure. These points are

I	the limit of proportionality
II	the elastic limit
III	the yield point
IV	the point of ultimate tensile stress
V	the fracture point

Elastic materials show linear elastic behaviour up to point I, and then they show non-linear elastic behaviour up to point II - if released before reaching point II the material will return to its original shape. Beyond point II the material deforms plastically and when released cannot return to the original shape - there will always be some permanent deformation.

At point III the material will give suddenly, if ductile, or break, if brittle. In a ductile material the stress may initially decrease as the strain is increased. The material will then appear to get stiffer until point IV is reached, at which point the highest load is achieved. At point V the material fails.

The desired working range for a material is up to point II. However, linear elastic behaviour is only observed up to point I. The ratio of stress to strain at point I is termed Young's modulus

$$E = \frac{\sigma}{e}$$

- E is Young's modulus, in N/m^2
- σ is the stress, in N/m^2
- e is the strain, in m per m of initial length

The stress σ is the force applied to the bar divided by the initial cross-sectional area of the bar

$$\sigma = \frac{F}{A_0}$$

- F is the force, in N
- A_0 is the cross-sectional area, in m^2

The small strain e is the increase in length of the bar divided by the initial length of the bar (the strain must actually be measured over a gauge length of the bar - near the ends of the bar the cross-section may not remain uniform during stretching)

$$e = \frac{L - L_0}{L_0}$$

- L is the stretched length of the bar, in m
- L_0 is the initial length of the bar, in m

As an example a typical steel might have a Young's modulus of 210×10^9 N/m^2, and a stress at the limit of proportionality (point I) of 250×10^6 N/m^2. The strain at the limit of proportionality is thus

$$e = \frac{250\times10^6}{210\times10^9} = 0.0012$$

In simple terms a uniform piece of this steel can be stretched by 0.12% and if released will 'spring' back to its original length. For a typical steel the strain at fracture may be around 0.4 (point V) and this is usually expressed as a percentage elongation (40% in this case).

Note that the expression for Young's modulus may be written in the form

$$f = Ee$$

- f is the applied force per unit initial cross-sectional area, in N/m^2

This linear relationship between applied force and resultant strain is termed Hooke's Law.

The material of the bar does not actually retain a constant cross-section throughout the test - as the bar is stretched so it becomes narrower. The strain perpendicular to the direction of stretching is a fraction of the strain in the direction of stretching and has the opposite sign (as the bar increases in length - positive strain - the width of the bar decreases - negative strain). The fraction is termed Poisson's ratio

$$\nu = -\frac{e_{lateral}}{e}$$

- ν is the Poisson ratio
- e is the strain in the direction of loading, in m per m of initial length
- $e_{lateral}$ is the strain perpendicular to the direction of loading, in m per m of initial width

If the bar is initially square in cross-section with sides of width W_0 then each side must reduce in width by an amount $\nu e W_0$. The cross-sectional area of the bar becomes

$$A = (W_0 - \nu e W_0)^2 = (1 - \nu e)^2 A_0$$

- A_O is the initial cross-sectional area of the bar, in m^2 ($=W_0^2$)
- A is the final cross-sectional area of the bar, in m^2

The volume of the material at a given load must be

$$V = (1+e)(1-\nu e)^2 V_0 = \left[1 + e(1-2\nu) + e^2\left(\nu^2 - 2\nu\right) + e^3\nu^2\right]V_0$$

- V_0 is the initial volume of the bar, in m^3 ($=A_0L_0$)
- V is the final volume of the bar, in m^3

For small strains the terms in e^2 and e^3 can be neglected, and

$$V = \left(1 + e(1-2\nu)\right)V_0$$

If the Poisson ratio is 0.5 then the material does not change volume during loading and is therefore incompressible. If ν was greater than 0.5 the volume would decrease as the material is stretched - this has never been observed (such a material would swell explosively if subjected to any compressive force).

All known engineering materials have a Poisson's ratio less than 0.5. Lindley (1968) gives a table of values of Poisson's ratio for different materials, which range from 0.17 for quartz, up to 0.44 for gold and lead, with the highest values of 0.4997 and 0.49989 reported for natural rubber.

4.1.1.1 Shear

The behaviour of materials in simple tension and compression can be linked to the behaviour of materials in shear (in a real mechanical component tension, compression and shear occur together).

If a cube of material is placed in shear (a force applied parallel to one surface so that it is displaced but remains parallel to its opposite surface, as shown in Figure 4.1.1.1) then a modulus of rigidity (or shear modulus) can be defined as

$$G = \frac{\tau}{\phi}$$

- G is the modulus of rigidity, in N/m^2
- τ is the shear stress, in N/m^2
- ϕ is the shear strain, in m per m of initial length

The shear stress τ is the force applied to the surface divided by the area of the surface

$$\tau = \frac{F}{A}$$

- F is the force, in N
- A is the surface area, in m^2

The shear strain ϕ is the displacement of the surface divided by the initial separation of the surfaces

$$\phi = \frac{\Delta x}{y}$$

- Δx is the displacement of the surface, in m
- y is the initial distance between the surfaces, in m

It can be shown (for example Ryder (1969)) that the shear modulus, Young's modulus and Poisson's ratio are then related by the relationship

$$E = 2G(1 + \nu)$$

4.1.1.2 Bulk modulus

A block of material can also be strained by applying a uniform pressure. The bulk modulus is the ratio between an applied pressure and the resulting volumetric change

$$K = \frac{-\Delta p}{\Delta V / V}$$

- K is the bulk modulus, in N/m^2
- Δp is the applied pressure change, in N/m^2
- ΔV is the resulting volume change, in m^3
- V is the initial volume, in m^3

The bulk modulus is related to Young's modulus and Poisson's ratio by the relationship

$$E = 3K(1 - 2\nu)$$

For a traditional material it is only necessary to know two of the material constants described above - the others can then be determined from simple formulae.

4.1.1.3 Strain energy

Strain energy is the work done in straining a material, which is equal to the area under a plot of the applied force against the resulting displacement. For a uniform bar in simple tension or compression over the linear part of the stress-strain characteristic the strain energy is given by

$$U = \frac{1}{2}F(L - L_0)$$

- U is the strain energy, in J
- F is the applied load, in N
- L is the final length of the bar, in m
- L_0 is the initial length of the bar, in m

The more general form of this relationship is

$$U = \int_{L_0}^{L} F dL$$

which can be applied to a non-linear stress-strain curve. In such circumstances the ordinary methods of analysis cannot be used and so strain energy is an important concept. This is usually the case for large strain behaviour of rubber materials and strain energy will be described in more detail in the following sections.

4.2 Mechanical properties of rubber materials

A uniform bar of a typical rubber can be stretched by more than 500% and will return to its original length, providing the load is not maintained for any significant period of time. The piece of rubber will not experience a proportional relationship between stress and strain, and its behaviour must be described in terms of large strains.

4.2.1 Large strain material behaviour

When describing large strain behaviour a different set of parameters is used. The length of a uniform bar that has been stretched is described in terms of the elongation ratio

$$\lambda = \frac{L}{L_0}$$

- λ is the elongation ratio, in m per m of initial length
- L is the final length of the bar, in m
- L_0 is the initial length of the bar, in m

At small strains the elongation ratio is related to the small strain by

$$\lambda = 1 + e$$

At large strains the reference length L_0 increases as the sample is further stretched, so that the strain is found by integrating the increase in the sample length. The natural strain is then given by

$$\varepsilon = \ln \lambda$$

which can be inverted, using a standard series, to give

$$\lambda = \exp \varepsilon = 1 + \varepsilon + \frac{\varepsilon^2}{2!} + \frac{\varepsilon^3}{3!} + \sum_{n=4}^{\infty} \frac{\varepsilon^n}{n!}$$

- ε is the natural strain, in m per m

Note that at small natural strains

$$\varepsilon = \lambda - 1 = e$$

The equation previously defined for strain energy in a material with a non-linear stress-strain characteristic is

$$U = \int_{L_0}^{L} F dL$$

In a material undergoing large strains the equivalent equation is

$$U = \int_{1}^{\lambda} \sigma d\lambda$$

Note that this equation still uses engineering stress - the applied force divided by the original cross-sectional area of the sample.

For small strains it is possible to define a Young's modulus for rubber materials. However, the industry standard definition of the stiffness of a rubber material is hardness, measured using a special spring-loaded indentor (the depth of indentation under a standard spring load is converted to a hardness number). There are a number of scales for rubber hardness, based on various indentors and spring strengths, but they are related. Hardness has also been linked directly to the small-strain Young's modulus of rubber. Brown (1986) gives two such sets of curves, and they are repeated in Figure 4.2.1. The first curve shows the relationship between the Shore 'A' and Shore 'D' hardness scales and the I.R.H.D. (International Rubber Hardness Degree) scale. The second curve shows the relationship between the I.R.H.D. hardness and Young's modulus. It must be noted however that this latter curve applies to an incompressible rubber, and it has been suggested that for some rubbers there is a variable relationship between hardness and Young's modulus.

Alternatively DIN 53 504 (1994) is a standard for assessing the stress-strain behaviour of rubber based on behaviour in simple tension. This standard determines properties at key points on the stress-strain curves, such as tensile strength at break and tensile stress at yield. However, in DIN 53 504 section 5 a number of different test pieces are defined for use in stress/strain tests, and then clause 5.1 of the standard states 'Test results obtained for test pieces of different shape are not comparable'. There are clearly some complex issues associated with the behaviour of rubber materials.

4.2.2 Three-dimensional stress-strain behaviour

Generally three-dimensional behaviour can be expressed using the concept of the unit cube, as shown in Figure 4.2.2. The initial length of each side of the cube is 1 unit, and so the extension ratio is also the true length of the side after strain has been applied.

The strain energy in the unit cube is now found from

$$U = \sum_{n=1}^{3} \left(\int_{1}^{\lambda_n} \sigma_n d\lambda_n \right)$$

The engineering stresses are therefore given by

$$\sigma_n = \frac{\partial U}{\partial \lambda_n}$$

Now, the true stress is the applied force divided by the cross-sectional area after strain has occurred, or

$$\sigma_i^c = \frac{f_i}{\lambda_j \lambda_k} = \frac{\sigma_i}{\lambda_j \lambda_k}$$

where *i*, *j* and *k* are used to denote the three dimensions of the cube (in any order).

The term σ^c is the Cauchy stress, which can also be written in the form

$$\sigma_i^c = \frac{1}{\lambda_j \lambda_k} \frac{\partial U}{\partial \lambda_i}$$

by combining the expressions above.

If a relationship can be determined between strain energy and the extension ratios then the stresses and forces in any rubber component can be predicted. There are a large number of such models, but many of the models are based on invariants, which are described below:

4.2.2.1 Invariants

Invariants are parameters which combine the strains λ_i, λ_j, and λ_k. A commonly used set of invariants is

$$I_1 = \lambda_i^2 + \lambda_j^2 + \lambda_k^2$$

$$I_2 = \lambda_i^2 \lambda_j^2 + \lambda_j^2 \lambda_k^2 + \lambda_k^2 \lambda_i^2$$

$$I_3 = \lambda_i^2 \lambda_j^2 \lambda_k^2$$

- I_1 is the first invariant
- I_2 is the second invariant
- I_3 is the third invariant

These terms are called invariants because if the values of λ_i, λ_j and λ_k are shuffled each equation will still give exactly the same result. It can be seen that the first of these invariants is the sum of the squares of the sides of the deformed cube, the second invariant is the sum of the squares of the face areas of the deformed cube and the third invariant is the square of the volume of the deformed cube.

The stress in dimension *i* can be related to any set of invariants by

$$\sigma_i = \frac{\partial U}{\partial I_1}\frac{\partial I_1}{\partial \lambda_i} + \frac{\partial U}{\partial I_2}\frac{\partial I_2}{\partial \lambda_i} + \frac{\partial U}{\partial I_3}\frac{\partial I_3}{\partial \lambda_i} = f_i$$

- f_i is the force applied to the unit cube, in N

and the same expression applies to dimensions *j* and *k*.

4.2.3 Strain energy models for rubber materials

In rubber materials the basic unit is a long molecule comprising a chain of several thousand atoms with various groups of atoms attached to the sides of the chains. The chains may be variable in length, and the length distribution must be described with a statistical model. The chains are not uniformly ordered, but are tangled together in a three-dimensional mass. The behaviour of rubber then differs in that as the material is strained the polymer chains may untangle themselves and straighten, which requires very little force, before any of the atomic forces are brought into play. The stress-strain behaviour of a rubber therefore goes through an untangling stage (as chains are pulled straighter), a straining stage (as the atomic bonds become stretched) and a failure stage (as bonds break).

4.2.3.1 The Gaussian model for strain energy in rubber

The simplest model for rubber behaviour is a statistical model based on the assumption that for a single polymer molecule with n atoms joined in a simple chain by identical bonds, each of length l, the distance between the ends of the chain is adequately predicted by a Gaussian distribution between the extremes of 0 (both ends together) and *nl* (chain fully untangled). In a random mass of such chains the mean length of the chains can be estimated from the Gaussian distribution and the energy required to strain the chains determined. If the model is developed (for example as in Ward and Hadley (1993)) then the strain energy is found to be related to the strains by

$$U = \frac{1}{2}NkT(I_1 - 3)$$

- N is the number of chains in a unit volume of the material
- k is the Boltzmann constant, $(=1.38054\times10^{-23}$ J/K)
- T is the absolute temperature of the material, in K
- I_1 is the first invariant, described in 4.2.2.1.

For many solid rubber materials this model is found to apply adequately in compression and for moderate levels of tension. However, there are other models for solid rubber, and there are different models for foam rubber (the gas within the cells is considerably more compressible than the rubber matrix and this modifies the behaviour of the material).

For a uniform bar in simple tension the extension ratios are

$$\lambda_1 = \lambda$$

in the direction of the applied force and

$$\lambda_2 = \lambda_3$$

perpendicular to this. If it is assumed that the rubber is incompressible (this is usually assumed, even if there is no data to support the assumption) then

$$\lambda_1\lambda_2\lambda_3 = 1$$

and so

$$\lambda_2 = \lambda_3 = \frac{1}{\sqrt{\lambda}}$$

If the Gaussian model is applicable then the applied force per unit initial cross-sectional area is

$$f = \frac{dU}{d\lambda} = NkT\left(\lambda - \frac{1}{\lambda^2}\right)$$

A plot of *f* against the function of λ should give a straight line through the origin with a slope of *NkT*, if a material is incompressible and follows the Gaussian model.

Now at small extensions ($\lambda=1+e$, $e^2<<e$) the force is

$$f = 3NkTe$$

This is identical in form to Hooke's Law

$$f = Ee$$

and materials which satisfy the Gaussian model are termed neo-Hookeian. For such materials the formulae above can be rearranged such that

$$U = \frac{1}{6}E(I_1 - 3)$$

4.2.3.2 Other models for the behaviour of solid rubber

There are several other models for the behaviour of solid rubber. Some are based on statistical methods, but other models are based on empirical observations, and one such is the Mooney model (Mooney (1940), also called the Mooney-Rivlin model), which is generally used in the form

$$U = C_1(I_1 - 3) + C_2\left(\frac{I_2}{I_3} - 3\right)$$

This model is also readily related to conventional behaviour at small strains and the small strain Young's modulus is

$$E = 6(C_1 + C_2)$$

The Mooney model is probably the most used, although it has been suggested that for compression and for tensile elongations of up to 40% the Gaussian model is often acceptable. For a uniform bar in simple tension the Mooney model gives the applied force per unit initial area as

$$f = \frac{dU}{d\lambda} = 2\left(\lambda - \frac{1}{\lambda^2}\right)\left(C_1 + \frac{C_2}{\lambda}\right)$$

This equation is then rearranged into the form

$$\frac{f}{2\left(\lambda - \frac{1}{\lambda^2}\right)} = C_1 + \frac{C_2}{\lambda}$$

A graph of the term on the left-hand-side of this equation against $1/\lambda$ should be a straight line of slope C_2 with intercept C_1 (although it is more usual to evaluate the term C_1+C_2 at $\lambda=1$). If the material satisfies the Gaussian model then the line will be horizontal ($C_2=0$).

This type of plot, called a Mooney plot, is frequently used to characterise a sample of rubber. Efforts are now being made to relate typical values for the coefficients C_1 and C_2 to the material type. Such a correlation may allow designers of rubber products to predict the performance of the product without first having to mix a batch of the intended material and test it to determine performance. A product such as a vehicle road tyre may contain several different blends of rubber for different parts of the tyre (for example carcass, sidewall, bead cushion, bead filler, base, tread, cap ply and belt ply zone, as analysed by Helnwein *et* al (1993)) and a realistic method for estimating the engineering properties of the rubber could save time in the development process (measurements might still be necessary, but a reasonable amount of development and fine-tuning could be carried out whilst the rubbers are being prepared). In the absence of such data it is necessary to mix batches of each type of rubber and carry out an in-depth series of tests to determine suitable performance coefficients before analysing the final product.

A large number of other models have been proposed, some of which are based on the invariants given above, some which are based on different invariants, and some which are based directly on the extension ratios. Amongst the simplest are the models proposed by Dickie and Smith (1971)

$$U = 2G(\lambda_1 + \lambda_2 + \lambda_3 - 1)$$

- G is the small strain shear modulus, in N/m^2

Ogden (1972) suggests that the use of invariants actually complicates the analysis, and that a more general model can be created, of the form

$$U = \sum_{j=1}^{n} C_j \Phi_j$$

where

$$\Phi_j = \frac{\lambda_1^\alpha + \lambda_2^\alpha + \lambda_3^\alpha - 3}{\alpha}$$

and n and α are selected to suit the available data. For a single term ($n=1$) with $\alpha=2$ this model reduces to the Gaussian form, and for two terms ($n=2$) with $\alpha=2$ and $\alpha=-2$ respectively it reduces to the Mooney model.

When applying these models it is often recommended that the rubber material is tested in as many different forms of strain as possible. If the Gaussian model is adequate for most rubbers in compression then there are obvious implications if materials are only tested in compression - the deviations from the Gaussian model which occur at higher tensile strains will not be observed. A common method of test is biaxial tension, in which a thin sheet of material is stretched in two directions simultaneously using a special test apparatus (two strains are being controlled).

It is usually recommended that the mechanical properties are at least determined using the type of loading which most closely approaches that expected in the final product. For a component such as an E-gasket however, which works by deflection, this may require tests in tension and compression, and yet these tests are never carried out - material selection is made on the basis of some simple parameters such as hardness and compression set, which are determined for uniform blocks of material and do not relate easily to the mechanical performance of the finished gasket.

4.2.3.3 *Models for the behaviour of foam rubber*

Foam rubber is more difficult to model because the presence of gas-filled pockets in the material modifies the mechanical behaviour. A single model is usually quoted for foam rubber, this being the model of Blatz and Ko (1962)

$$U = \frac{fG}{2}\left[J_1 - 3 + \frac{1}{\beta}\left(J_3^{-2\beta} - 1\right)\right] + \frac{(1-f)G}{2}\left[J_2 - 3 + \frac{1}{\beta}\left(J_3^{2\beta} - 1\right)\right]$$

where the invariants are

$$J_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 = I_1$$

$$J_2 = \frac{1}{\lambda_1^2} + \frac{1}{\lambda_2^2} + \frac{1}{\lambda_3^2} = \frac{I_2}{I_3}$$

$$J_3 = \lambda_1\lambda_2\lambda_3 = \sqrt{I_3}$$

$$\beta = \frac{\nu}{1-2\nu}$$

and the parameter f is determined by experiment.

Note that if Poisson's ratio is $\nu=0.4997$, as reported by Lindley (1968) for natural rubber, then $\beta\approx830$, suggesting that very accurate experimental data is required to fit this model to near-incompressible rubbers (even though J_3 would be near to unity it has to be raised to the power of 2β).

It should be noted that when Blatz and Ko applied their model to a polyurethane foam they obtained values of $G=38$, 29 and 27 psi and $f=0.13$, 0.07 and -0.19 for simple tension, strip biaxial tension and homogeneous biaxial tension respectively, with $\nu=0.25$ obtained from direct measurements in simple tension. These results demonstrate that behaviour does depend upon the type of stress, and Blatz and Ko had to take average values of $G=32$ psi and $f=0$!

4.2.4 Time-dependent behaviour of materials under strain

All materials exhibit time-dependent behaviour, but for most materials the time-scale is so long that the effects are not noticed. This is not so for rubber materials.

There are two sides to time-dependent behaviour - creep, in which the strain of a material subjected to a constant stress increases with time, and relaxation, in which the stress of a material subjected to a constant strain decreases with time.

The traditional model for material behaviour, Hooke's law, assumes that force and extension are proportional - the material is then equivalent to a simple spring. To model creep and relaxation it is necessary to introduce an additional element, which is mechanically equivalent to a piston moving in an oil-filled pot - the rate at which the piston moves (strain) is proportional to the applied force (stress). Three typical such models are shown in Figure 4.2.4.

The Kelvin model (also called the Voigt model) is used to describe creep, and is equivalent to a linear spring in parallel with an oil-filled pot (Figure 4.2.4(a)), which then relates stress and strain by

$$\sigma = E_K e + \eta_K \frac{de}{dt}$$

- E_K is the spring modulus, in N/m^2
- η_K is the viscosity of the oil in the pot in, Ns/m^2
- t is time, in s

If a constant stress σ is suddenly applied to a sample then the solution of this equation is

$$e = \frac{\sigma}{E_K}\left[1 - \exp(-t/\tau)\right] \qquad \tau = \frac{\eta_K}{E_K}$$

- τ is a time constant, in s

The Maxwell model is used to describe relaxation, and is equivalent to a linear spring in series with an oil-filled pot (Figure 4.2.4(b)), which relates stress and strain by

$$\frac{de}{dt} = \frac{1}{E_M}\frac{d\sigma}{dt} + \frac{\sigma}{\eta_M}$$

- E_M is the spring modulus, in N/m^2
- η_M is the viscosity of the oil in the pot, in Ns/m^2

If a constant strain is suddenly applied to a sample then the solution of this equation is

$$\sigma = \sigma_0 \exp(-t/\tau) \qquad \tau = \frac{\eta_M}{E_M}$$

- σ_0 is the initial stress, in N/m^2

The Kelvin and Maxwell models describe creep and relaxation in isolation. In a real material these phenomena occur together and a combined model is required. The 'standard linear solid' model comprises a Maxwell element of a linear spring in series with an oil-filled pot, in parallel with another linear spring (Figure 4.2.4(c)), which gives the time-dependent stress-strain behaviour defined by

$$\sigma + \tau\frac{d\sigma}{dt} = E_a e + \left(E_a + E_m\right)\tau\frac{de}{dt} \qquad \tau = \frac{\eta_m}{E_m}$$

- E_a is the modulus of the parallel spring, in N/m^2
- E_m is the modulus of the series spring, in N/m^2
- η_m is the viscosity of the oil in the pot, in Ns/m^2

4.2.4.1 Demonstrating creep behaviour

The application of these models for creep and relaxation is not straightforward - in the combined model there are three material parameters to be defined. However, some simple tests have been performed to demonstrate the creep of rubber.

For the demonstration two lengths of gasket have been fixed at one end and loaded at the other in 10 N load increments. The load-deflection characteristic, for a gauge length near the centre of each length of gasket, is shown in Figure 4.2.4.1 - the characteristic on the left is for a solid thermoset rubber, and that on the right is for a foam thermoset rubber.

An additional 10 N load was added to each gasket approximately every 15 seconds. After the final load had been applied and the elongation noted a timer was started and the elongation recorded again after 60 s and after 120 s. The entire load was then removed and the deflection recorded immediately, and then again after 60 s. Finally the lengths of gasket were left, unloaded, to recover for 72 hours and the final elongation recorded. It is apparent that even in a short time period of 60 s the length of the gaskets increased by nearly 5% under load, and recovered by a similar amount when the load was removed.

In practice a rubber gasket is installed and left in a compressed state for several years. During this period the internal structure of the gasket material will rearrange itself and the stresses within the body of the gasket will reduce; the gasket will also exhibit some permanent deformation. This combined stress relaxation and creep is a significant phenomena in rubber materials and materials should be tested to estimate the creep and relaxation that will be observed in practice. However, the only tests directly related to creep and relaxation are the tests for compression set and deflection recovery.

4.2.4.2 Compression set and deflection recovery

In a compression set test a block of material is compressed by a fixed amount and then heated to encourage the molecular structure to rearrange itself more rapidly. When the material is released it is allowed to recover for a defined period, and the residual deformation is then measured and expressed as a 'compression set' (the permanent deformation is expressed as a percentage of the applied deformation). However, the compressive force is not measured, and so this test only gives an idea of the degree of creep in the material (it is also feasible to determine a tension set for a material - the material is placed in tension rather than compression).

Unfortunately there does not appear to be any information relating the compression set of a material to the creep observed in gaskets. It is to be expected that those parts of the gasket that are more highly stressed will experience a greater rate of relaxation and creep, whereas the compression set test is carried out on a uniform block of material under simple compression (the material is uniformly strained). It is also unfortunate that, in the UK at least, rubbers for use in gaskets are only tested for compression set if they are thermosets - a different method of test (deflection recovery) is applied to thermoplastic rubbers, which places a hollow cylinder of material in compression (so that there are a combination of tensile and compressive stresses). Compression set and deflection recovery, although comparatively simple 'properties' to determine, may not actually yield any useful information about the gasket performance.

4.2.4.3 Accelerated ageing of polymers

It is stated above that the test for compression set uses a high temperature to encourage rearrangement of the molecular structure of the material. This accelerated ageing of polymers is a subject open to much debate.

The objective of accelerated ageing may be twofold - in the first instance it is necessary to shorten the time required for a test, and heating of materials is known to accelerate stress relaxation and creep. However, this can be achieved with any increased temperature providing the temperature is sustained for long enough, and as a result there is little incentive to relate accelerated ageing tests to real behaviour - i.e. if a block of rubber is compressed and heated at 70°C for 24 hours how long would it require to obtain the same degree of compression set if the same rubber block were compressed and exposed to normal service conditions? From the engineers point of view it is desirable that the ageing regime imposes on a material or component a realistic regime of forces and phenomena so that the material undergoes the same physical changes that would occur due to normal weathering over a real time-span. It is then also possible to describe accelerated ageing as artificial weathering.

Whether or not a particular ageing regime replicates real life depends on the environment that the material will experience in service. Many ageing regimes applied to polymers only involve subjecting the polymer, whilst under stress, to high temperatures. However, in service a material may experience direct contact with water and other chemicals (ozone has a particularly deleterious effect on some polymers) and may be exposed to ultraviolet radiation from the sun. Some artificial weathering regimes thus combine cycles of heat and cold with water spray, cycles of high and low humidity and direct radiation from UV lamps - freezing of the water may also take place, which is significant for porous and cellular materials.

The response to accelerated ageing regimes selected to be convenient, rather than realistic, will depend on the material under test. Different materials will react to different phenomena in different ways. Clearly an artificial weathering regime must subject a material sample to a representative range of real phenomena, and not to just one phenomenon in isolation. Davis and Sims (1983) discuss weathering of polymers in some detail, and note that correlation between natural weather trials and oven ageing is currently less than satisfactory, and that there are a number of parameters that are significant. A key problem is to decide which material property should be compared between naturally weathered and artificially aged samples, because some properties may not vary greatly. It may be that a group of properties needs to be compared, similar to the dimensionless groups used in many other forms of comparative assessment, which obviously complicates any attempt at correlating data. Whatever the outcome however, it is reasonable to say that the performance of the finished gasket is most important, and that isolated material tests cannot properly represent the ageing behaviour of a complex product.

ISO 471 (1995) identifies a procedure for ‘conditioning’ rubber prior to testing. However, it is not stated explicitly that this conditioning (which may take place at temperatures of up to 300°C) is intended to age the rubber, although it is stated that changes in the rubber depend on the test temperature, and that samples may be tested at a number of time-intervals. The conditioning is carried out without light, and there is no direct statement of the relative humidity to be used, other than in a definition of the laboratory ambient conditions. This is typical of many standards for accelerated ageing.

An interesting demonstration of the effect of identical weathering regimes on different materials is given by Spetz (1986). In this paper a number of different materials were aged using the same combination of heat, humidity, UV and ozone and the behaviour of the aged materials compared with identical naturally weathered specimens. It was found that EPDM and CR (chloroprene rubber) weather-strips required 2 weeks of artificial ageing but a silicone rubber weather-strip required 20 weeks of artificial ageing to replicate the effects of 10 years of natural weathering. The conclusion of Spetz was that different materials need different ageing regimes, but an obvious alternative conclusion is that the ageing regime was not properly balanced - that some phenomena was perhaps included at an unrealistic level which influenced the EPDM and CR weather-strips, but not the silicone rubber weather-strip (or vice-versa).

Bolin and Camnerin (1986) also aged a large number of different polymers by heating in air, water and oil at various temperatures for periods of up to 5 years! It was noted that different rubber additives have an effect on long-term performance, and also that whilst some properties may show little change others can vary significantly. As the ageing temperature was increased so the materials generally failed sooner. However, there is no comparison of how the same material aged in air, water and oil.

Holmström and Eriksson-Widblom (1986) discuss the ageing of gaskets, and note that the degree of compression and recovery time (time allowed for the samples to recover after being released from compression at the end of a period in an oven) are important for the EPDM gaskets that they studied. The method of ageing comprised the use of a climatic chamber with a high relative humidity.

Clark and Manley (1986) consider stress relaxation and make the important observation that ‘tests must be carried out at strains appropriate to service conditions’. The sample size in a stress relaxation measurement is important, and the sample should be tested in compression if it is to be used in compression, and tested in tension if it is to be used in tension. A chart is plotted for the stress relaxation of an NBR rubber, and the relaxation is shown to occur rapidly at first, but at a diminishing rate as the ageing process continues (which is in accordance with the various formulae for creep and relaxation). The rubber was aged in air at 120°C and required about 400 hours for 50% stress relaxation in a sample under tension.

Work reported by Seeberger (1986) notes that the results of ozone ageing can depend on the circulating air-flow within the test chamber. It was found that identical samples showed different ageing behaviour within the same chamber, and that when fresh samples were used each showed the same patterns of damage as previous samples that were placed in the same location within the chamber. The need for a steady and uniform air-flow within the test chamber was clearly demonstrated.

There is clearly a need to establish a fair regime of artificial weathering which gives realistic results when applied to different polymers. The use of high temperatures alone must be considered inadequate given the wide range of environmental factors to which gaskets are usually subjected.

It is an important requirement to know the probable life-span of a particular material - if gaskets will need to be replaced then a statement of when they should be replaced is essential, and the cost of regular replacement may make a different approach to sealing more economical. It is worth noting that in the automotive industry the life of a vehicle may be comparatively short, and the gasket is likely to outlive the car, whereas in the aerospace industry there are stringent safety checks and regular maintenance procedures in which a defective seal should be spotted at an early stage and replaced ('refurbishment' is an ongoing process). In the domestic housing market however it is expected that a house have a life of at least 50 years and windows and doors are sold on the basis that they will 'last for a lifetime', with the home owner expected to be able to prove all ongoing maintenance! Given that current material tests bear no relation to the conditions that a material will encounter in service it would be interesting to know on what basis the 'last for a lifetime' statement is made.

A final and rather important point is that at the present time large numbers of buildings are being refurbished and whole facades replaced. The opportunity to retrieve gaskets that have been in service for 25 years or more has never been greater, but there do not appear to be any significant efforts underway to tap into this enormous resource of natural ageing data.

4.2.5 Current material tests for polymers

The sections above have described some of the engineering relationships important to the description of the mechanical behaviour of materials. However, the suitability of a polymer for use in gaskets is usually described using a small number of tests on the material, many of which do not relate easily to the formulae above.

BS 903 defines a number of basic tests for properties of rubber, and these tests are commonly referred to in standards relating to gaskets:

BS 4255:Part 1 (1986) applies to a named group of materials (all thermosets!) but divides these into classification groups dependent only upon nominal hardness, with each group having limits on tensile strength, elongation at break and compression set. The tear strength is also considered for non-black materials. Properties are required not to change by more than a specified amount after ageing - the ageing regime is a simple high temperature regime (100°C for 70-72 hours). Ozone resistance, staining resistance and low-temperature hardness change are also assessed.

BS 7412 (1991) allows the use of thermoplastic materials in PVC-U windows (this has the particular advantage that thermoplastic rubbers can be produced without additives which could otherwise migrate into the PVC-U and cause problems, Shaw (1994)) and uses similar tests for gaskets and weather-strips, but abandons the test for compression set in favour of a test for 'deflection recovery'. The reason for the change is not made clear, but data that has been obtained for one thermoplastic material shows that the compression set of such materials may exceed 75%, whereas the limit on compression set in BS 4255:Part 1 is 25% (or 30% for coloured materials). Similar findings were given in the comparative study of compression set of various rubbers published by Park Rubber Ltd (1980s) and shown in Figure 4.2.5. It is noticeable that the PVC and PVC/NBR (NBR - nitrile rubber) materials have very high compression set, and that the thermoplastic rubber (TPR, in this case a polypropylene/EPDM mix with 'a high proportion of vulcanised material') is also above the 25% limit for compression set. Note that the standard test for compression set (as described in BS 4255:Part 1 (1986)) is performed at 70°C for 1 day, and the usual accelerated ageing regime is performed at 100°C for 3 days. Clearly the data suggests that the PVC and PVC/Nitrile materials are unsuitable for gaskets which are permanently compressed, such as glazing gaskets. Current high performance TPRs may offer better performance, but as they do not have to be tested for compression set and as there are no tests for long-term properties of gaskets (rather than materials) it is not possible to prove this.

It would be unfair to suggest that the creation of a test for 'deflection recovery' was intended to work around the poor compression set of thermoplastic rubbers, but the question must be asked of whether there should be a common test for all gasket materials - if deflection recovery is a better test for gaskets then it should be applied to all materials and the test for compression set discontinued. However, it could be argued that for a component which is generally used in compression the compression set is a sensible measure of performance - the high compression set of some thermoplastic rubbers is consistent with reports of thermoplastic gaskets falling out of windows after a short period of service. Whilst this may in part be due to undersize gaskets being used originally there is a clear need to devise performance related standards for gaskets, regardless of their material.

Several American specifications exist for gaskets, all of which call upon material tests. ASTM specifications C 509 (1984), C 864 (1984) and C 1115 (1989) require general tests for hardness, compression-deflection, compression set, compression-deflection after heat ageing, tensile strength and elongation, tear strength, dimensional stability after heat ageing, ozone resistance, low temperature brittleness, staining, water absorption and flame propagation. Although there is a separate specification for silicone rubber all of the tests are standardised and there are no distinctions between thermoset and thermoplastic - the suitability of a gasket material is related only to the performance requirements of gaskets. ASTM C 542 (1982) gives a similar specification for lock-strip gaskets, again independent of material type, and also introduces a test for the pressure exerted by the lips of the gasket on the glazing or infill.

With regard to cellular foam glazing tapes AAMA 800 (1986) gives a number of tests which measure compression/deflection, compression set, water absorption, water penetration, tensile adhesion and peel adhesion, together with a pump test which assesses the performance of the glazing tape when subjected to typical movements under conditions of high temperature (produced by sun lamps) and water application.

4.3 Additives and compatibility of polymers

The majority of the tests described above are related to the mechanical properties of materials. However, there are some tests which relate to the composition of rubber materials - rubber materials contain a number of additives to improve performance, and each of these additives is a reactive chemical which may interact with any other chemical present and so introduce issues of material compatibility.

As well as the basic polymer and the filler (a bulk material used to fill out and strengthen the polymer) a typical rubber contains several additives intended to improve the processibility and performance of the material. Each additive is a complex chemical and potentially could react with any other material that the rubber comes into contact with.

Bament (1980s) published a formulary containing 116 recipes for Du Pont's trademark Neoprene rubber, covering applications from pipe seals, to underwater face masks, to car components to glazing gaskets. A typical such recipe, for a 70 hardness (Shore 'A' scale) glazing gasket is, by parts and action:

65 parts	Neoprene TW	raw polymer (polychloroprene rubber)
35	Neoprene TRT	raw polymer (polychloroprene rubber)
2	high activity magnesia	acid acceptor
3	octylated diphenylamine	antioxidant
10	factice	processing aid
3	microcrystalline wax	antiozonant, processing aid
1	stearic acid	processing aid
2	petrolatum	release agent
45	FEF carbon black	reinforcing filler
15	aromatic process oil	plasticiser
8	dispersed calcium oxide	desiccant
5	zinc oxide	vulcanising agent
1	DETU	cure accelerator

(Cured for 1 minute at 230°C, tensile strength 14 MPa, elongation 300%)

These are just some of the additives which are available. The selection of the additives is a specialised task, and the omission of just one additive from a batch of rubber may result in a useless product - some material tests are therefore used for quality control. Note also that there are two types of the basic Neoprene polymer used in this rubber - the processing of the polymer may allow different molecular structures for what is essentially the same polymer (for example the two types of Neoprene may have different mean chain lengths).

A typical wet-applied sealant may contain a similar array of chemicals, and the risk of cross-contamination is very high unless great care has been taken to check compatibility. Some companies that produce gaskets and sealants take great care to specify the exact sealant that should be used to seal over joins between gaskets - substitution with a cheaper sealant from another supplier may lead to a situation where the sealant does not actually adhere to the join. Similarly, trying to remedy a leakage problem by applying a sealant over a gasket may actually cause more problems than it solves, and lead to expensive works to remove the sealant and replace the gasket! Advice should always be sought on issues of compatibility - the gasket and sealant manufacturer should be the first point of inquiry for such advice.

Compatibility of the gasket material with the mounting and contact surfaces (and surface finishes) is also important, particularly if the surfaces are coated or will need to be re-coated in use (paints and stains also contain additives and could react with gasket or sealant materials).

4.4 Effect of fire on rubber

The effect of fire on components such as gaskets is often ignored. This situation is not helped by Approved Document B (1992) of the Building Regulations, which fails to give guidance on small components such as gaskets, even though in a curtain wall the design may permit a single length of gasket to span several floors.

Approved Document B makes the statement (clause 6.2) 'But a wall does not include: c. doors and door frames, d. window frames and frames in which glazing is fitted ...', which appears to say that window and door frames, and their associated gaskets, can be neglected. Indeed, small areas of wall with no fire resistance appear to be acceptable. However, concern has been expressed within the facade industry as to whether gaskets can transmit a fire between compartments of the building if they ignite, or whether a gasket will melt and release the joint. It is possible that a gasket material that burns can move a fire along a joint, and transfer a fire into another compartment in a building. Clearly this risk is less if the gasket is fitted locally around a glazing unit in a window frame. The joint designer may need to consider the risk of fire propagation if a gasket does ignite - a sensible view is that the damage caused by any fire should not be disproportionate to the source of the fire.

Another problem with fires is that in some types of building, such as food processing and pharmaceutical plants, the production of gases and particles from a burning gasket could lead to pollution of the product - a small fire could then lead to the destruction of an entire production run of a commercially valuable product.

The joint designer must clearly consider issues of fire safety, and the gasket producer should be involved in discussions. On the whole it may not be necessary to take any special precautions with regard to the selection of gasket material, but it may be important to consider the implications for replacement of gaskets should fire damage occur.

4.5 Closure

Although there are many tests which relate the properties of rubber materials, it is unusual for those tests used by the rubber industry to relate to the models for the material behaviour under mechanical loading. Furthermore there is little information relating material behaviour to gasket performance. The mechanical performance of gaskets is discussed in the following chapter.

Figure 4.1.1 **Stress-strain behaviour of a traditional engineering material in simple tension**

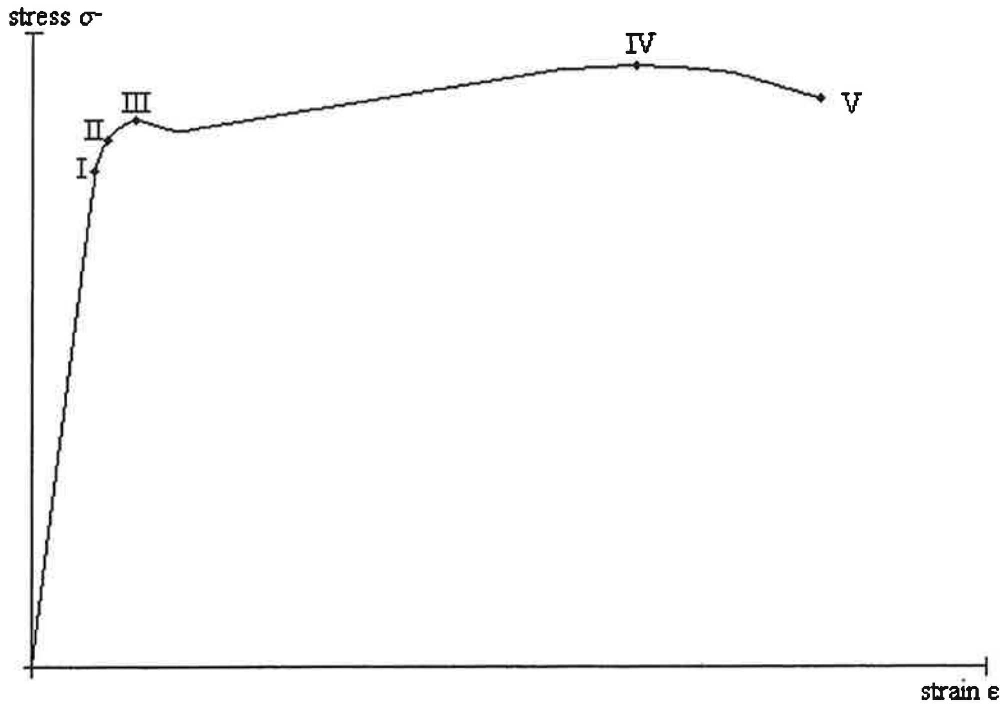


Figure 4.1.1.1 **A cube of material in shear**

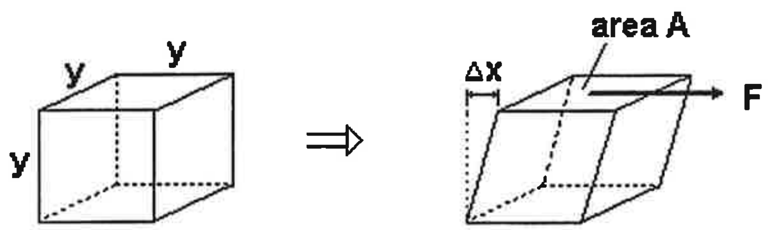


Figure 4.2.1 **Relationship between hardness and Young's modulus for incompressible rubbers (from Brown (1986))**

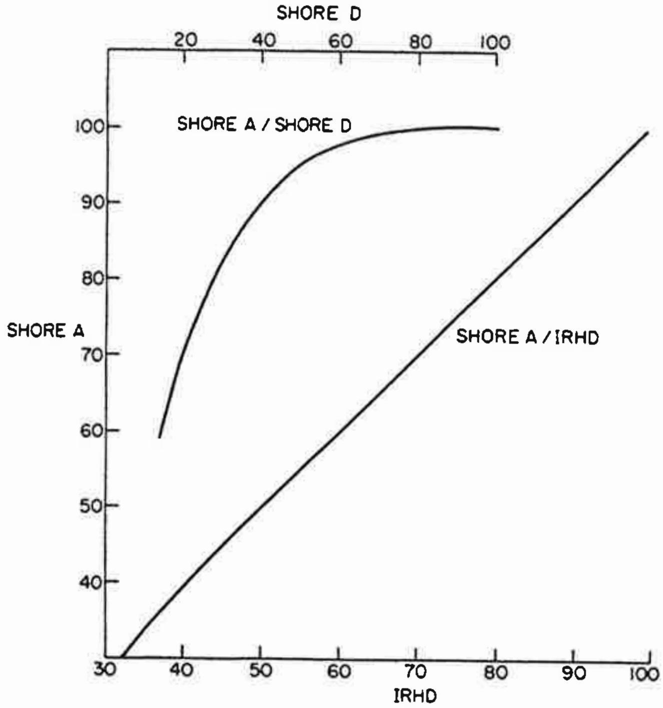


FIG. 8.6. Approximate relationships between Shore A, Shore D and IRHD scales (test piece 10 mm thick).

a) the relationship between the Shore 'A', Shore 'D' and International Rubber Degree of Hardness (I.R.H.D.) hardness scales

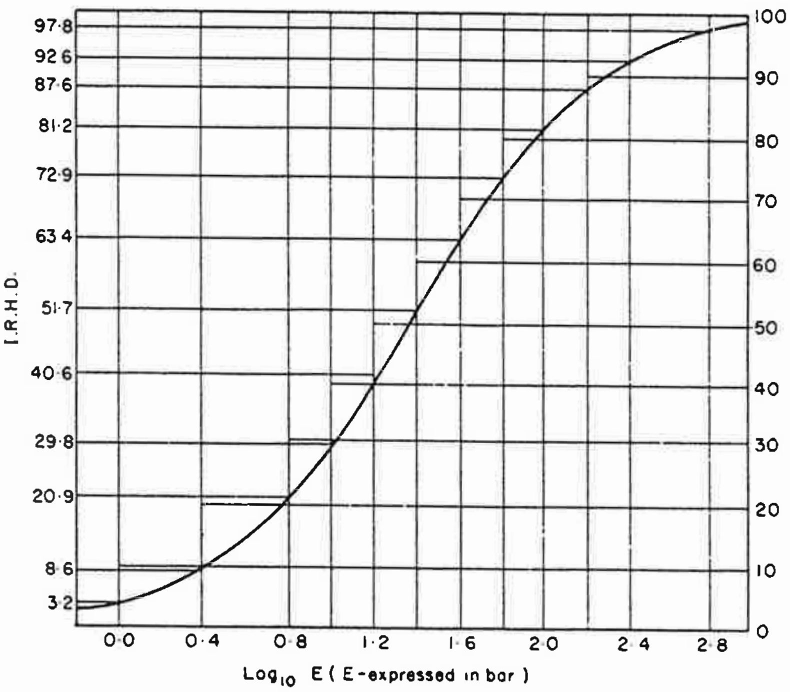


FIG. 8.1. Probit curve relating logarithm of Young's modulus, E, and hardness in IRHD.

b) the relationship between I.R.H.D. hardness and small-strain Young's modulus

Figure 4.2.2 **Three-dimensional stresses in the unit cube**

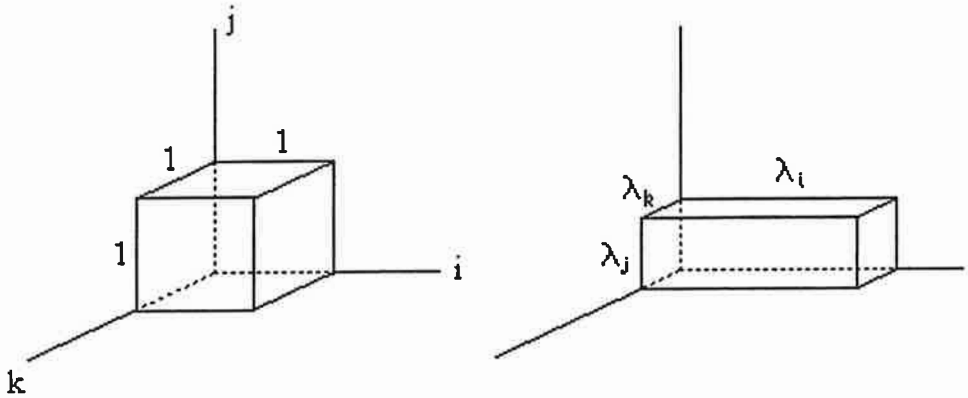
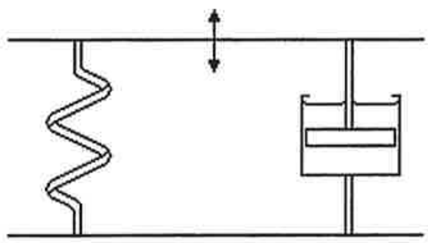
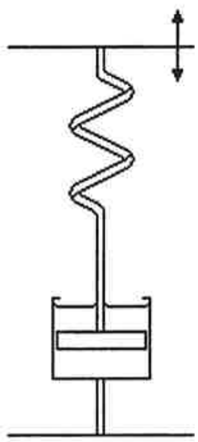


Figure 4.2.4 **Models for creep and relaxation in materials**

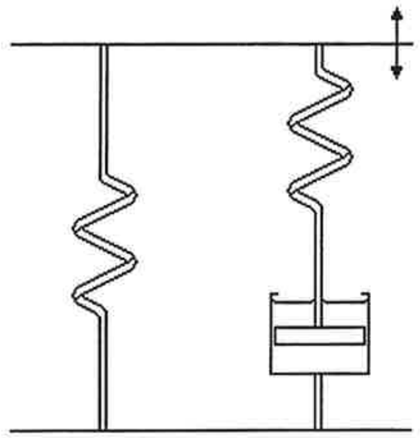


a) the Kelvin model for creep



b) the Maxwell model for relaxation

Figure 4.2.4 Models for creep and relaxation in materials



c) the 'standard linear solid' model for combined creep and relaxation

Figure 4.2.4.1 Time-dependent load-extension characteristic of rubber

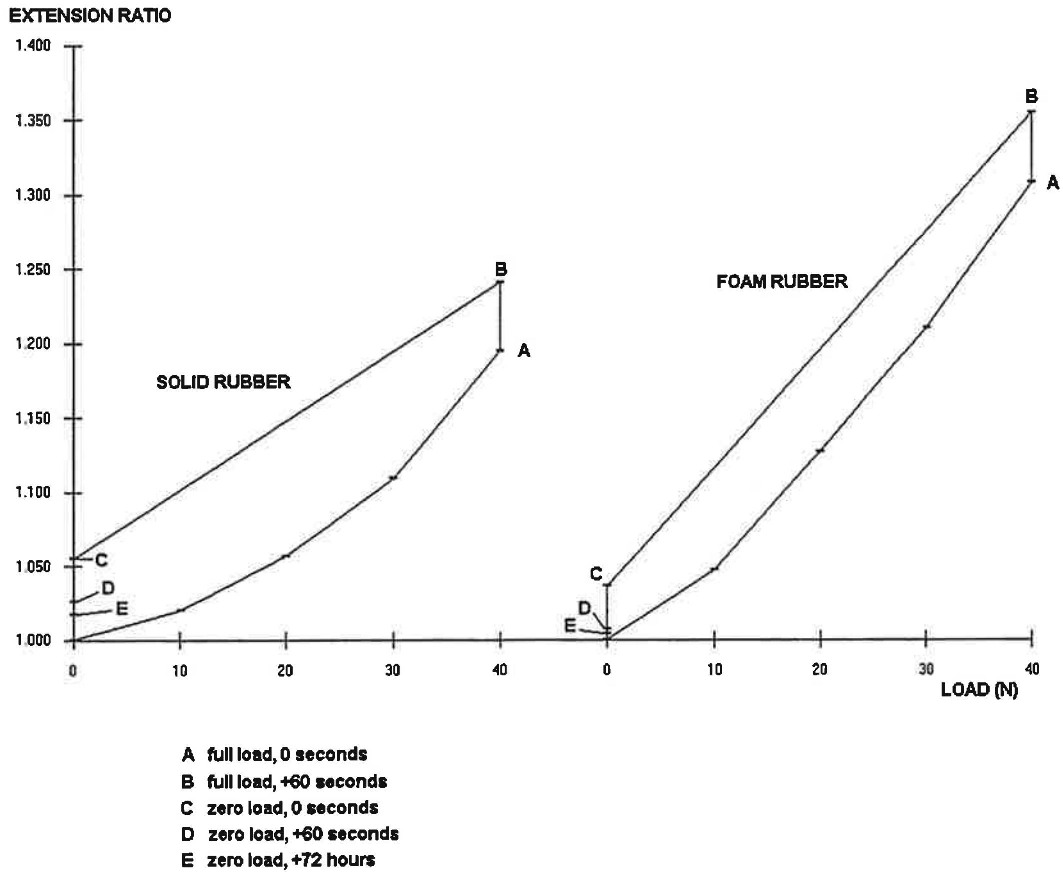
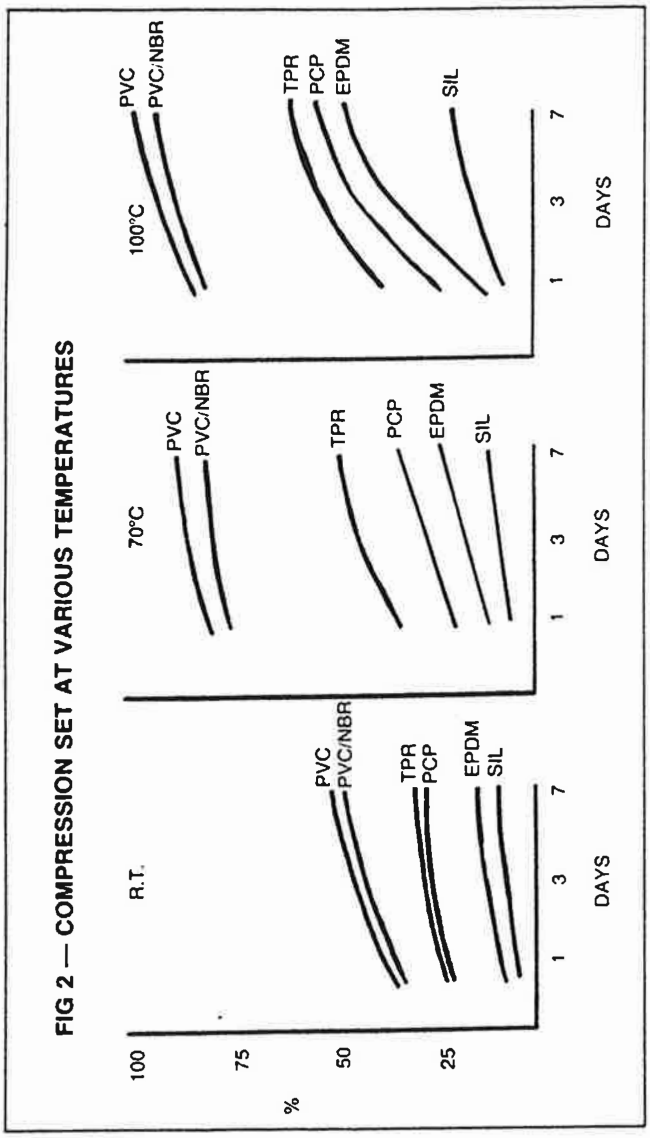


Figure 4.2.5 **Comparative study of compression set of different rubbers tested at different temperatures (from Park Rubber Ltd (1980s))**



5 THE PROPERTIES OF GASKETS

In Chapter 3 the relationship between gasket compression and air- and water-tightness was discussed. However, of equal importance is the relationship between gasket compression and the force that the gasket imposes on the joint surfaces. This is important for weather-strips, where the effort required to open and close a window or door depends on the stiffness of the seals, and is also important for glazing and infill gaskets, where the ability of the gaskets to support wind-loads without excessive deformation is important.

Covington (1982) suggests a maximum force for opening and closing of a hinged or pivoted window as 65 N - for a single-light casement window 600 mm wide by 900 mm high this would equate to a force of about 45 N per metre of draught-strip (or 22.5 N per metre if a two parallel strips are used). For an adult opening a door Covington suggests a force of 75 N - equal to a force of 26 N per metre for a door 2 m high and 0.9 m wide. Note that BS 7386 (1990) identifies a test for the force required to compress a draught-strip and indicates that the maximum acceptable force of compression or deflection is 60 N per metre for doors and 80 N per metre for windows. The study of Höglund and Wånggren (1980) takes 25 N as an acceptable closing force for a door (based on requirements for disabled people, equivalent to 8.6 N per metre for the door above) and the New Zealand study of Bassett and Beckert (1990) allows a force of 50 N per metre of draught-strip (the closing force would then be about 145 N for a typical door). It is therefore important that the force-compression characteristics of a particular weather-strip is known if these various requirements are to be met.

With glazing gaskets the force of compression may affect the ease of installation (particularly for wedge gaskets or gaskets which are installed with the glazing bead) and can also have an effect on the edge of the glazing. For example, there is a modern trend towards the use of sealed double glazing units with comparatively soft insulating materials (compared to the traditional aluminium alloy) being used for the edge-spacer - this is particularly important in cold climates where an insulating edge spacer may mean the difference between the formation of condensation or ice. If the glazing gaskets place a high load on the edge of the glazing then a softer edge spacer could be crushed, or a rigid spacer may press into the glass surfaces. It is important that the force-compression characteristic of the gasket should be known, and it is essential that the correct gasket is put into a given joint - the gasket must not be too stiff or the joint will be over-stressed. It should also be noted that loads such as wind-loading (and snow-loading for slope glazing) will increase the compression of the gasket opposing the load and will allow relaxation of the opposite gasket - the gasket must therefore be compressed sufficiently to prevent separation of the joint during loading. US practice suggests that the force of a glazing gasket on a glazing unit should be between 4 and 10 lbs per linear inch - about 700 to 1750 N per linear metre (FGMA (1990)).

5.1 Force-compression characteristics

5.1.1 Measuring force-compression characteristics

Gasket force-compression characteristics may be measured comparatively easily; for the purposes of this project a mechanical jig was designed as shown in Figure 5.1.1. With this jig a short length of gasket is mounted in an adjustable race (or an adapter-nib is used for wedge gaskets) and loaded by hanging weights at the end of the lever-arm. The mean deflection of the gasket is measured with dial gauges fixed at each end of the race. Five gaskets have been assessed using this jig. Additional tests have been carried out, using longer pieces of each gasket, to estimate the properties of the gasket materials.

The following sections describe the full test procedure that has been carried out, and also describe how attempts have been made to predict the behaviour of each gasket using computer simulation. The general sequence of measurement and simulation is:

- install a short length of the gasket (about 100 mm long) in the jig described above and measure the force-compression characteristic, which has been scaled up to give the force of compression per metre length of gasket (note that the lever-arm of the jig together with the weight of the dial gauges, adds a load of about 7 N to the gasket, and this is allowed for in the results; the effect of the different distances from the pivot of the lever-arm to the gasket, dial gauges and load has also been allowed for)
- fix one end of a greater length of gasket (about 1000 mm long) and hang weights from the other, whilst measuring the change in length of a gauge section (about 150 mm long) near the centre of the gasket, to determine the relationship between stress and strain for the material in simple tension
- using the material stress-strain data to obtain material properties, set-up and perform simulations to predict the force-compression characteristic of each gasket

This approach is somewhat simplified, particularly the test to determine stress-strain behaviour. However, a key objective of the test sequence was to assess whether these measurements could be made without the use of high technology - a simple test to check the load-extension behaviour of a length of gasket could be used for quality control, to make certain that the right gasket has been delivered or to check that the material is not too stiff as a result of low temperatures on the building site. Tests which rely on nothing more than a pencil, ruler and a set of weights (or even just one or two weights) are more likely to be used than tests which require complex equipment and the use of computer-based data-loggers.

The tests described below were carried out on two days, in an unheated laboratory at 15°C air temperature, where the gaskets had been stored, uncoiled, for several days prior to testing.

Although simple tension tests are usually carried out on samples with regular cross-section (circular or square) it has been necessary here to apply these tests to lengths of gasket with complex cross-sections. The results from the simple tension tests are presented in the form of the Mooney plot, as described in 4.2.3.2, and the appropriate coefficients determined. These coefficients are then used in a computer simulation, as described in Appendix A, to obtain a predicted force-compression characteristic. The force-compression tests were carried out in two groups - in the first series the gasket was compressed against a glass surface (the face of a mirror) in a dry condition. In the second series the tests on two of the gaskets were repeated with a film of oil between the gasket and the mirror to relieve friction (these tests were carried out several days after the others, to allow the rubber to recover its original shape completely). The use of a lubricant was considered important because rubber is often used for its non-slip properties - the coefficient of static friction for rubber on solid surfaces has been quoted as being '1-4', with a coefficient of dynamic (sliding) friction of around 1 for rubber on various solid surfaces - Lide (1992) - and friction may increase the force required to compress some types of gasket. Note also that the force-compression characteristic continued to be measured as the load was removed from the gasket, and that in every case there was a significant degree of hysteresis, with the deflection generally increasing slightly as the first few weights were removed.

5.1.2 Gasket A - the tubular weather-strip

The first gasket, as shown in Figure 5.1.2(a) is a hollow weather-strip, made from a black EPDM rubber with a nominal hardness of 70 I.R.H.D. The nominal thickness of this gasket (thickness at zero deflection) is 5.9 mm.

This gasket has only been measured on dry glass - the point of contact is unlikely to slide in practice.

The simple-tension test gave the results plotted in Figures 5.1.2(b) (applied load against extension ratio) and 5.1.2(c) (Mooney plot). Also plotted on these graphs are three lines corresponding to three different sets of Mooney coefficients.

Line 1 corresponds to the Mooney coefficients

$$C_1 = -3.24 \times 10^5$$

$$C_2 = 1.49 \times 10^6$$

which were obtained from a least-squares fit to the data. Note that the first coefficient is negative, whereas both coefficients are usually expected to be positive.

Line 2 corresponds to the Mooney coefficients

$$C_1 = 9.10 \times 10^5$$

$$C_2 = 0$$

These values were determined from Figure 4.2.1(b), which relates the I.R.H.D. hardness to the small-strain Young's modulus, for a hardness of 70 I.R.H.D. Young's modulus is then related to the Mooney coefficients by

$$E = 6(C_1 + C_2)$$

as described in section 4.2.3.2, and the second Mooney coefficient has been set to zero (a Gaussian material).

Line 3 corresponds to the Mooney coefficients

$$C_1 = 7.00 \times 10^5$$

$$C_2 = 0$$

These values were chosen, by inspection, to give an asymptote to the Mooney plot at high extensions, on the basis that the errors associated with measuring the extension of the gasket with a ruler would be most significant for points near an extension ratio of 1.0. This is because the Mooney plot is a plot of

$$\frac{f}{2\left(\lambda - \frac{1}{\lambda^2}\right)} \qquad \text{against} \qquad \frac{1}{\lambda}$$

A ruler with a resolution of ±0.5 mm, measuring an extension of 1 mm on a gauge length of 100 mm, would give an error of ±0.5% on the second term, but ±50% on the first term! For an extension of 10 mm the possible error on the first term reduces to just ±4.5%, and so the data points above a value of 0.9 on the x-axis of the Mooney plot could be disregarded, and the asymptote to the curve becomes more significant.

The measured and predicted gasket force-compression characteristics are shown in Figure 5.1.2(d). It is clear that up to the point at which the simulation finishes there is a reasonable match for the third set of Mooney coefficients, with both other sets giving higher forces for a given compression. Note that zero deflection corresponds to a nominal gasket thickness of 5.9 mm (measured), and so at the maximum deflection (3.341 mm) the gasket is compressed by 57%.

In each case the simulation finished prematurely due to a point being reached at which the weather-strip buckled. The deflected shape of the weather-strip at this point is shown in Figure 5.1.2(e). It should be noted that at the failure point the compressive force on the weather-strip was in excess of 100 N per metre of length - this is much greater than would be expected from a weather-strip in normal service.

5.1.2.1 Relationship between force of compression and Young's modulus

For an ordinary engineering material, in simple tension or compression, the force required to strain a material by a given amount is proportional to the Young's modulus of the material, as indicated by Hooke's law. From the results in Figure 5.1.2(d) it can be shown that the same rule applies to the force-compression characteristic of a gasket. The small strain Young's modulus for a Mooney material is defined by

$$E = 6(C_1 + C_2)$$

At the point where the three predicted characteristics in Figure 5.1.2(d) finish the compression of the gasket is identical, at 2.408 mm. The force at this point can be tabulated against the calculated small-strain Young's modulus, to give

Simulation	C_1 [N/m²]	C_2 [N/m²]	E (=6(C_1+C_2)) [N/m²]	F [N/m]	F/E [m]
1	9.10×10^5	0	5.46×10^6	202.8	3.71×10^{-5}
2	-3.24×10^5	1.49×10^6	7.00×10^6	261.2	3.73×10^{-5}
3	7.00×10^5	0	4.20×10^6	156.0	3.71×10^{-5}

The force divided by the Young's modulus for each simulation is a constant, and so the force-compression characteristic could be determined for one set of materials, and extrapolated for other values.

The relationship between Young's modulus and hardness has already been discussed, and Figure 4.2.1(b) can be used to derive the following table

I.R.H.D. hardness	Young's modulus [N/m²]	C_1+C_2 [N/m²]
30	1.01×10^6	1.7×10^5
40	1.54×10^6	2.6×10^5
50	2.34×10^6	3.9×10^5
60	3.48×10^6	5.8×10^5
70	5.48×10^6	9.1×10^5
75	7.09×10^6	11.8×10^5
80	9.36×10^6	15.6×10^5
90	1.98×10^7	33.0×10^5

Note that the relationships in these tables may only be applied to near-incompressible rubbers, and will not apply to rubber after some time in service. However, this table does allow the designer to gain some idea of the relationship between rubber hardness and the force-compression characteristic.

5.1.3 Gasket B - the E-gasket

The second investigation concerned an E-gasket, made from black EPDM with a nominal hardness of 60 I.R.H.D. This gasket was expected to be affected by friction, as it relies on the arms of the 'E' sliding over the glass, and so the gasket was tested first on dry glass and then on lubricated glass. The nominal thickness of this gasket is 6.8 mm

It was observed during the testing that the gasket rotated so that the two extreme arms of the 'E' made contact almost simultaneously. This has been allowed for in the simulation, and the gasket was simulated as shown in Figure 5.1.3(a) - contact with friction was then modelled on both the mounting and contact surfaces.

The simple-tension test gave the results plotted in Figures 5.1.3(b) (applied load against extension ratio) and 5.1.3(c) (Mooney plot). Also plotted on these graphs are two lines corresponding to two different sets of Mooney coefficients. Line 1 corresponds to the Mooney coefficients

$$C_1 = -1.29 \times 10^6$$

$$C_2 = 2.27 \times 10^6$$

which were obtained from a least-squares fit to the data. Note that the first coefficient is again negative.

Line 2 corresponds to the Mooney coefficients

$$C_1 = 5.80 \times 10^5$$

$$C_2 = 0$$

These values were again determined using Figure 4.2.1(b) and the relationship between Young's modulus and the Mooney coefficients. Note that these values give a good approximation to the asymptote of the curve and so a third set of coefficients has not been required.

The measured and predicted force-compression characteristics are shown in Figure 5.1.3(d). The measured data actually shows very similar behaviour with and without oil, although there is more deflection for the same maximum load with oil between the rubber and the glass. The arms of the 'E' all point in the same direction, and this may have an effect on the force because the glass was not restrained laterally and could slide, thereby relieving the friction force.

The simulations were performed with friction coefficients of 0.0, 0.5 and 1.0. As before there is a constant relationship between the force and the Young's modulus for the two sets of coefficients, even in the presence of significant friction! Interestingly the simulations both failed prematurely with a friction coefficient of 1.0 - the friction was high enough to prevent the arms from sliding and so a numerically complex buckling condition was generated. With a friction coefficient of 0.5 however the behaviour is quite complex, with the force required for a given deflection actually decreasing once a deflection of about 1.5 mm was reached. This emphasises the fact that the simulations only determine the stable shape of the gasket for each deflection, whereas for the measured gasket the force and deflection are dynamically linked. The computational effort required for a dynamic simulation is too high to justify this type of analysis, and the time-varying properties of the rubber may be significant. The large amount of hysteresis on the experimental force-compression characteristics clearly demonstrates the time-dependence of the rubber material properties.

The complex nature of friction was also observed during the measurements. It was noted during the dry gasket tests that at a load of about 470 N per metre the gasket arms began to slide over the glass - static friction was sufficient to hold the gasket up to this load, but once the static friction was broken a lesser dynamic friction came into play and the gasket collapsed as the arms of the 'E' were no longer held back by friction forces. It is probably because of the complex nature of the friction forces that the predicted characteristics do not match the measured characteristics, although the shape of the predicted characteristic without friction is reasonably close to the shape of the measured characteristic. Where high friction (μ=1.0) was simulated there is a definite kink in the predicted force-compression characteristic near to the point where the measured characteristics showed sudden slipping between the rubber and the glass. The implication is that friction is initially high, causing the force to increase rapidly with compression, followed by a period of sliding, with a lower dynamic friction coefficient, followed by a period when the rubber cannot slip any further and the force increases. It would seem that the ideal simulation would use high friction initially, low friction in an intermediate stage, and possibly high friction for the last stage. Note that the coefficients determined from the least-squares fit to the Mooney plot give closer forces to those measured.

5.1.4 Gasket C - the black crescent-wedge gasket

The third investigation concerned a crescent-shaped wedge gasket, made from black EPDM with a nominal hardness of 80 I.R.H.D. This gasket was also expected to be affected by friction, as the arms of the crescent make an almost perpendicular contact with the glass. The gasket was simulated as shown in Figure 5.1.4(a). The nominal thickness of this gasket is 7.5 mm.

The simple-tension test gave the results plotted in Figures 5.1.4(b) (applied load against extension ratio) and 5.1.4(c) (Mooney plot). Also plotted on these graphs are three lines corresponding to three different sets of Mooney coefficients. Line 1 corresponds to the Mooney coefficients

$$C_1 = -4.25 \times 10^6$$

$$C_2 = 6.51 \times 10^6$$

which were obtained from a least-squares fit to the data. The first coefficient is again negative.

Line 2 corresponds to the Mooney coefficients

$$C_1 = 1.56 \times 10^6$$

$$C_2 = 0$$

These values were determined using Figure 4.2.1(b) and the relationship between Young's modulus and the Mooney coefficients.

Line 3 corresponds to the Mooney coefficients

$$C_1 = 1.40 \times 10^6$$

$$C_2 = 0$$

These values give a better approximation to the asymptote of the Mooney plot.

The measured and predicted force-compression characteristics are shown in Figure 5.1.4(d). The measured data now shows very different behaviour with and without oil - there is a considerably higher compression for a given force with oil between the rubber and the glass. The arms of the crescent oppose each other and so friction dominates the behaviour of this gasket.

The simulations were performed with friction coefficients of 0.0 and 1.0. As before there is a constant relationship between the force and the Young's modulus for the three sets of coefficients, even in the presence of friction. The most realistic forces are found when the Mooney coefficients are taken from the least-squares fit to the data, although there is again evidence that the initial high static friction causes the measured force to increase more rapidly than the predicted force. The oil does not appear to have an effect for the initial small deflections - although the force required to cause sliding is small it is not generated until the gasket is compressed by a reasonable amount initially.

5.1.5 Gasket D - the white crescent-wedge gasket

The fourth investigation concerned a crescent-shaped wedge gasket, made from white EPDM with a nominal hardness of 70 I.R.H.D. Although this gasket should also be affected by friction it was only tested on dry glass. The reason for this is the somewhat awkward shape of the gasket - the groove on the back of the gasket is not initially parallel to the contact line across the arms of the crescent, with the result that during the force-compression tests the gasket was found to twist off and then re-seat itself on the nib. As a result it is difficult to measure the behaviour of the gasket, and removing friction between the gasket and the glass was thought likely to increase the difficulties already being experienced with the measurement.

This behaviour also caused problems with trying to decide how to simulate the gasket, and it was decided to simulate the gasket as initially flat against the contact surface, with the mounting groove on the back of the gasket fully constrained. The gasket was therefore simulated as shown in Figure 5.1.5(a). The nominal thickness of this gasket is then 5.8 mm.

The simple-tension test gave the results plotted in Figures 5.1.5(b) (applied load against extension ratio) and 5.1.5(c) (Mooney plot). Also plotted on these graphs are three lines corresponding to three different sets of Mooney coefficients. Line 1 corresponds to the Mooney coefficients

$$C_1 = -6.31 \times 10^6$$

$$C_2 = 1.00 \times 10^7$$

which were obtained from a least-squares fit to the data. Yet again the first coefficient is negative.

Line 2 corresponds to the Mooney coefficients

$$C_1 = 9.10 \times 10^5$$

$$C_2 = 0$$

These values were determined using Figure 4.2.1(b) and the relationship between Young's modulus and the Mooney coefficients.

Line 3 corresponds to the Mooney coefficients

$$C_1 = 2.50 \times 10^6$$

$$C_2 = 0$$

These values give a better approximation to the asymptote of the Mooney plot.

The measured and predicted force-compression characteristics are shown in Figure 5.1.5(d). The measured characteristic is clearly irregular, and the initially low force required for a high compression is a result of the nib initially pushing into the locating groove on the back of the gasket.

The simulations were performed with friction coefficients of 0.0 and 1.0. Once again there is a constant relationship between the force and the Young's modulus for the three sets of coefficients, even in the presence of friction. On this occasion the Mooney coefficients taken from the least-squares fit to the data give forces which are much higher than those measured. It is difficult to draw conclusions from this however, because of the difficulties experienced during the testing of the gasket.

5.1.6 Gasket E - the cellular rubber block

The final investigation examined a simple trapezoidal foam rubber block, as shown in Figure 5.1.6(a). This block of material was not expected to be significantly affected by contact friction and so was only tested against dry glass. The nominal thickness of this gasket is 9.6 mm.

As the material is a foam rubber it was not expected that the Mooney model would apply. However, a simulation was still carried out using this model to show the difference with other models.

The simple-tension test gave the results plotted in Figures 5.1.6(b) (applied load against extension ratio) and 5.1.6(c) (Mooney plot). Also plotted on these graphs are three lines corresponding to three different sets of material properties. Line 1 corresponds to the Mooney model using the coefficients

$$C_1 = 1.95 \times 10^5$$

$$C_2 = 2.32 \times 10^5$$

obtained from the least squares fit to the data. Note that the Young's modulus obtained from these coefficients is

$$E = 2.56 \times 10^6 \qquad \text{N/m}^2$$

The Blatz-Ko model has also been applied to this gasket. Unfortunately the simulation package ANSYS does not provide the full Blatz-Ko model, as described in 4.2.3.3, but instead only offers the limited case of $f=0$, as found for one particular foam by Blatz and Ko (1962). In this form the model is

$$U = \frac{G}{2}\left[J_2 - 3 + \frac{1}{\beta}\left(J_3^{2\beta} - 1\right)\right]$$

where

$$J_2 = \frac{I_2}{I_3}$$

$$J_3 = \sqrt{I_3}$$

$$\beta = \frac{\nu}{1-2\nu}$$

The value of the Poisson ratio ν was set to the value of 0.25 obtained by Blatz and Ko (1962), as there was no means by which it could otherwise be measured.

The shear modulus G was selected to give a close match to the measured force on the simple tension test. The Young's modulus is then related to the shear modulus by the standard relationship

$$G = \frac{E}{2(1+\nu)}$$

With this model a value of

$$E = 3.12 \times 10^6 \qquad \text{N/m}^2$$

was found to be satisfactory, and gives the second line plotted in Figures 5.1.6(b) and (c).

Finally a third model was applied to this material. This model is the traditional linear stress-strain model, but with large deflections allowed for, and it was found that a value of

$$E = 1.75 \times 10^6 \qquad \text{N/m}^2$$

gave a reasonable match to the simple tension test result, and this is plotted as the third line in Figures 5.1.6(b) and (c).

The measured and predicted force-compression characteristics are shown in Figure 5.1.6(d). It is clear that the material properties which gave such a good match to the simple tension test results generate compression forces much higher than those which have been measured. Using the Blatz-Ko and Hooke models it has been possible to determine the values of Young's modulus which would give a reasonably match to the measured characteristic as

$$E = 0.53 \times 10^6 \qquad \text{N/m}^2$$

for the Blatz-Ko model (compared to 3.12×10^6N/m^2 originally), and

$$E = 0.73 \times 10^6 \qquad \text{N/m}^2$$

for the Hooke model (compared to 1.75×10^6N/m^2 originally).

As there is only one model generally available for foam rubber, and as the Poisson ratio also needs to be determined, it is not unusual that there is a poor match between simulation and measurement. As stated in 4.2.3.3 even Blatz and Ko (1962) report different values for the material properties in simple tension, strip biaxial tension and homogeneous biaxial tension of one polyurethane foam.

5.1.7 Summary of measuring and simulating force-compression characteristics

The measurement of a gasket force-compression characteristic is subject to problems related to the satisfactory mounting of the gasket and the effects of friction. It has been shown that in some types of gasket contact friction plays an important role, and that the friction coefficient may not be constant. The role of friction during dynamic movement of the contact surface may be even more complex.

The jig used here is reasonably straightforward to use, and BS 7386 (1990) identifies other apparatus that could be used. The only uncertainty is in knowing how ageing will change the characteristics of the gasket; it has not been possible, within the time-scale of this project, to investigate the force-compression characteristics of aged gaskets. In particular such a study would require a sensible method of ageing compressed gaskets, coupled with a simulation package that could deal with the time-varying properties of stressed rubber components - note that a phenomena such as stress relaxation is likely to be greater in areas where the gasket is more highly stressed - and it may not be possibly simply to assume that a gasket will lose a certain percentage of its compressive force over a given period of time. It would also be appropriate to measure the weather-tightness (or at least the air-tightness) of the original and aged gaskets, which is again beyond the scope of this project.

The simulation of force-compression characteristics depends upon the availability of sensible experimental data for the rubber, combined with models that can be fitted to the data with least effort and a reasonable chance of success. The inability to measure the actual Poisson ratio of a rubber is a limiting factor, and it has been assumed in the first four of the examples above that the Poisson ratio is 0.49 - near incompressible. The wide range of potential materials, and the possibility that the standard relationships will not apply to materials that are not 'nearly incompressible', complicates the situation even further.

It is not expected that simulation will be of significant value unless the materials used for gaskets are properly researched and sensible tests for their engineering properties standardised. The traditional tests such as 'hardness' and 'compression set' have little relevance when trying to evaluate the mechanical behaviour of a system, and are of little relevance to the designer unless they can be related to engineering properties.

5.2 Using gasket force-compression characteristics

If a force-compression characteristic is known for a gasket then it can be used to determine the forces placed on the joint, taking due account of manufacturing tolerances, and to estimate changes in the compression of the gaskets due to applied loads such as wind-loading. The following sections show how force-compression characteristics could be used.

The performance of a gasket can be defined in terms of a force-compression characteristic, together with a nominal thickness, which is the thickness of the gasket when just in contact with the contact surface (i.e. at the zero point on the force-compression characteristic). In the following sections the nominal thickness of the gasket is denoted by T.

5.2.1 Design joint force

If there is a single gasket in a joint then the joint force is simply read from the gasket force-compression characteristic for the required compression, noting that the force-compression characteristic gives the force per linear metre of gasket and so must be multiplied by the total length of gasket in the joint if the total force is needed.

For joints with opposing gaskets retaining some other component (i.e. glazing and infill gaskets) the compression of each gasket depends on the difference between joint width and infill thickness. Figure 5.2.1(a) shows a typical arrangement of joint, infill and gaskets immediately prior to assembly. The combined compression of the gaskets must be

$$\Delta = T_1 + T_2 + P - J$$

- Δ is the required overall compression, in m
- T_1 is the nominal (un-compressed but in contact) thickness of gasket 1, in m
- T_2 is the nominal (un-compressed but in contact) thickness of gasket 2, in m
- P is the design thickness of the infill panel edge, in m
- J is the design joint gap, in m

The joint gap depends on the fit between the frame and the bead, which can be assumed to be in contact at one point such that

$$J = F - B$$

- F is the distance from the contact point to the frame mounting surface, in m
- B is the distance from the contact point to the bead mounting surface, in m

These formulae define how much the two gaskets must be compressed overall to fit into the joint. The formula assumes that the infill and joint do not deflect under loading, although this could be allowed for if the stiffness of the infill and joint components were known.

The particular compression of each gasket must satisfy a force balance - the force provided by each compressed gasket should be equal in the absence of other applied loads (this can be assumed to be the case as the gaskets are installed - the subsequent addition of other loads is described below). The compression of each gasket can then be determined by plotting the gasket force-compression characteristics on a common set of axes, as shown in Figure 5.2.1(b). The first characteristic is plotted in the normal way starting from zero compression, but the second characteristic is plotted starting from a compression of Δ and working backwards! The force applied by each gasket is equal where the curves cross and the compression of each gasket is then readily determined. This whole operation is made easier if the curves are each plotted to identical scales on separate pieces of transparent paper - one of the pages can simply be reversed over and overlaid on the other.

5.2.2 Allowing for joint and gasket tolerances

The toleranced joint force is the gasket compression allowing for tolerances on the gasket size, infill thickness and joint gap (the tolerance on the joint gap are affected by tolerances on the components which form the joint surfaces). In the worst case the overall tolerance on a joint should be determined by adding together the tolerances on each of the components. For a typical joint, as shown in Figure 5.2.2, the worst case overall tolerance (the tolerance on the compression Δ) is

$$\delta = f + b + p + t_1 + t_2$$

- δ is the overall tolerance on the required gasket compression, in m
- f is the tolerance on the frame dimensions, in m
- b is the tolerance on the glazing bead dimensions, in m
- p is the tolerance on the infill panel edge thickness, in m
- t_1 is the tolerance on the nominal thickness of the first gasket, in m
- t_2 is the tolerance on the nominal thickness of the second gasket, in m

The procedure outlined in 5.2.1 should now be repeated for the total compressions of $\Delta+\delta$ and $\Delta-\delta$, to determine the likely range of forces that can be expected from the selected gaskets. This is shown in Figure 5.2.2(c), where one of the gasket force-compression characteristics has been shifted to either side of the initial position by an amount δ. If it is found that the force might be too high or too low then it may be appropriate to have alternates for one or both of the gaskets. The window installer may already be using a range of different wedge gaskets to ensure that one is used which best fits the joint - the installer measures the gap rather than applies the procedure above, but the designer using this procedure could determine whether a range of gasket sizes is likely to be required.

Typical tolerances which relate to windows and claddings are given in BS 1474 (1987), BS 7413 (1991), BS 7414 (1991), BS 952:Part 1 (1978), BS 5713 (1979) and BS 3734 (1978). As an example consider a joint in a PVC-U window frame with a 20 mm double glazing unit. The dimensions of the various parts have been calculated and the selected gaskets are required to be compressed by 4 mm in order to fit into the joint. The following tolerances are then defined in various standards:

- PVC-U extrusions (BS 7413 (1991)): most dimensions ±0.3 mm
- extruded gaskets (BS 3734 (1978)): unsupported extrusion, 5 mm thickness, ±0.35 mm (class E1)
- double glazing unit (BS 5713 (1979)): thickness, glass panes each less than 6 mm thick, ±1.0 mm

This gives the following results:

$f = b = 0.3$ mm

$t_1 = t_2 = 0.35$ mm

$p = 1.0$ mm

$$\delta = f + b + p + t_1 + t_2 = 2.3 \quad \text{mm}$$

If the nominal required compression Δ is 4.0 mm then the actual compression could vary from 1.7 to 6.3 mm - it is unlikely that a single pair of gaskets will meet this requirement!

It may also be necessary to allow for changes in the joint width due to structural, moisture and thermal movements. Alexander and Lawson (1981) discuss movements which may occur in buildings and identify methods for calculating structural, thermal and moisture movements.

Bonshor (1977) gives some examples of typical problems that arose from poorly toleranced joints, where the joint designer has not allowed for possible misalignments during assembly, or has improperly calculated critical dimensions. It is essential to note that some types of gasket can cater for greater misalignments than others. The crescent-shaped wedge gasket, with a single contact point on either side of the mounting groove, is self-levelling. Gaskets with a basically rectangular profile and made from a hard rubber may not make a good contact with a surface if there is an angular misalignment. Note that a good contact is more likely to occur with a solid gasket if the gasket material is more flexible or if the gasket is hollow. Alternatively a profiled gasket (such as an E-gasket) will accommodate greater misalignments if the profile has a number of contact elements which can deflect.

In CIRIA SP87A (1992), some information is given about the design of joints, and in particular there is a note to the effect that tolerances may be less significant with wider joints - the extra force given by a gasket that is over-compressed due to the accumulation of tolerances will be less if the range of compression of the gasket is greater to begin with. Curtain walling systems often use a combination of a foam-rubber glazing gasket opposing a rigid rubber glazing gasket - the foam rubber gasket has a much wider range of operation for which the compression force varies only slightly and can actually be used to accommodate significant tolerances during fixing. The only possible drawback of this system occurs during wind- and snow-loading - when the loading is such that the softer gasket is compressed, the rigid gasket must have enough flexibility to be able to relax and yet still remain in contact with the glazing or infill panels.

These simple analyses need nothing more than a force-compression characteristic for each gasket. The force-compression characteristic may also provide a quality control function for the gasket user - with a suitable, simple, jig it could be checked on site. At present the gasket user has little assurance that the gasket in use was properly manufactured, or manufactured from the correct material, and tests which can at least prove the mechanical integrity of the delivered gasket are desirable.

5.2.3 Joint movement due to wind- and snow-loading

The effect of wind-loading should be allowed for in the design of joints with opposing gaskets. The procedures of 5.2.1 and 5.2.2 above should first be used to determine gasket compression during installation and the possible effects of tolerances. The wind-loading can then be estimated for the particular product and the following procedure applied:

Firstly the wind-load must be converted to an equivalent force per unit length of gasket. Consider a wind pressure acting over a rectangular infill. The total force on the infill is

$$F = pXY$$

- F is the force, in N
- p is the pressure, in Pa
- X and Y are the dimensions of the infill between gaskets, in m

This force can act in either direction (suction pressures are as likely as positive pressures) and must be supported by the gasket. The added load per unit length of gasket is the total force divided by the perimeter of the infill

$$f = \frac{F}{2(X+Y)} = \frac{pXY}{2(X+Y)}$$

- f is the force per unit length of gasket, in N/m

The value of f should be determined for each different size of infill (the infill may be glazing or an insulated panel). The largest value of f should then be used in conjunction with the previous analyses to assess the performance of the gaskets under wind-loading.

Now consider the diagram of Figure 5.2.3. This is the force-compression characteristic of an assembled joint, with tolerances already accommodated. The wind-load may act in either direction and will compress one of the gaskets whilst allowing the other to relax. The load on the compressed gasket will increase, whilst the load from the other gasket will decrease. The final position of the infill will be such that the wind-load plus any force from the relaxed gasket equals the force from the compressed gasket. This is the point at which one of the force-compression characteristics exceeds the other by an amount equal to the wind-load. These points are readily found and are shown on Figure 5.2.3.

Note that if both points fall within the initial range of compression from 0 to Δ then both gaskets will remain in contact with the infill. Indeed it is possible to determine the wind-load at which either gasket will separate from its contact surface from this figure as the difference in the gasket forces at the point 0 and Δ on the x-axis of the diagram.

The wind-loading assessment should also be carried out for the extreme conditions indicated by the tolerances on joint, infill and gasket sizes.

The effect of snow-loading is important for horizontal and sloped glazing systems and must also be allowed for. If the expected weight of snow is determined then this too can be converted to a force per unit length of gasket. The snow-loading will always act downwards, and so adds to the wind-loading in one direction but can be subtracted from the wind-loading in the other. Note that snow-loading is potentially more of a problem because the weight of the snow may hold a glazing unit down below the expansion limit of the external gasket, thereby creating a stable opening into which melt-water can flow. Methods of calculating the snow-load are described in BS 6399:Part 3 (1988), and the method for determining the resulting gasket compression/relaxation is as detailed above for wind-loading.

This approach can be used to determine the movement of a joint due to applied loads. The only issue that remains to be determined is the effect of creep and relaxation.

5.2.4 Effect of ageing on force-compression characteristics

The force produced by a gasket in compression will gradually decrease over a period of time due to the effects of creep and stress relaxation. This phenomena is measured for gasket materials by means of either the compression set or deflection recovery. Compression set is probably the best indicator of the properties of a rubber product that is placed in bulk compression, as a glazing gasket is likely to be. Deflection recovery, being based on tests on a tube-section, is probably more appropriate for thin-walled tubular gaskets, which are mostly used as weather-strips.

In general terms compression set will cause the gasket to lose its ability to recover from deflection, and will also lower the forces shown in Figure 5.2.1(b), such that the force at a given compression will become less over a period of time. This may not move the equilibrium point as both gaskets could relax by a similar amount. However, it will increase the risk of the relaxed gaskets separating from the contact surface under wind-loading. Unfortunately there is no data to say how the compression set of a material actually relates to long -term compression of the compressed gasket under wind-loading, and the following analysis is somewhat arbitrary:

Rubbers used for gaskets should have less than 25% compression set (the limit defined by BS 4255:Part 1 (1986) except for coloured/silicone rubber which is limited to 30%). It might then be assumed that each gasket will, over a period of time, lose 25% of its range of recovery - this means that the extremes of the range of acceptable deflections (the points indicated by *0* and *Δ* on the x-axis) will move closer together. To determine the reduction of the range of operation requires that the distance from the equilibrium point (as shown in Figure 5.2.1(b)) to each extreme be reduced by 25%; the effect of this is shown in Figure 5.2.4. Note that the force-compression characteristics of each gasket have not been altered in any way - the compression set test only identifies the creep of the rubber over a period of time, it does not make any assessment of the stress relaxation that has occurred. If Figure 5.2.4 is now used for an assessment of the effect of wind-loading the results may be of little significance, because the true aged gasket force-compression curves may be closer to those indicated by the dotted lines on Figure 5.2.4. The reduction in the force at equilibrium following combined set and relaxation is difficult to determine, and further research is needed.

As a final point Kehrli (1992) states that proper compression ratios must be maintained during wind-loading and thermal movements, and that seals must be maintained in compression. It is however noted that water penetration is probable, and that the joint designer should design for water management! There is also a strong emphasis on keeping the joint design 'simplistic and pure'.

5.2.4.1 Gaskets operating on principles of deflection

Not all gaskets are designed to operate in bulk compression. Some gaskets, particularly those used as weather-strips, work on a principle of deflection, either of a cantilevered arm or of a hollow tube. However, some gaskets work on a principle of wiping, with minimal deflection. Carruthers and Bedding (1981) describe various types of weather-strip, and include a chart which allows the type of weather-strip to be selected for a given joint. However, these other types of gasket could all be analysed using methods similar to those outlined above.

5.3 Tests and standards which relate to gasket performance

The previous discussion has concentrated on the force-compression characteristics of the gasket. However, there are many tests and standards which purport to relate to gasket performance, and which the designer presently needs to be aware of.

There is little information currently available in standards to help the joint or gasket designer to get best performance. Standards are usually divided into one of four groups:

1. Design standards
2. Performance standards
3. Material property standards
4. Component property standards.

The distinction between these types of standard is as follows:

5.3.1 Design standards

Design standards identify the way in which a system (either a component or some assemblage of components) is constructed. Materials and processes may be closely defined, with little room for variation. Standards of this type prevent innovation by excluding the unknown. For example BS 4255:Part 1 (1986) is titled *Rubber used in pre-formed gaskets for weather exclusion from buildings*, implying that all gaskets used in building facades must meet this standard, and yet the first clause of the standard states that it 'applies to chloroprene, butyl, halobutyl, ethylene propylene, chlorosulphonated polyethylene and silicone rubbers used in the gaskets'. This statement appears to exclude all other materials and as a result BS 7412 (1991) includes a clause (4.3.1) which allows any material to be used for gaskets providing it complies with a new table of tests, even though BS 7412 (1991) then states (clause 4.3.2) that thermoset rubbers must also comply with BS 4255:Part 1! The right of one British Standard to supersede another should be questioned (BS 7412 may have been heavily represented by the plastics industry, given that it is a standard for plastic window frames, and there may have been a vested interest in allowing the use of materials that do not comply with BS 4255:Part 1), but this situation would not have arisen if BS 4255:Part 1 had been performance based rather than prescriptive.

5.3.2 Performance standards

Performance standards identify levels of performance that the system must achieve. These standards do not limit the use of any material or process, providing the stated level of performance is achieved, using the defined tests. BS 7412 (1991) would fall into this category where gaskets and weather-seals are concerned, except that it forces thermosets into complying with an additional set of tests that thermoplastics need not meet.

5.3.3 Material property standards

Some standards define how base material properties should be determined. BS 903 is typical of this type, as it defines how the various properties of the rubber material should be measured. These standards are useful from the point of quality control, but there is often little information to relate material properties to product performance where more complex material behaviour is encountered. Thus a test for compression set or deflection recovery might give some information about the behaviour of a material but there is little information as to how different designs of gasket will behave when made from the same material - in practice the stress relaxation in a real gasket will be greatest where the stresses are greatest, and some gaskets do not behave as a simple compressed block, although of course there are those that do.

The Japanese standard JIS A 5756 (1989) is of this type, and caters for thermoset and thermoplastic elastomers. However, the required performance is different for different types of elastomer (different materials) although the tests are identical. Interestingly the requirements for 'compressive permanent strain' are: 'less than 75%' for vinyl chloride system elastomers and 'less than 45%' for thermoplastic elastomers (both to be tested at 70°C), but 'less than 35%' for chloroprene system and EPDM system elastomers (both to be tested at 100°C).

5.3.4 Component property standards

The final type of standard is that which defines a procedure for assessing the properties of a component. Such a standard might define a procedure and test apparatus with which some property of a whole-system is determined. A typical example is the test method laid out in Appendix G of BS 7412 (1991) for determining the tear resistance of co-extruded glazing beads. The purpose of this procedure is to test the bond between a rigid PVC-U bead and a co-extruded glazing gasket - typically there is no attempt to identify the properties of either part of the co-extruded bead-and-gasket and the test is simply a go/no-go assessment.

5.3.5 British Standards relevant to gasket design

BS 4255:Part 1 (1986) has already been identified as the main standard relating to the use of gaskets in building. However, there are also a number of British Standards relating to the design of products incorporating gaskets, including:

Wood windows	BS 644:Part 1 (1989)
Aluminium windows	BS 4873 (1986)
Aluminium framed sliding glass doors	BS 5286 (1978)
Steel windows	BS 6510 (1984)
PVC-U windows	BS 7412 (1991)

In general these standards place limitations on the materials that can be used for gaskets and weather-strips, and as such they both prevent innovation and fail to inform the gasket or joint designer as to the key performance issues. Ideally these standards should refer to a common general standard for gasket properties, since they do refer to common standards for weather-tightness (BS 6375:Part 1 (1989)) and operation and strength (BS 6375:Part 2 (1987)).

Standards relating to gaskets for use in buildings have been summarised by the BPF (1993). This document is basically a repeat of the tests given in BS 7412, although cellular adhesive glazing tapes are also referred to. A performance classification scheme for components is given, based on current work in European standardisation. However, tests for compression set are not mentioned.

5.4 Closure

There is a significant gulf between the science that is applied to the design of gaskets in windows and cladding systems (and gasketted joints) and the science that could be applied. The gasket should be assessed to determine whether it will fit into the joint and whether it will perform over a period of time. The fact that there are no British Standards which relate to gaskets (they all relate to the base material) indicates how long UK designers have been working without any form of rule-based assessment which can be applied to gasket design and joint performance.

Figure 5.1.1 **A jig for measuring gasket force-compression characteristics**

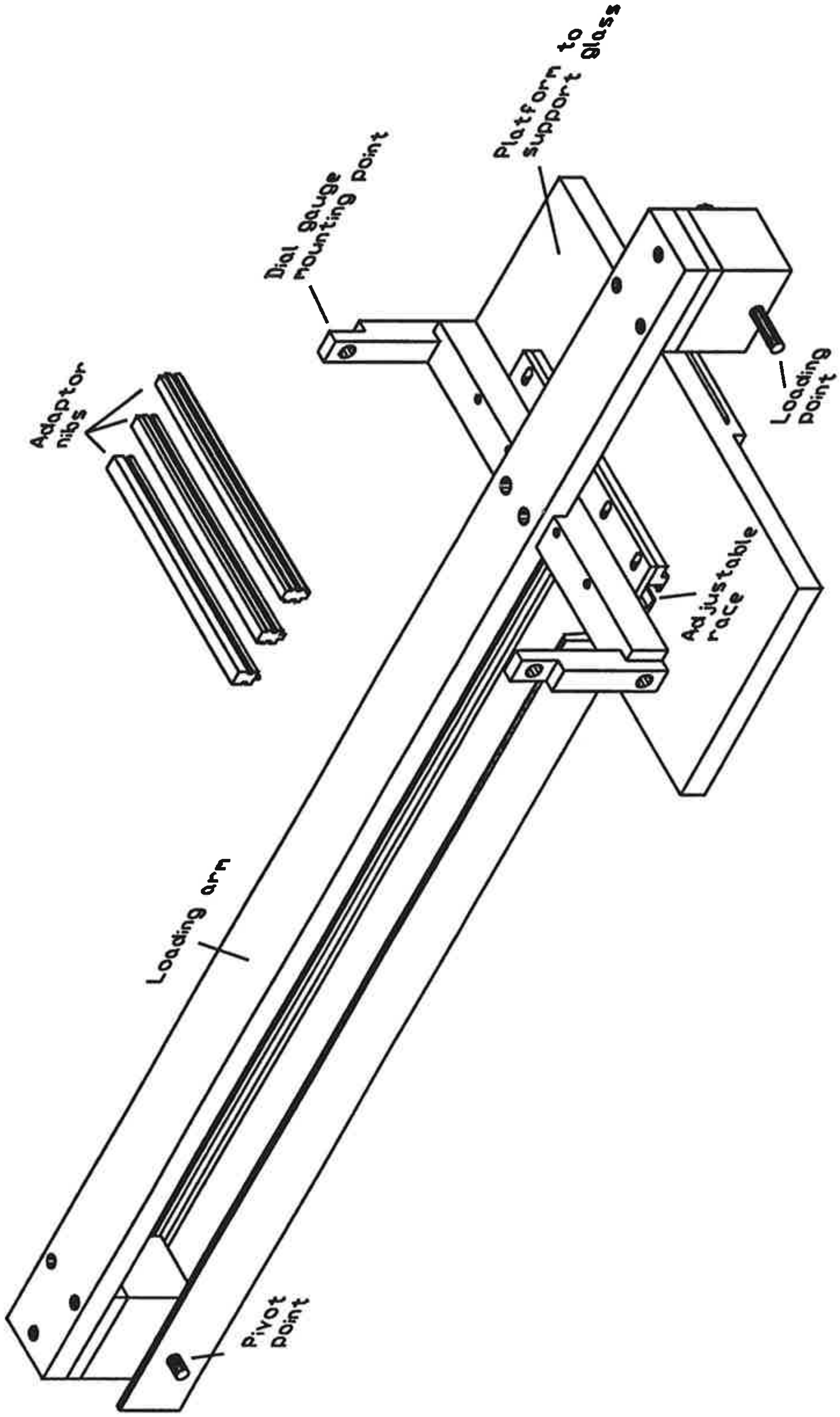
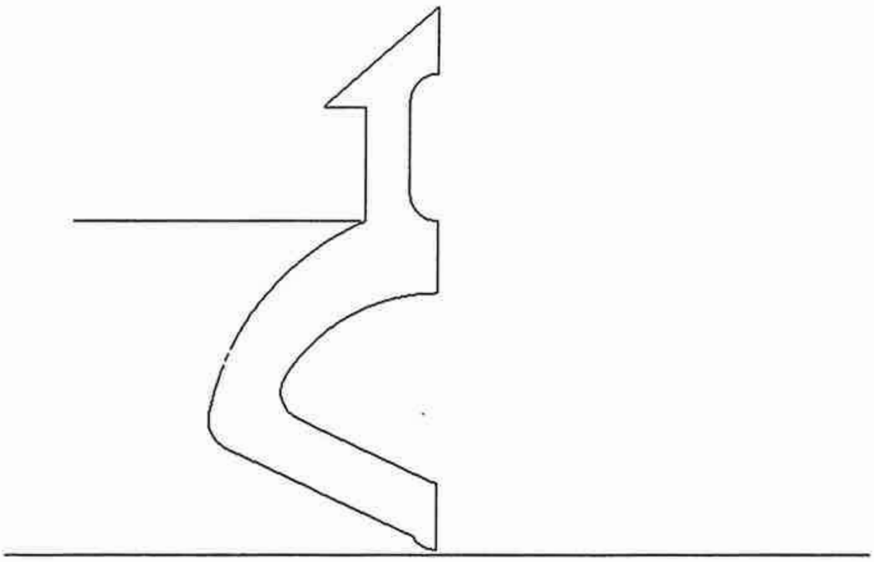
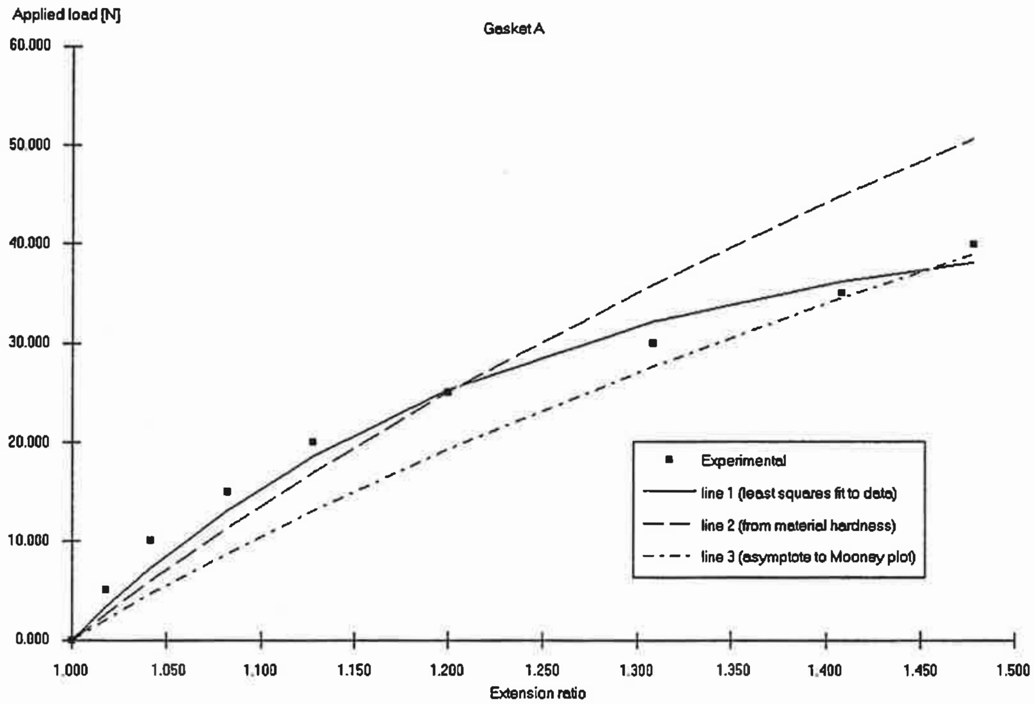


Figure 5.1.2 **Gasket A - the tubular weather-strip**

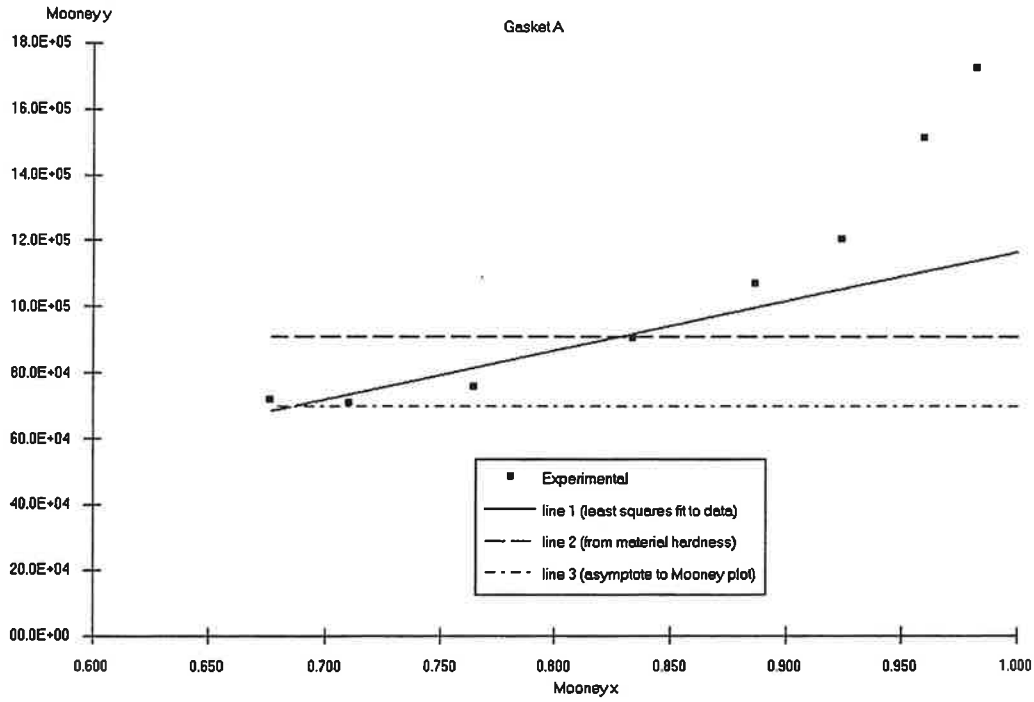


a) the gasket

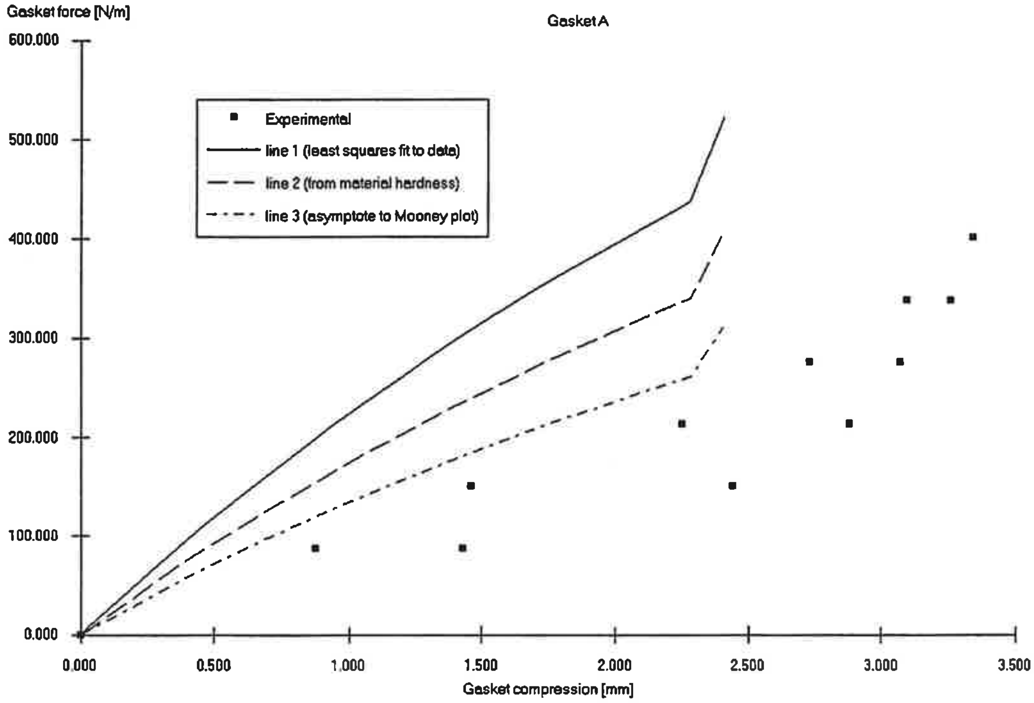


b) results of the material load-extension test

Figure 5.1.2 Gasket A - the tubular weather-strip

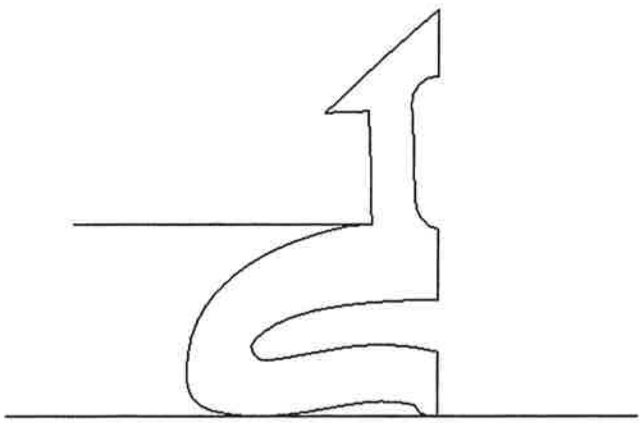


c) Mooney plot of the material load-extension test results



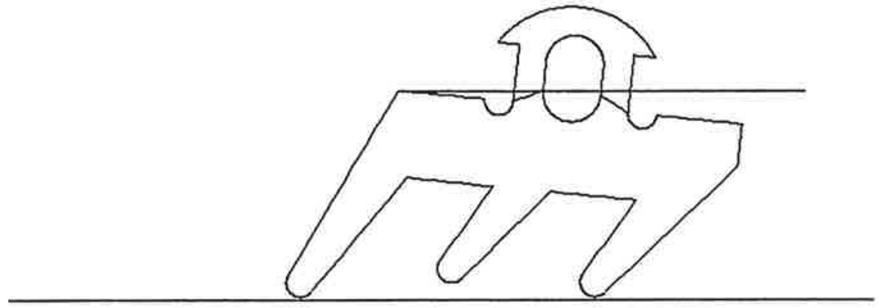
d) measured and predicted gasket force-compression characteristics

Figure 5.1.2 **Gasket A - the tubular weather-strip**

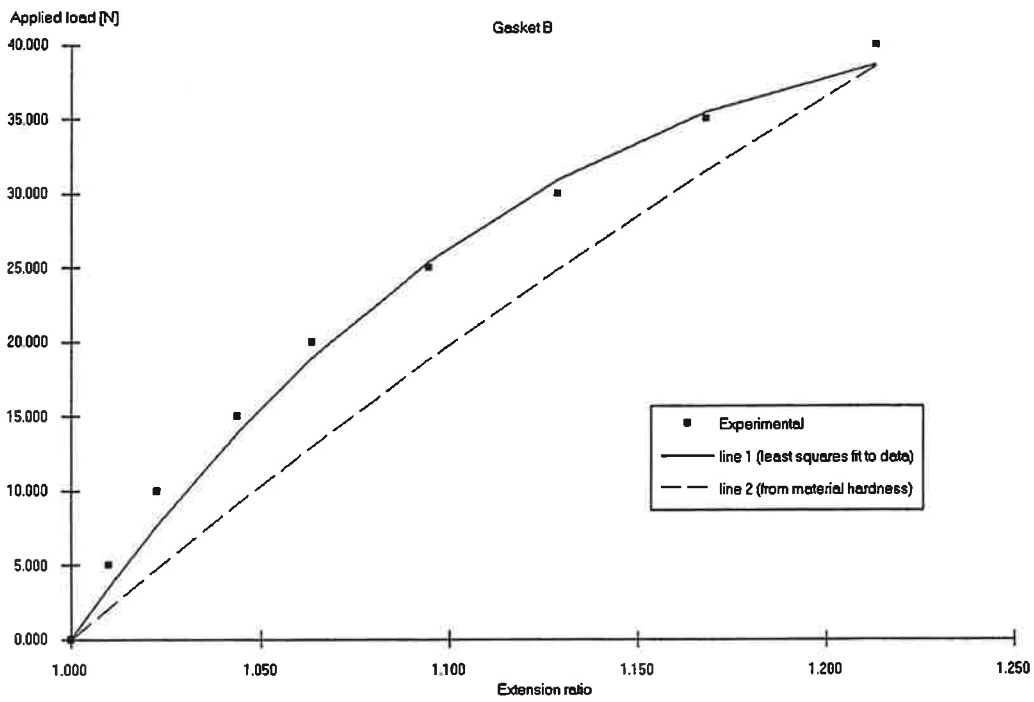


e) shape of the weather-strip at simulation failure

Figure 5.1.3 Gasket B - the E-gasket

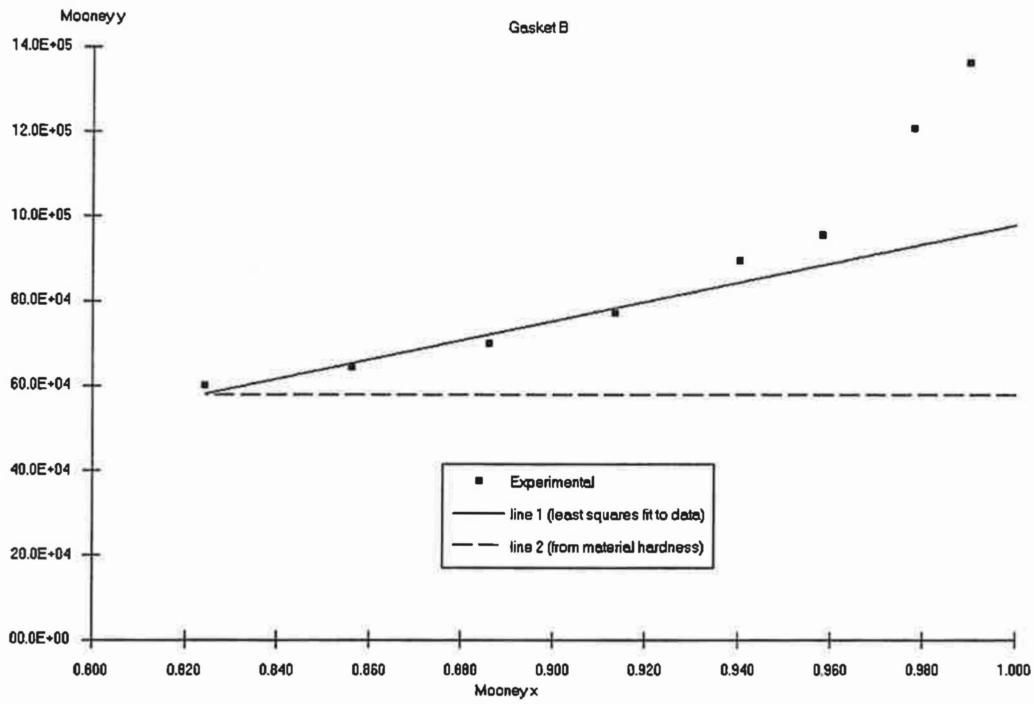


a) the gasket

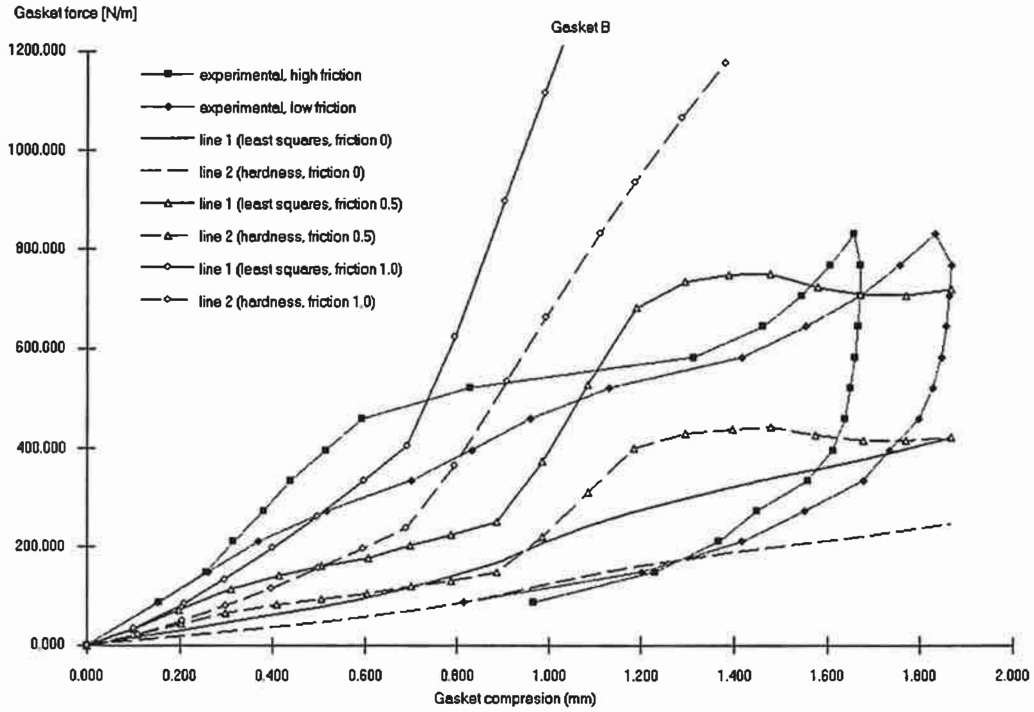


b) results of the material load-extension test

Figure 5.1.3 Gasket B - the E-gasket

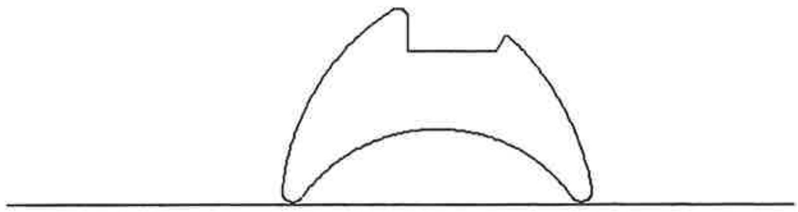


c) Mooney plot of the material load-extension test results

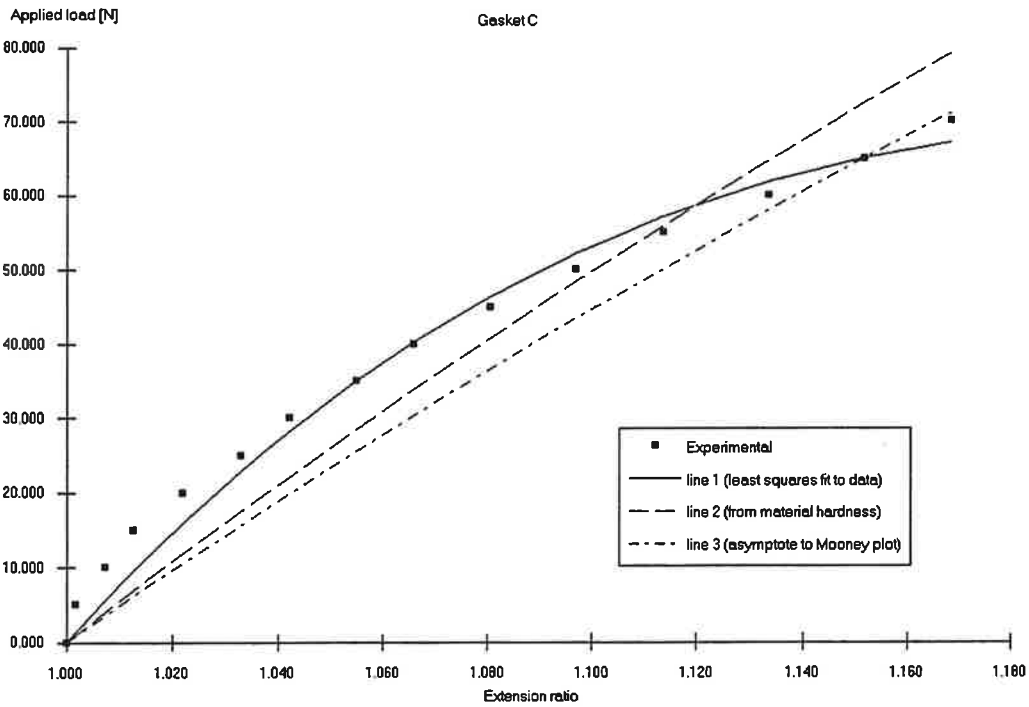


d) measured and predicted gasket force-compression characteristics

Figure 5.1.4 **Gasket C - the black crescent-wedge gasket**

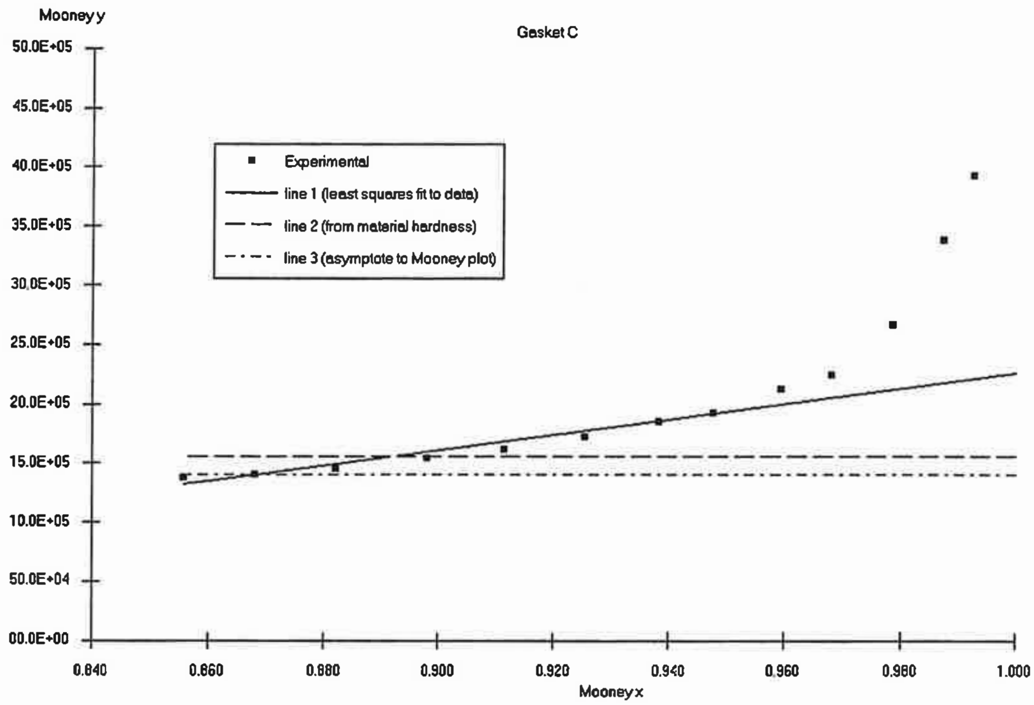


a) the gasket

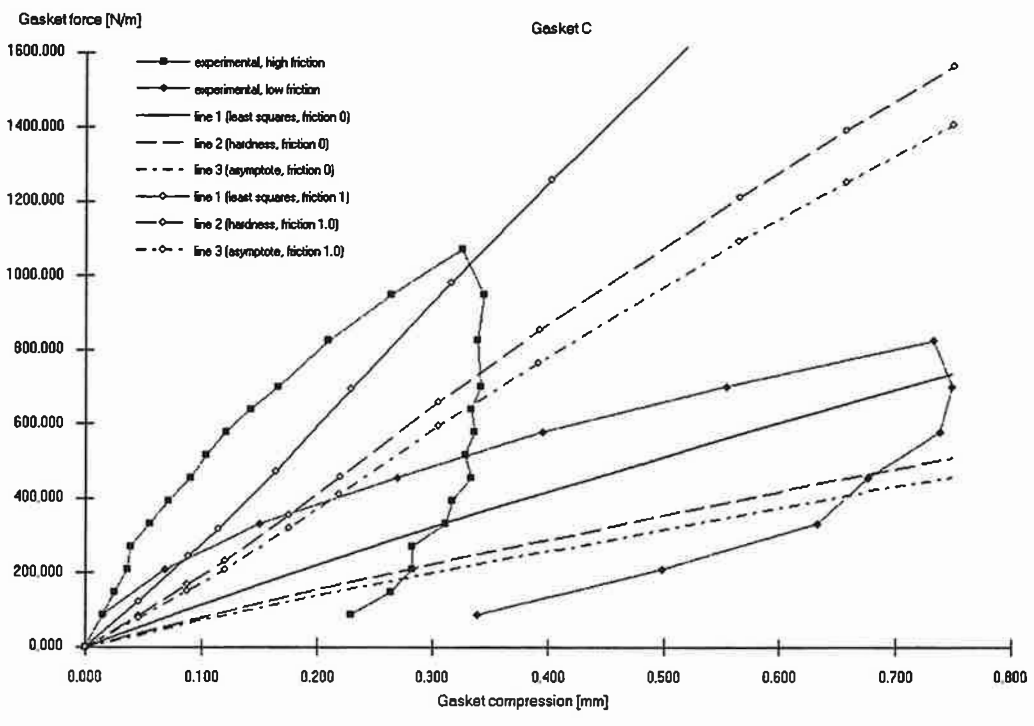


b) results of the material load-extension test

Figure 5.1.4 **Gasket C - the black crescent-wedge gasket**

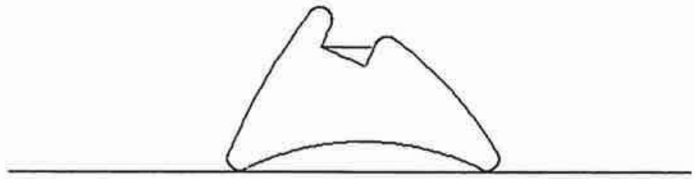


c) Mooney plot of the material load-extension test results

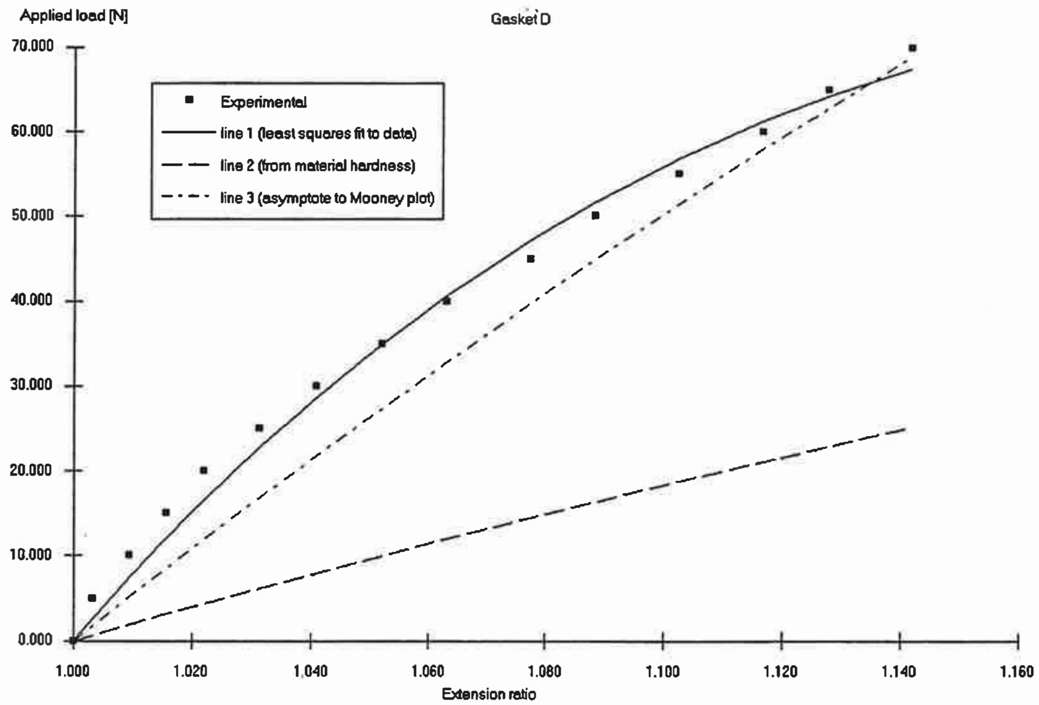


d) measured and predicted gasket force-compression characteristics

Figure 5.1.5 **Gasket D - the white crescent-wedge gasket**

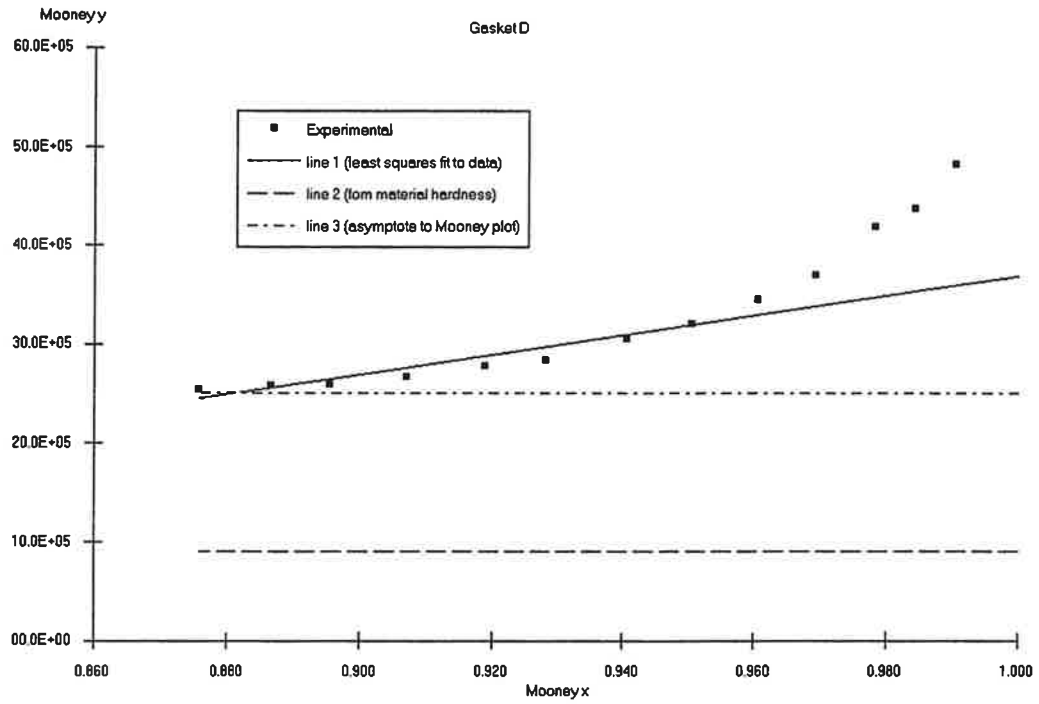


a) the gasket

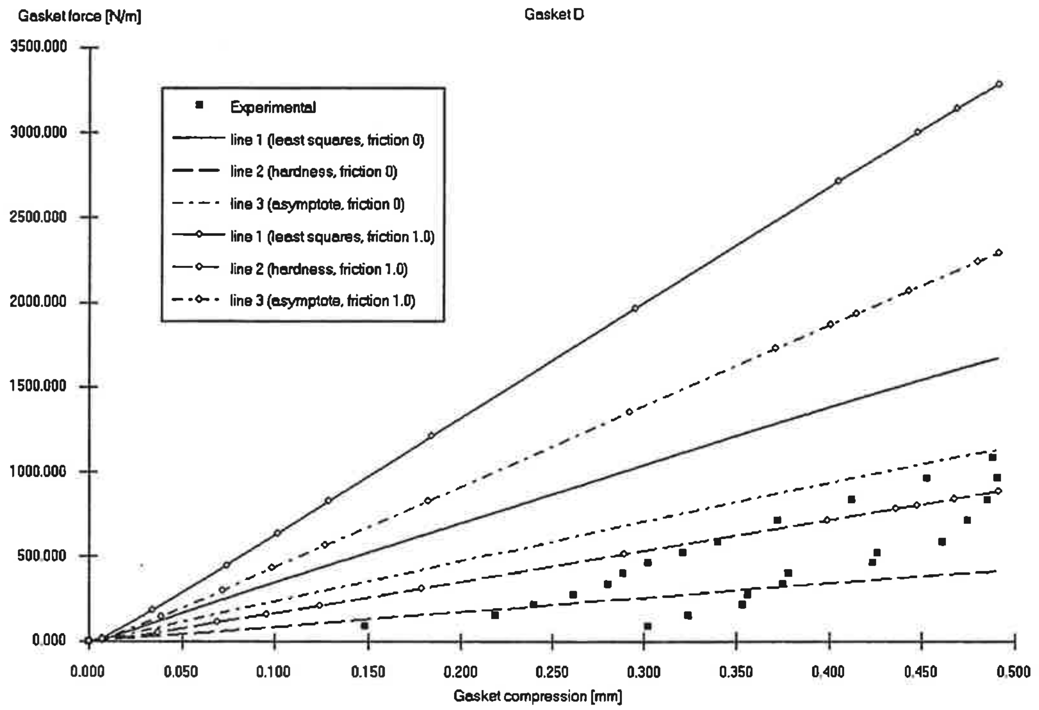


b) results of the material load-extension test

Figure 5.1.5 **Gasket D - the white crescent-wedge gasket**

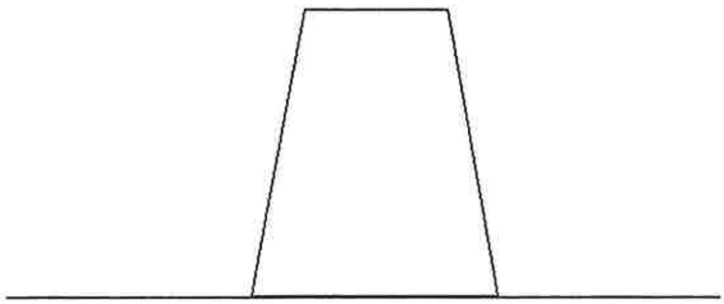


c) Mooney plot of the material load-extension test results

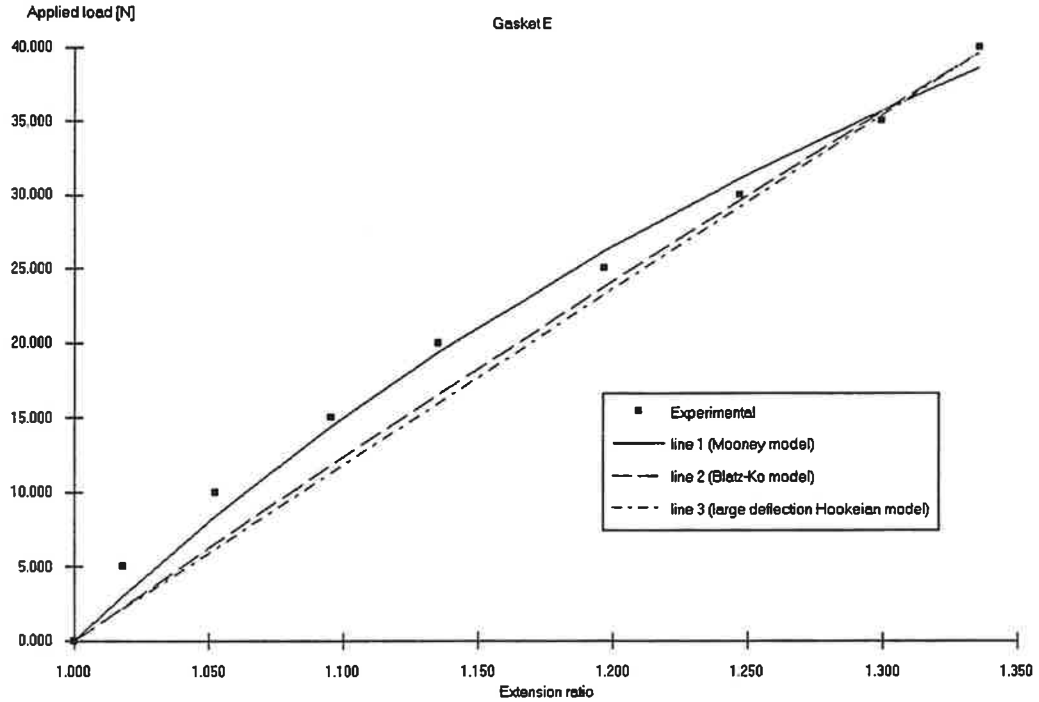


d) measured and predicted gasket force-compression characteristics

Figure 5.1.6 Gasket E - the cellular rubber block

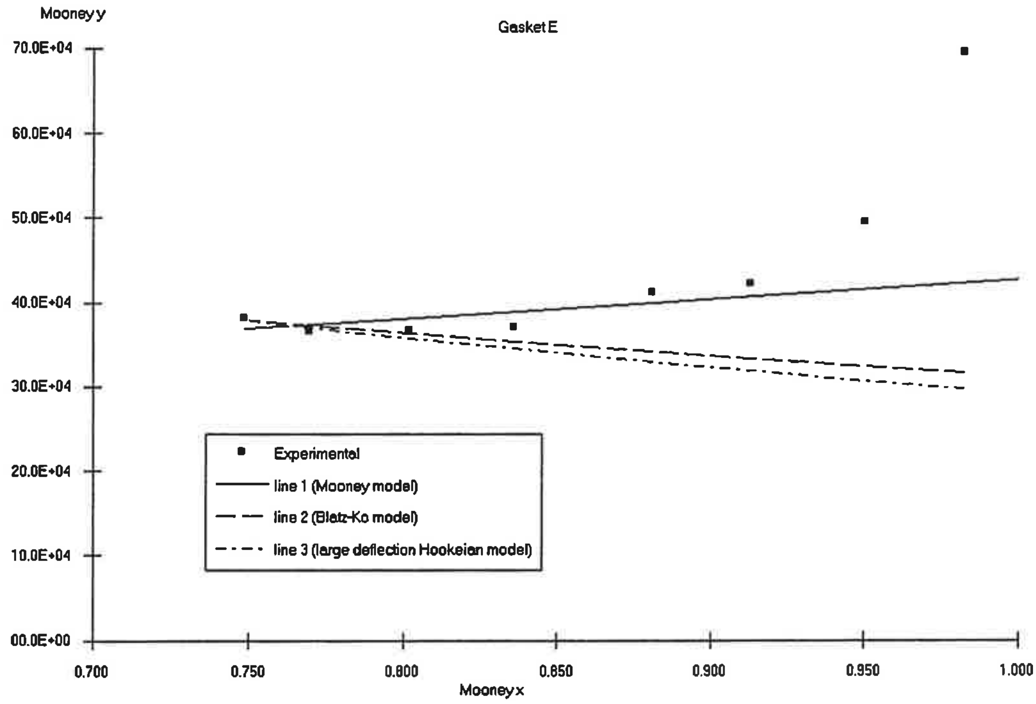


a) the gasket

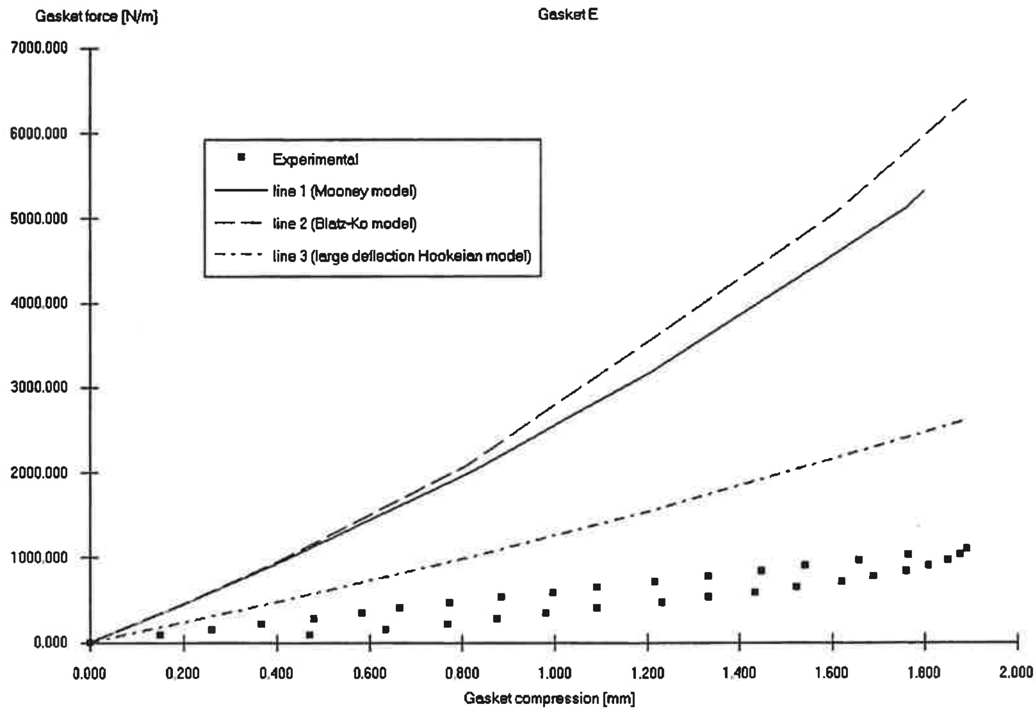


b) results of the material load-extension test

Figure 5.1.6 **Gasket E - the cellular rubber block**

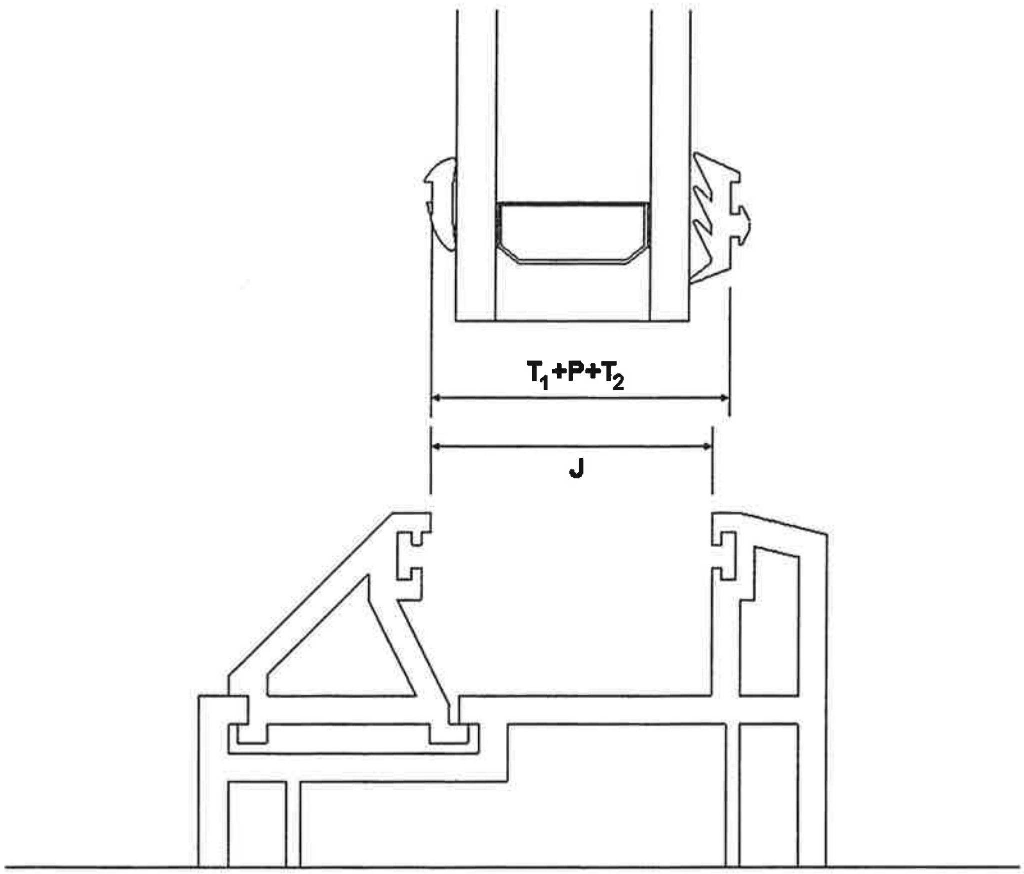


c) Mooney plot of the material load-extension test results

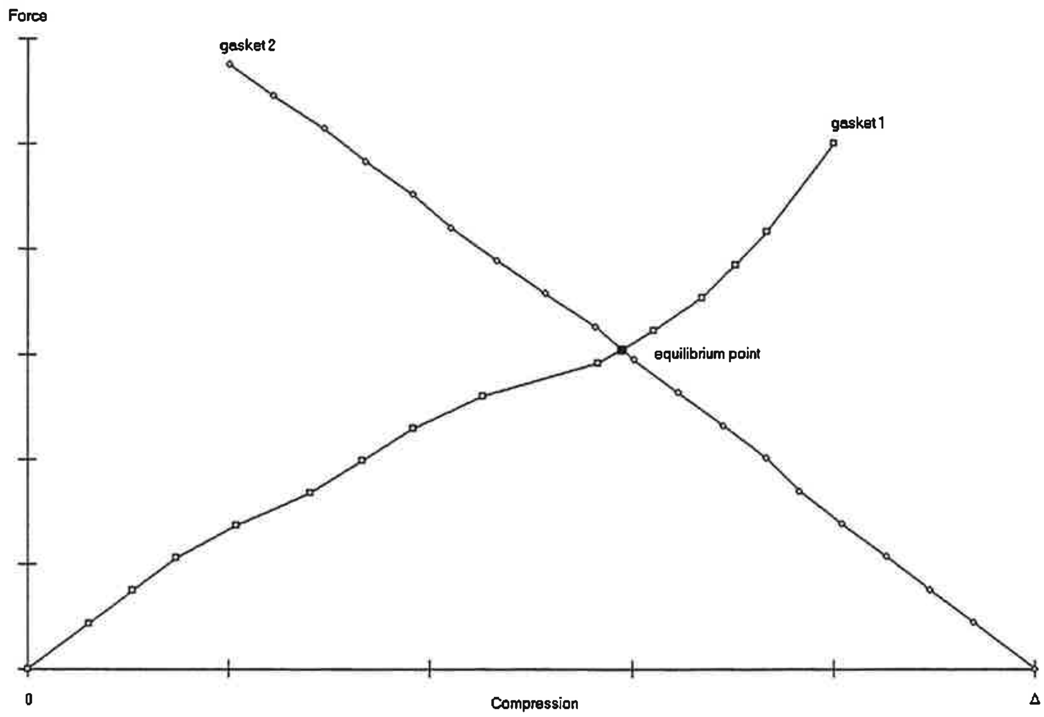


d) measured and predicted gasket force-compression characteristics

Figure 5.2.1 A typical joint with opposing gaskets retaining an infill

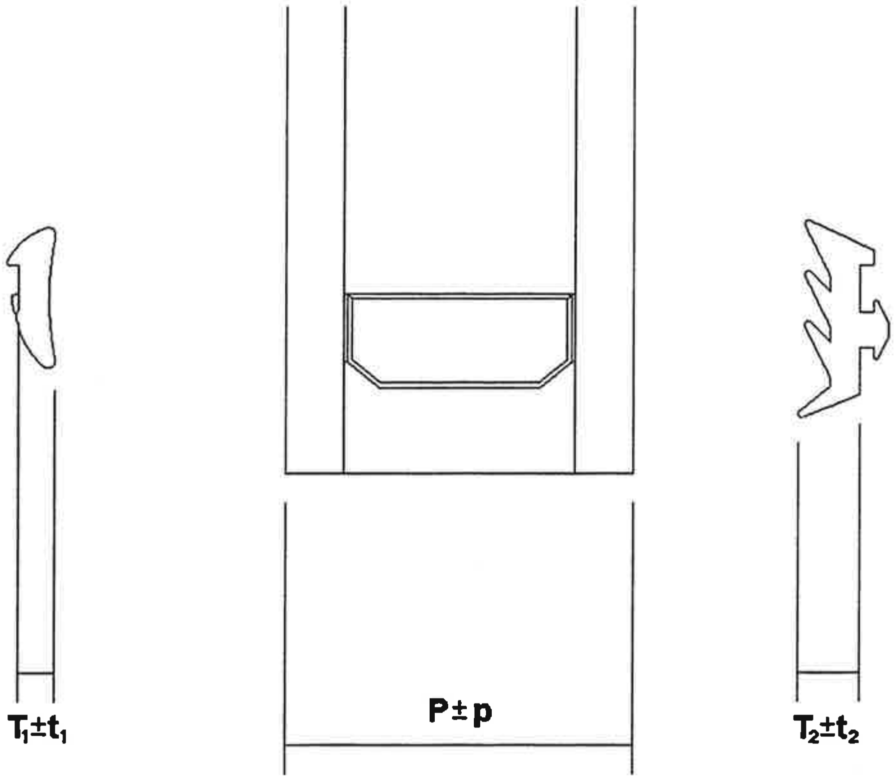


a) joint components prior to assembly

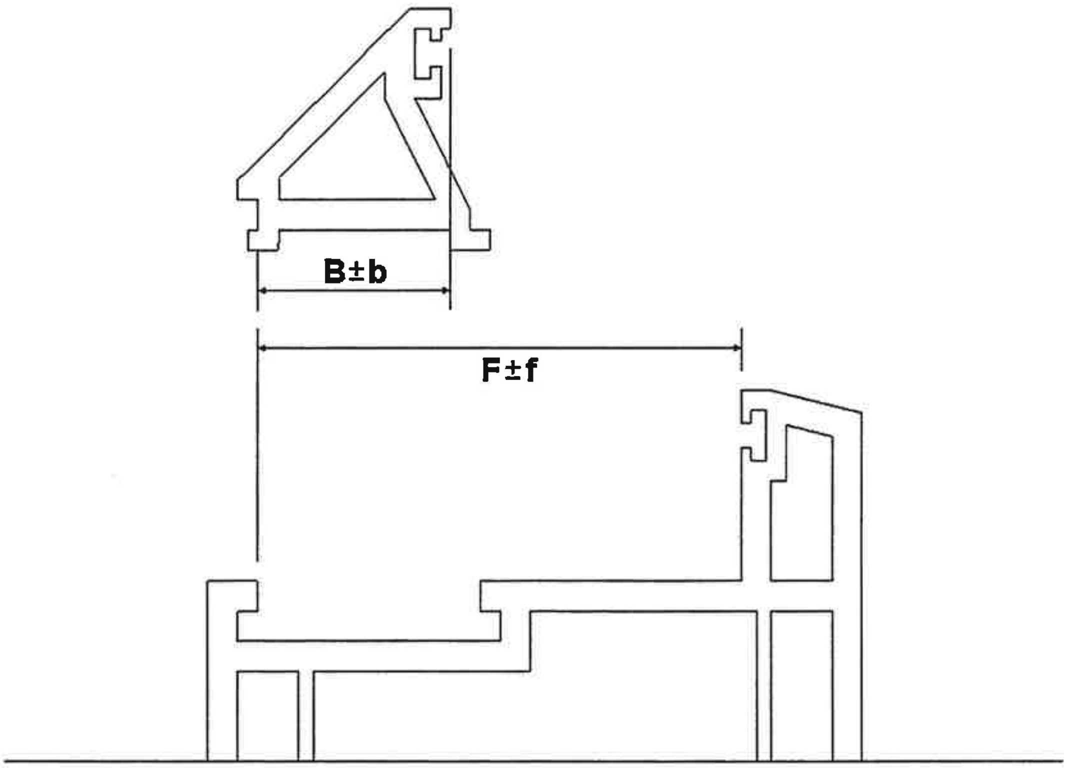


b) combining the force-compression characteristics of opposing gaskets

Figure 5.2.2 **Effect of tolerances on a typical joint with opposing gaskets retaining an infill**

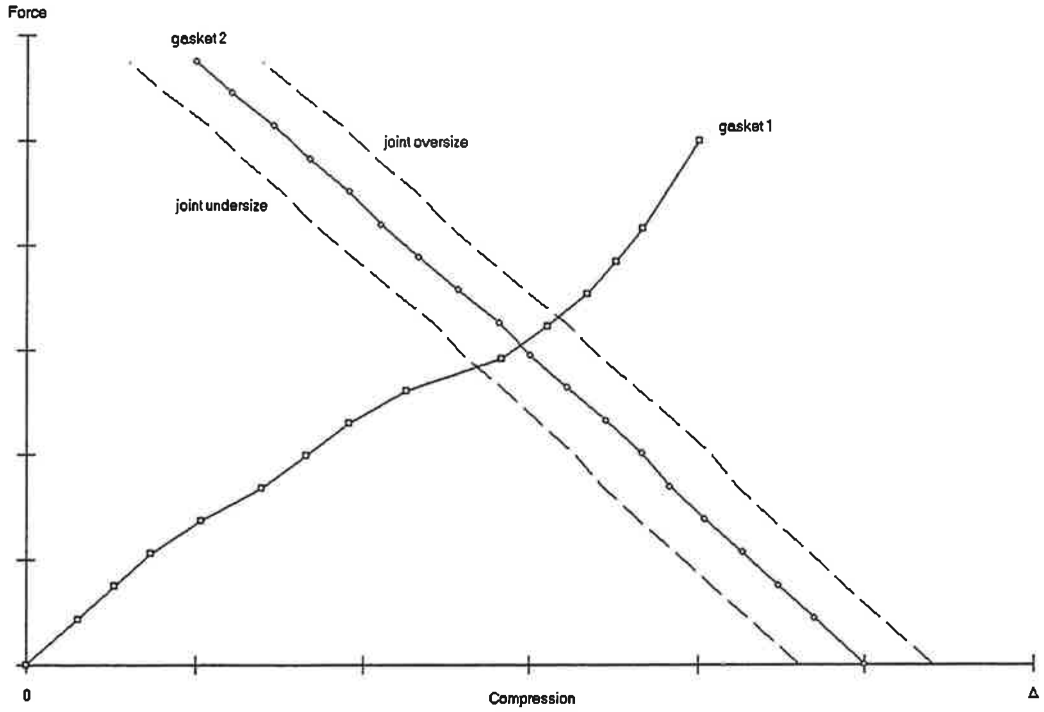


a) gasket and infill tolerances



b) frame tolerances

Figure 5.2.2 **Effect of tolerances on a typical joint with opposing gaskets retaining an infill**



c) the combined force-compression characteristic

Figure 5.2.3 **The force-compression characteristics of two opposing gaskets, showing the effects of a nominal wind-load**

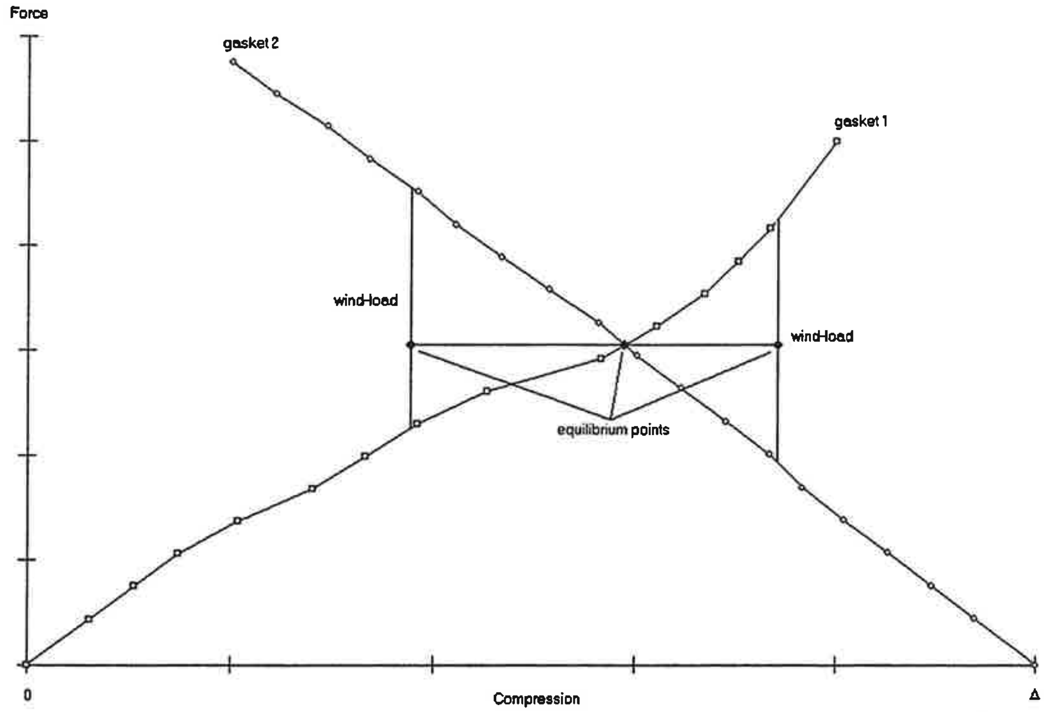
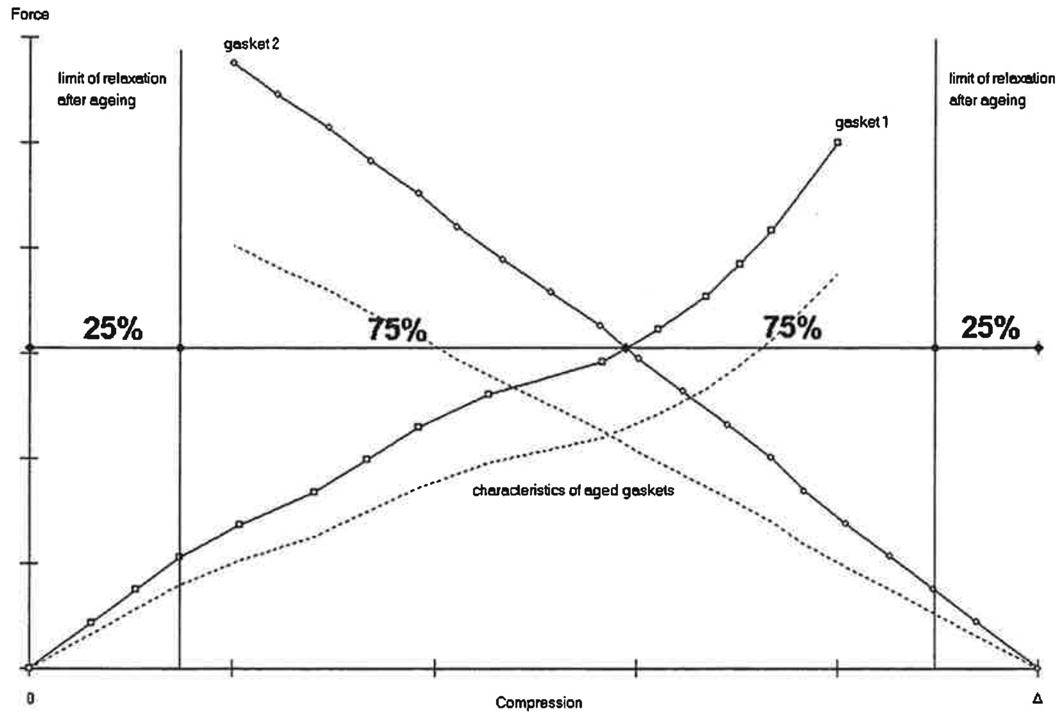


Figure 5.2.4 **The force-compression characteristics of two opposing gaskets, showing possible effects of compression set**



6 INSTALLATION AND REPLACEMENT

It does not matter how much effort is expended in designing the perfect joint and the perfect gasket if it is then installed by an untrained work-force with little appreciation of the performance requirements of a sealed joint. Many joints appear to be formed on the basis that 'I can't see a gap, so it must be tight', and yet the time-dependent behaviour of most polymer materials means that a gap-less installation may soon become an open joint.

The need for proper seals, backed up with good drainage, is nowhere more important than in systems glazed with sealed multiple glazing units. The durability of the edge seal of multiple glazing can be strongly reduced by the presence of standing water at the edge of the unit (Garvin 1993). Ultra-violet radiation can also have a detrimental effect on some edge sealants, and good cover of the glazing unit edge detail by the gasket is recommended. However, the installation of glazing units is often carried out by an unsupervised and untrained work-force - a poorly supervised and untrained worker will always attempt to do the job in the least time and with the least effort. There are several steps that should be taken to improve the chance of successful installation of the gasket and acceptable performance of the joint:

6.1 Designing for installation

It is not acceptable to blame the installer for all sealed-joint failures. In many cases the designer could take steps to reduce the opportunity for the installer to 'cut corners'. A case in point is the problem of stretching gaskets into place, which might provide a weather-tight joint for a short period, but which would ultimately lead to gaps appearing at joins in the seal and the consequent passage of air and water. The results of section 4.2.4.1 clearly illustrate how a length of rubber that has been stretched can continue to contract several days after installation. The retraction of a piece of rubber may not be reduced significantly by the presence of friction - wind-loading will continuously work the joint, helping the gasket to return to its original length.

6.2 Installation guidance

The Canadian standard CAN/CGSB-51.92 (1992) gives significant guidance for weather-strip installation. Amongst the guidance is the requirement that weather-strips are stored un-wrapped for 4 hours at room temperature, prior to use, and that all weather-strips shall have been tested. The user is to prefer weather-strips with the highest range of deflections (thereby minimising problems due to poor installation, poor construction of the joint and cumulative tolerances) and with the best durability performance. There is also a requirement to inspect weather-strips before installation and reject any with visible defects. Replacement weather-strips should match existing strips as closely as possible, and the old seal should be fully removed. Replacement seals should not be installed until the door or window has been properly realigned. Adhesive backed products should not be installed in temperatures below 4°C, where the mounting surface is below 4°C, or where there is frost on the surface. Minimum distortion of the weather-strip should occur during installation, and the proper fixing method should be used. Where joints must be formed at corners these should be made air-tight with the application of a minimum amount of silicone sealant. The seals should be cut over-long if possible. Although the Canadian climate is somewhat more severe than the UK climate this guidance is in fact common-sense and ought to be followed regardless of the conditions of service.

ASTM C 963 (1985) and C 716 (1987) give guidance on the packaging, shipping, storage and installation of lock-strip gaskets. The need to protect the gasket prior to installation is emphasised, and significant guidance is given for the installation process. ASTM C 716 stresses the need for a clean, dry, warm environment during the installation process, with the gasket remaining flexible enough to install. It is recommended that gaskets are unpacked and left in a relaxed state for 24 hours at 21°C prior to installation, to allow the gasket to recover its natural shape, although the use of immersion in hot water is allowed when the ambient temperature is below 10°C and there isn't a suitable warm room for recovery. It should be noted however that the gasket will expand when warm and so must be cut over-length! This specification also requires that both joint and gasket be inspected prior to installation, and that critical dimensions are checked. The use of sharp or pointed tools is to be avoided, to minimise the risk of damaging the gaskets, and if a lubricant is used to aid installation then 'the lubricant shall be nonstaining, nontoxic, noncorrosive, chemically stable, compatible with all contact components, easily removable from exposed surfaces by dry wiping or with water, and acceptable to the manufacturer of the supporting frame, panel, and gasket'!

BS 6262 (1982) gives general guidance on the installation of a number of different types of gasket system. An interesting point is made in the use of distance pieces wherever a sealant is used to fix glazing into a frame: the distance pieces provides a support for the glazing and prevent the sealant from being squeezed out of the joint. Such distance pieces should also be used wherever a pre-formed sealant tape is used, unless the sealant tape contains some form of shim. As an example Tremco (1994) produce the *Polyshim* range of sealant tapes, which contain an EPDM-based rubber cord running through the butyl sealant. This rubber cord prevents the sealant tape from being over-compressed. BS 6262 also includes a table (Table 22) which summarises external glazing systems suitable for different types of glass. However, although guidance is given as to the use of gaskets it is generally of the form 'refer to the manufacturers/gasket designers instructions'. BS 8000:Part 7 (1990) repeats the installation guidance given in BS 6262.

Low-temperature flexibility of rubber is an important factor where gaskets have to be installed on site. The general relationship between temperature and flexibility is shown in Figure 6.2, as presented by Park Rubber Ltd (1980s). It is worth noting that silicone rubber has the best low-temperature flexibility, and that the EPDM and the TPR are also very good. As a general rule however it is not recommended that any gasket or sealant be installed in temperatures below 5°C - even at this moderate temperature the joint may have opened up due to thermal contraction of the joint components, leading to the risk of crushing the seal at higher summer-time temperatures.

6.2.1 Joining guidance

Gaskets are often joined to form a continuous seal around the perimeter of an infill component. There are a number of ways by which corners can be formed:

6.2.1.1 Notched corners

A notched corner is formed by cutting a V-shaped section from the hidden side of the gasket and then folding a continuous length into place, with a butt-join near the midpoint of one side of the frame. The butt-join may be 'buttered' over with a sealant, or a significant gap may be left to encourage pressure-moderation. There is no guarantee with this method that the corners will not fail - the presence of a cut could even encourage the rubber to tear, particularly under the influence of fluctuating wind-loads.

A similar approach is to simply fold the gasket around the corner, without cutting. Such a corner is unlikely to give a good seal - the folded shape of the gasket creates a non-flat contact face, and the additional material that is pushed into the corner may hold the joint apart.

6.2.1.2 Pressure- or sealant-sealed corners

A simpler approach is to cut the gasket and install it as a number of discrete lengths. The corner joins may be buttered over, although if the gaskets are compressed into place length-wise the corners might be left without further sealing, relying on compressive force to hold the cut ends together. Indeed, cutting the lengths of gasket too short is the major reason for failure of such joins, although careless selection of sealant may also be a factor. Before applying any sealant to a gasket the advice of the gasket and sealant manufacturers should be sought, because there are issues of material compatibility as highlighted in 4.3.

The SFTC (1986) identify several ways in which seals can be joined together by the two methods above, depending on the profile of the seal. The basic methods are shown in Figure 6.2.1.

6.2.1.3 Glued corners

A third possibility is that joins can be sealed by the application of an adhesive. The major drawback with this method is that many gasket joins are made on-site, usually at a late stage in the construction process, and the level of surface preparation required for a good adhesive bond is unlikely to be achieved. Adhesive bonds are more reliable if factory-made, in a controlled environment, and are useful for bonding to form corners at unusual angles. The higher stress concentrations that may occur at sharp corners should be considered before adhesive bonds are specified however. Furthermore the adhesive may not remain flexible in the long term, and compatibility of the adhesive with the gasket material must be checked.

There is a clear need for the merits of adhesive joins to be investigated. It may be easiest to form an adhesive join with a gasket which has a simple profile, but these gaskets might also be dry (pressure) joined most successfully. Where dry-joins can be difficult, for example with some of the more complex E-gaskets (particularly those with several arms of very different lengths) it may also be difficult to make a satisfactory adhesive join. An alternative is to make the join as a dry-join and 'butter' over the join with a sealant immediately before assembly. There is clear scope to investigate the air-tightness of different joins, and to investigate how long an adhesive join must be left to cure before assembly - it is almost certain that a labourer on a building site will neither read the instructions on the tube of adhesive or allow the appropriate cure time before compressing the joined gasket into the joint.

An interesting and simple test might be to take a length of gasket and cut it at the midpoint with a single cut at 45° to the length of the gasket. The ends can then be bonded together with the relevant adhesive and two tests carried out: for the first test the gasket should be compressed into a joint and then released (or compressed using a simple jig). The state of the bond after compression can then be investigated. This test will be more realistic however if a corner sample of the gasket is tested. The second test would take the length of gasket (this can be performed after the first test, or on a freshly prepared join) and simply stretch the gasket by applying a load to the ends. The load at which the join fails can be noted. Such a test could be performed on a range of joins which have been cured for differing time periods, and will show how the bond-strength varies with cure-time.

With the methods of 6.2.1.2 and 6.2.1.3 it is also possible to use gasket corners which have been formed by moulding, and to join lengths of extruded gasket between the moulded corners. The join is perpendicular to the length of the gasket, and stress concentrations in the corner can be reduced by moulding a curved corner. This approach is often used where the gaskets along the edges of the opening are of different types or thickness and could not be joined together otherwise.

6.2.1.4 Welded corners

A welded corner can be formed if the rubber is a thermoplastic. The gasket is cut with a hot knife and the molten ends then pressed together.

6.2.1.5 Vulcanised corners

Vulcanised corners are formed using a special 'glue' that is able to link itself into the chemical structure of the rubber - after application of the glue the cut ends of the gasket are placed into a special mould, where they are heated to cure the joint. This type of joining can be carried out on-site as the heating units are portable.

6.2.1.6 Injection-moulded corners

To form an injection-moulded corner the cut ends of two lengths of gasket are placed into a special mould and more rubber is injected into the mould under high pressure and high temperature. The injected rubber (which is generally a thermoset) vulcanises and bonds to the cut ends. The join is continuous, and again the corner may be shaped to reduce stress concentrations. The injected rubber may be of a different grade.

The choice of corner-joining method is often dictated by cost, the need to make joins on-site, and the short time period in which the gaskets must be supplied and fitted. There is also a concern that gaskets which are formed into frames in the factory may not fit if the construction tolerances are not carefully controlled. However, a gasket should not be used unless the designer is either prepared to insist on tolerances being achieved or to allow for the worst effects of tolerances, and it is not acceptable to sacrifice performance by refusing to supervise and control the construction process. If the joint designer feels that the joint size cannot be controlled then alternative methods of sealing should be found. It is reasonable to argue that only factory-assembled systems, or systems which are designed to accommodate tolerances should make use of gaskets. Systems such as stick-system curtain walling are usually provided with adjustable brackets which allow poor construction tolerances on the frame of the building to be compensated for, and full-frame gaskets can be (and are) specified for such systems.

In terms of the effect of the installed gasket on water leakage Cronshaw (1974) reports tests in which the weather-tightness of a number of gasketted windows was tested, and in all cases the joint did not leak at the gasket/glass seal line but did leak where there were gaps in the gasket around the perimeter of the joint.

Ruggiero and Myers (1992) report typical failures in joints fitted with gaskets as being related to gaps opening at the corners of gaskets. The effects of non-uniform compression (angular tolerances, variable tightening of fixing screws) are also identified as leading to water penetration.

Kudder and Lies (1992) highlight the fact that the joint designer should consider potential joins between seals, where gaskets may need to be joined together or sealed-between. Very often the installer is left to solve problems of poor detailing and may simply leave a gap in the joint. The need to design the joint to allow water to drain away is also repeated.

ASTM C 964 (1988) is a guide to lock-strip glazing, and identifies several issues of design which can affect the seal performance, with regard to wind-loading and leakage. The need to avoid protrusions of the contact surface is stated, as is the need to achieve a continuous and uniform pressure along all of the sealing surfaces. It is recommended that moulded corners are curved, because a curved sealing lip gives a more even contact than a square corner lip. Where corners are made by adhesive bonding, or cut ends simply butted together and filled with sealant, it is stated that the installation technique, and location and type of adhesive and sealant, should be as recommended by the manufacturer. The need for proper drainage is again stated, indicating that seal failure may still occur even if carefully installed. The effect of tolerances is also discussed, as are different types of loading.

6.2.2 Gasket and joint identification

It is always desirable to be able to identify a gasket through some form of permanent marking and, for frame gaskets, to identify the joint into which the gasket is to be fitted. Best practice in terms of gasket identification within the construction industry currently marks the gasket with an identification number during the manufacture process. This allows the gasket to be traced by the production company and the material identified, assuming that their records are properly maintained. For identifying the particular joint into which a frame gasket must be fitted best practice is currently to label each frame gasket (with a removable label) with an identification code which relates to a master drawing of a building elevation.

Both of these labelling methods are adequate, and immeasurably preferable to the production of unlabelled gaskets. However, even if a gasket carries an identification number it may not be possible to trace the original supplier of the gaskets, or the manufacturing records may be lost. A better form of labelling is one that is universal and based on the properties of the material. A typical such procedure is that given in SAE J200 (1988).

SAE J200 defines a 'line call-out' specification for rubber used in automotive applications. An example of a line call-out is

SAE J200M2BC507A14EO34

The various terms mean

Basic requirements:

SAE J200	line call-out to SAE J200
M	based on SI units
2	grade number 2
B	type of material (defines temperature for heat ageing test), in this case 100°C
C	class of material (defines volume swell of material), in this case 120%
5	durometer hardness, in this case 50±5
07	minimum tensile strength, in this case 7 MPa

Suffix requirements:

A	heat resistance required,
1	tested to ASTM D 573 for 70 hours,
4	at 100°C
EO	fluid resistance required,
3	tested to ASTM D 471 in No. 3 oil for 70 hours,
4	at 100°C

The grade number defines the standards that must be used to determine the following properties - required tests differ for different grades. There are additional suffixes that may be added to the line call-out, including some to define the particular type of material to be used, and there are extensive tables of tests and acceptable properties.

The call-out is intended for specification. However, it is equally possible to define a simple line call-out to list the measured properties of a particular gasket material, and this alternative should be considered. The number of tests defined in BS 4255:Part 1 (1986) is not great, and a simple coding system could be readily established. Indeed, a simple system exists in the Japanese standard JIS A 5756 (1989), which creates an identification of the following type

Gl-CR-J [4]

in which the terms mean

Gl	glazing gasket
CR	chloroprene system
J	mounted on glazing bead
[4]	dimension (in mm) between glazing bead and glass surfaces

This system identifies the basic type and dimension of the gasket, the joint type and the class of rubber. There are also classifications for solid and hollow gaskets (in the case of air-seals).

Canadian standard CAN/CSGB-51.91 (1992) gives guidelines for the labelling of weather-stripping, including statements as to the location (exposed or non-exposed), mode of operation (compressive, bending, wiping, sliding), installation type (gap-controlled, settable, adjustable, blade) and restraining method (clamped, restrained, un-restrained). The properties of the seal are also to be stated, as determined from the standard tests in CAN/CSGB-51.90.

6.3 Designing for replacement

It is nonsensical that if a window 'fails' due to significant water penetration then it is easier to replace the whole window than it is for the ordinary home-owner to buy a new set of seals and fit them. Traditional timber windows on the other hand, with single glazing retained using putty, are still in service after more than 100 years. These windows were simple to maintain, and the home-owner could replace defective parts with little effort. Today's windows are far more complex, incorporating many advanced features, and yet the window designer rarely appears to consider that some parts will have to be replaced by the home owner. The home owner may not be able to identify the original source of the gaskets, may find the original window installer to be less than helpful, and is unlikely to find similar gaskets in the local DIY super-store - at least if there were standards for the basic performance features of gaskets (particularly mounting details) this would not be a problem, as replacement gaskets could be obtained from a number of sources. It is worth considering whether the window designer would be happy to find that his new car has spark plugs of a unique design, from an unidentified source, with a non-standard fixing, and not available in his local motor-spares retail outlets!

Perera, Turner and Scivyer (1994) make the significant statement that 'Designers should anticipate the need for gasket replacement at some stage of the building's life by opting for designs which allow easy access, removal and replacement of gaskets and any associated flashings'. Draught-strips are included in this statement, and are perhaps more likely to be replaced. Clearly the long-term air-tightness of the building envelope is important, and the design of the gasket is going to be significant in terms of the ease with which it can be replaced in future years. A typical example is a timber door in which the weather-stripping pushes into a kerf in the door frame. The seal material may become rigid during its life, and prevent the door from opening or closing properly. However, finding a replacement seal suitable for the same slot in the frame may be difficult, and the householder is more likely to purchase a roll of self-adhesive draught-strip from the local DIY superstore. Fitting such a product is only going to be possible however if the door frame has a suitable platform onto which the draught-strip can be fixed, and the door designer may consider this possibility and make suitable provision.

6.3.1 Standardisation of gasket profiles

The use of standard gasket profiles would greatly simplify the design of joints. The ability to choose a suitable gasket off-the-shelf would simplify the design of many systems, and indeed some gasket producers, most commonly those producing wedge gaskets, do offer a range of gaskets. Some manufacturers also recommend shapes for the mounting foot-and-race or groove-and-nib. However, there is still a tendency for some systems producers to want a unique design of gasket for each product, with the result that there are literally thousands of different gasket designs currently available.

Some systems suppliers do act sensibly in the production of gaskets - it is not unusual for the design of a new window or curtain walling system to start by discarding the previous system but retaining the gaskets if they have worked satisfactorily before. However, there are problems where, for example, the hardware on a window has been changed and the new hardware interferes with the operation of seals - in this case the gaskets are unlikely to be re-designed.

The advantages of common gasket designs are several-fold:

- standard dies can be used for extrusion and moulding, thereby reducing production lead-time and start-up costs
- it is only necessary to select a suitable material, reducing the number of design decisions which need to be taken - materials could also be standardised, subject to compatibility requirements
- costs could be reduced, because the gaskets would be available from a number of suppliers
- the risk of failure could be reduced, because the standard gaskets would be selected from the best currently available
- it would be easier to select a gasket to meet a specified level of performance
- replacement gaskets may be made available for the home owner or building owner to make suitable repairs as part of ongoing maintenance

Even if gasket profiles are not standardised there is much to be said for the standardisation of mounting details. This would also improve the chances of finding a suitable replacement gasket for systems that have begun to leak, and would reduce the number of variables that the joint designer has to contend with.

6.4 Gaskets and weather-tightness

A commonly reported problem with many window and curtain walling systems is that fabrication companies buy the framing profiles but do not buy the gaskets and weather-stripping from the same supplier. Subsequent failures are then unfairly blamed on the systems company, whose name is associated with the window or curtain walling frame. Clearly this problem could be avoided if the frame and gasket were packaged together, but also the fabricator and customer both need to be made aware that:

- any weather-tightness rating of the product does not apply if the gaskets have been substituted
- the cost saving for a substitution gasket is actually very small compared to the potential costs of having to repair damage due to water penetration if the gasket fails
- it is the responsibility of the fabricator to show that a 'hybrid' system meets the required performance specification

It may be advantageous for the system supplier to insist on the fabricator using the proper gasket for the job, although the competitive nature of the market may discourage this - the fabricator might opt to buy frames from a supplier who is not being so 'unreasonable'. However, it can be argued that it is the fabricator who is being unreasonable in assuming that he knows more about the performance of the joint than the system supplier and is educated enough to re-select the joint seal.

6.5 Closure

The installer is usually blamed if there are problems with the weather-tightness of the finished product. However, in many cases the installer is allowed to change the system that is being installed, use ancillary products such as adhesives and sealants without checking their suitability, and is not provided with any guidance to do the job properly. Furthermore, the joint or seal may not have been sensibly designed and may produce problems that the installer has to fix on site in a very limited time-span. Standardisation of joints, gaskets and gasket materials would clearly reduce the problems, but is unlikely to happen without the consensus of the industry.

Figure 6.2 **Low temperature flexibility of different types of rubber (from Park Rubber Ltd (1980s))**

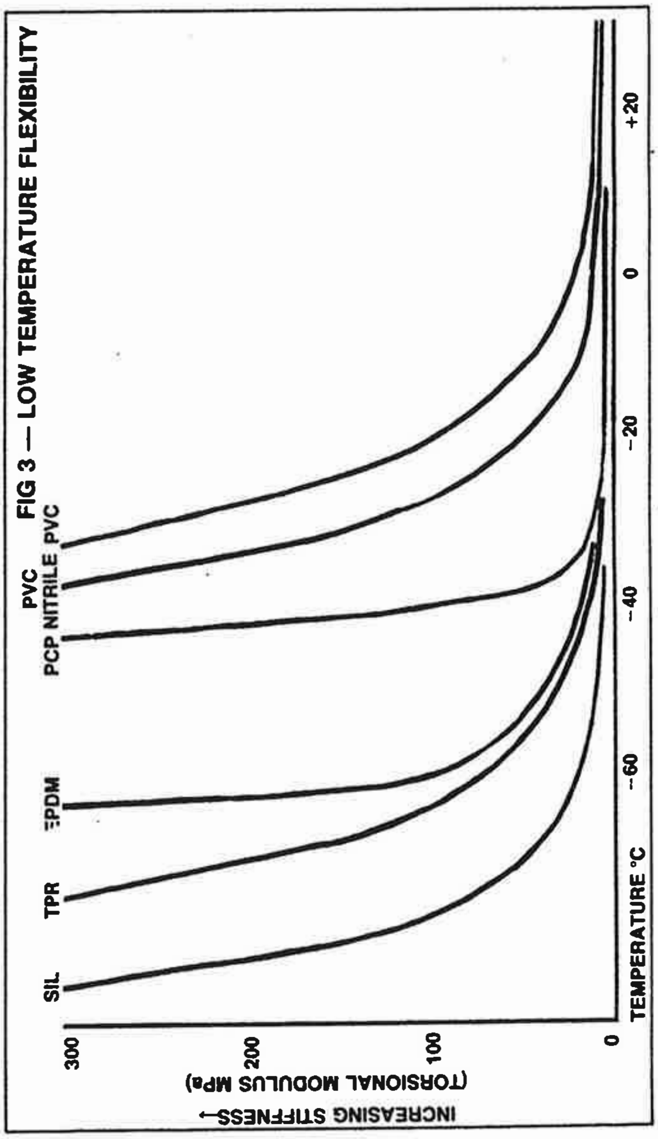


Figure 6.2.1 Methods of joining gaskets (from SFTC (1986))

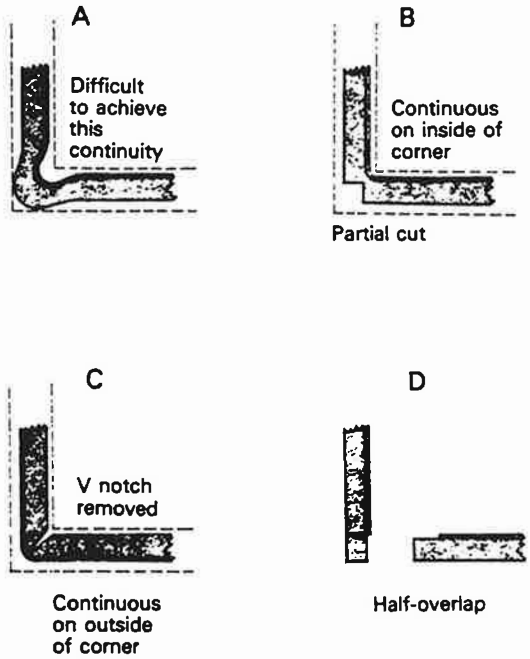


Fig. 12 Corner Details

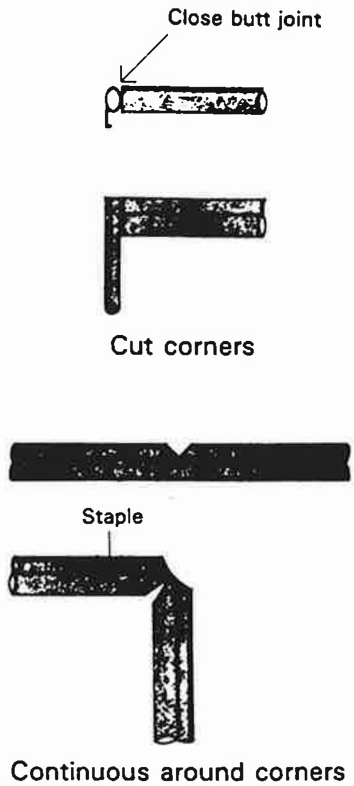


Fig. 17 Corner Details

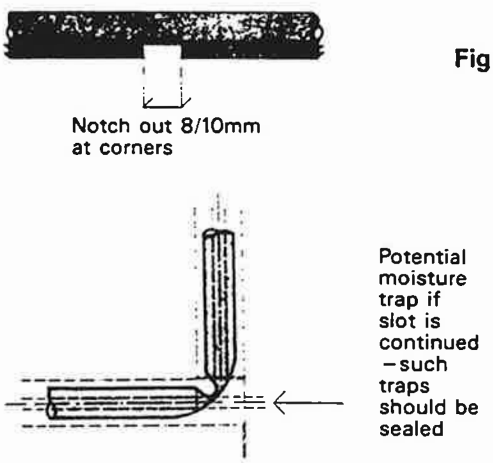


Fig. 18 Cut Out at Corner

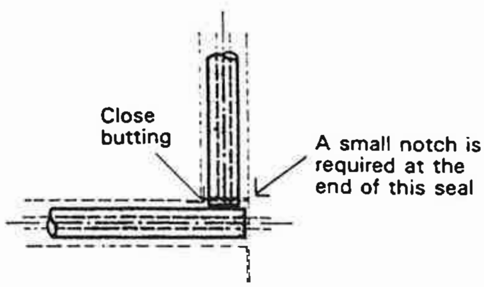


Fig. 19 Butting at Corner

7 COMMUNICATION IN JOINT AND GASKET DESIGN

A significant finding of this research project has been that there are many shortcomings in the design process which arise as a result of a lack of communication between the individuals responsible for the design and production of the joint and those responsible for the design and production of the seal. It has become apparent that a typical way of working is for the joint designer to progress the design to the point where manufacture of the joint components is underway before the gasket producer has even been approached. In one case, which it has been suggested is quite typical, the gasket producer had been sent a box of frame sections for a new window system and asked to provide a new gasket! The gasket producer simply did not have the option to change the design of the frame, as this would have required the frame manufacturer to produce new extrusion dies for the product. A better method of working is to involve the gasket producer in the design of the product at the earliest possible stage, and a number of companies have reported that by doing this they feel much more in control of the performance of their products, and are happier that the gasket producer is doing the best job.

7.1 Performance requirements

An important finding of this research project is that many gasket producers do not actually know what performance is required of window, curtain walling or cladding systems, and yet they are expected to design a component that has a significant effect on performance. Weather-tightness must be the commonest aspect of performance that is measured for any window or cladding system, and yet it is the most likely to be compromised by the lack of communication in the gasket and joint design processes.

In part the lack of communication is caused by the lack of written guidance defining the significant performance criteria of gaskets and cladding systems. If a simple checklist existed of gasket-related performance factors then this might encourage the joint designer to communicate more with the gasket producer. Indeed, it should be possible to define a range of standard gasket profiles, available in a choice of materials, which give a known performance.

Clearly the duty of a joint and a joint gasket is complex, and there are many factors that need to be taken into consideration. The wide range of products that use gaskets is also a factor; typical products include:

- fixed windows
- casement windows
- vertical sliding windows
- horizontal sliding windows
- vertical axis tilt windows
- horizontal axis tilt windows
- tilt-turn windows
- roof windows and sky-lights
- louvres
- glazed-in ventilators
- conservatories
- curtain walling
- patent glazing and sloped glazing systems
- cladding systems
- casement doors
- bi-directional doors
- rotating doors
- double doors
- sliding doors
- split doors
- internal doors
- access hatches

Some of the qualities that may be required of a gasket, and which could be communicated, are:

- high temperature operation
- low temperature operation
- low temperature flexibility (for installation on cold days)
- UV stability
- impact resistance
- abrasion resistance
- resistance to set
- resistance to deflection
- high stiffness
- low stiffness

The gasket might also need to be:

- strongly retained
- easy to remove
- easy to deflect
- hard to stretch
- easy to join

Furthermore the gasket may be used in a joint that is:

- permanent (glazing gasket)
- working (window weather-strip)
- exposed
- sheltered
- low duty
- medium duty
- heavy duty

The joint designer can do worse than decide from the above lists what performance issues are significant - the gasket designer should then be consulted at an early stage in the overall design process and allowed to make recommendations as to the joint width and mounting details. When the gasket is produced and the final product is tested the gasket producer should be kept informed as to the performance of the various seals, and should be allowed to make suggestions as to possible improvements in the design. Only by a process of communication and feedback can the design of any component or system be properly understood.

7.1.1 The joint and gasket design process

The design process for a joint and its associated gasket(s) could be broken down into 7 key steps:

- size
- shape
- type
- fixing
- joining
- material
- installation

These points are elaborated upon in the following sections:

7.1.1.1 Size

The first issue is to determine the mean size of the joint, making due allowance for movements (structural, thermal and moisture related) and tolerances (manufacture and installation). The range of movements may preclude the use of a gasket, or may need the joint to be designed so that a gasket is used in a wiping mode (rather than a compressive mode). Alternatively the range of tolerances may mean that a number of gaskets have to be made available and instructions given to the installer to measure the joint and select the right gasket on-site.

The joint size may also be influenced by issues such as aesthetics - a small joint is less visible and does not disturb the appearance of a surface.

7.1.1.2 Shape

The shape of the joint is important - it has already been discussed how a joint can be designed to minimise water penetration by suitable shaping of the joint. It is also necessary to consider how the joint will perform if water does get in, and this requires drainage channels to be included in the joint. The interaction between horizontal and vertical joints in a cladding system may also be important.

7.1.1.3 Type

The next stage is to determine the type of seal that is required, and this may be influenced by the materials from which the joint surfaces are made, and by the ease with which a given type of seal can be installed and replaced. It may be decided that a wet-applied sealant is appropriate, or that the joint can be left open, with a simple baffle to intercept water.

Of course, if a gasket is to be used it may be possible to buy gaskets of a standard design. Some gasket manufacturers produce ranges of basic gasket profiles, and some manufacturers also provide recommended details for the frames, in terms of the shape of support nibs and gasket races, together with clear installation guidance. This will make the design process easier and levels of performance may be guaranteed.

Carruthers and Bedding (1981) include a chart which allows the best type of weather-strip to be identified for a particular joint size. Such a chart is invaluable to the door and window designer for selecting the type of weather-strip according to the joint.

BRE Digest 319 (1987) also looks at weather-stripping and provides a chart of which types of weather-stripping are suitable for which types of window or door (steel or timber, casement, sliding or pivot). The benefits of draught-proofing are also shown in the form of charts comparing air leakage before and after draught-stripping.

7.1.1.4 Fixing

If a gasket is to be used then the designers must consider how it is to be fixed, and this will also have an impact on how it can be replaced. It may be appropriate to design the joint so that several types of seal could be applied - for example a door frame could be provided with a slot for inserting the initial weather-strip and a flat surface for subsequent application of adhesive-backed draught-strips by the building owner.

7.1.1.5 Joining

Joins in the gasket must be considered and the method of joining established. Many seals perform adequately but leak at improperly formed joins. Note that the gasket shape may influence the choice of joining method.

7.1.1.6 Material

The material does not need to be selected until the end of the design process. At this point the location and duty of the seal should have been determined and the gasket producer will know whether the gasket is exposed or sheltered, and the range of environmental conditions to which it will be subjected.

The selection of gasket material is one decision that the joint designer often takes without consultation, and on the basis of little more than prior experience (there is a difference between having a lot of experience and having experience of doing the job properly!) and hearsay. The selection of material may even be based on a chart similar to that of Figure 7.1.1.6, which is a simple comparative study of different materials. It should be noted that the values in this chart are representative of the materials at the time of preparation, and cannot take account of changes in technology, new additives which give better performance, or the fact that terms such as 'EPDM' refer to a class of materials based on the basic EPDM polymer but with a wide range of attainable properties. Furthermore such charts are not necessarily produced just to apply to the cladding joint designer - they may be intended to be of equal use to the automotive, aerospace, hydraulic and textile industries.

7.1.1.7 Installation

The final stage is to examine how the gasket will be installed. Installation guidance should be straightforward to prepare if the joint and gasket have been properly designed. In this final stage the designers should aim to identify possible problems which could occur on-site and which the installer would be expected to work around. It might be possible to anticipate the need for a sealant to butter over joints, and suitable sealants could be identified - the preparation of a list of approved sealants would discourage the installer from changing the process.

The steps outlined above are quite simple to follow, and communication between the various parties involved will increase the likelihood of a successful design. However, it should be remembered that this process need not be performed for every joint, because it is often possible to use a design of joint and gasket that has been used before! This variation on the design process is followed by a number of companies, often door and window producers - put simply if a joint and gasket works then keep on using it! It is always sensible to start the design of a new product around those parts of the previous product that performed well and can be retained. It may only be that a gasket or joint needs to be redesigned if some performance rating of the product needs to be increased, usually the weather-tightness.

BRE Digest 137 (1977) also identifies issues which have to be considered when designing a joint. A checklist is provided in which several items are listed which would require communication between the joint designer and the gasket designer.

As a final note in this section Trueman (1993) notes that fitting of a seal is very important, and that the fit of the gasket into the joint is important. However, the author also states that his company produces more than 3000 different designs! Selecting the right seal for the job can only be made more difficult if there is such a proliferation of choice.

7.2 The role of standards

Standards are often used as a means of communication between specifier and designer. However, there are few standards which apply to the performance of gaskets in isolation, and the current gasket material standards cannot be easily related to current standards for assessing weather-tightness. If there were a standard for assessing gasket performance then this would also serve to encourage better communication between joint designer and gasket producer.

In the absence of standards it is usually up to the specifier and designer to rely on common sense. However, this rarely happens, and a particular issue might never be mentioned in a specification if the specifier doesn't have clear written guidance - the specifier is trying to be a 'Jack of all trades' and cannot take the time to formulate a strategy for a single component.

This report has identified a number of texts which give guidance on various issues relating to joint and gasket design and performance, and the best of this guidance should be incorporated into a standard or code of practice for gasketted joints.

7.3 Summary

This report has reviewed the design of joints and gaskets, and it has been found that there are a large number of existing publications which give guidance on these issues. The major reason for the failure of joints and gaskets appears to be due to two issues - a failure to understand basic physical and engineering principles, and a failure to communicate. However, there is a clear need for a more rational approach to performance and standardisation, and for more importance to be placed on issues such as performance of gaskets, rather than the large number of tests for material properties.

Figure 7.1.1.6 **A typical comparative chart of rubber material performance (from Park Rubber Ltd (1980s))**

QUICK REFERENCE CHART (TYPICAL PROPERTIES OF A BLACK COMPOUND)

COMPOUND POLYMER	Availability	Available Colours	Resistance to serious loss of properties when subjected to continuous exposure to:—					
			Compression	Ageing	Temperature High +100c	Temperature Low −20c	Ozone	UV Light
E P D M (e.g. Dutral)	Solid & Expanded	Limited Colours	Outstanding	Outstanding	Good	Outstanding	Outstanding	Outstanding
POLYCHLOROPRENE (e.g. Neoprene)	Solid & Expanded	Black	Good	Outstanding	Good	Moderate	Good	Outstanding
NATURAL RUBBER	Solid	Black	Good	Good	Good	Good	Poor	Moderate
NITRILE	Solid	Black	Good	Good	Moderate	Poor	Poor	Moderate
POLYISOPRENE	Solid	Black	Moderate	Good	Good	Good	Poor	Moderate
S B R	Solid	Black	Moderate	Good	Good	Poor	Moderate	Moderate
SILICONE	Solid	Colours	Outstanding	Outstanding	Outstanding	Outstanding	Outstanding	Outstanding
P V C †	Solid	Colours	Poor	Good	Poor	Poor	Good	Good
T P R †	Solid	Colours	Good	Outstanding	Good	Good	Outstanding	Good

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APPENDIX A Simulating the force-compression characteristics of gaskets

This appendix is intended to describe briefly the method used to predict the force-compression characteristics of gaskets. However, a detailed description of the finite element method is beyond the scope of this report, and the reader is referred to books such as that by Fagan (1992).

A.1 Setting up the analysis

The analyses have been performed using the commercially available simulation software ANSYS.

The first stage in the analysis is to prepare a drawing of the product to be analysed, and to import this into the simulation package. The drawing has been prepared from measurements on the samples of gasket as they were being prepared for testing. Figure A.1(a) shows the drawing for gasket A - the tubular weather-strip. Note that because the weather-strip is symmetrical it is only necessary to simulate one-half of the weather-strip. Furthermore, because a straight length of gasket has been tested it is only necessary to simulate a cross-section of the gasket - a simulation of a corner joint would have to be three-dimensional and would need a far greater computing resource. When a two-dimensional drawing is input ANSYS assumes that the properties and behaviour of the object are uniform in the third dimension.

After the drawing is imported a grid of finite elements is created automatically by ANSYS, subject to various constraints. The finite element mesh for gasket A is shown in Figure A.1(b). The type of element is selected to suit the type of material. ANSYS has a range of element types which use different equations for the mechanical behaviour of the material. Note that there are elements which use traditional models based on small strain behaviour and elements which are based on the Mooney and Blatz-Ko models. Furthermore there are elements specifically for two-dimensional simulations, as used here, and there are other elements for three-dimensional simulations.

As part of the meshing procedure a set of contact elements have been defined for the parts of the weather-strip that are expected to come into contact with the contact surface. These elements allow friction to be defined between the gasket and the contact surface, on the basis of a constant coefficient of friction.

The material properties are defined for the gasket material as part of the setting-up procedure. ANSYS includes a utility for determining the Mooney coefficients from stress-strain data for the material. This facility has been used to obtain a least-squares fit to the data, but other values for these coefficients can be entered by hand.

The process of defining the gasket generally takes about one hour, including the preparation of the drawing.

A.2 Defining the loads and running the analysis

The simulation is performed by notionally fixing the gasket at one or two points so that it cannot move at those points and then defining a movement of the contact surface to compress the gasket. The contact surface is moved by a fixed amount in a fixed time, the amount being defined by the experimental data. When the simulation is run the movement of the contact surface actually occurs in a number of small steps, with the simulation software automatically deciding on the length of time-step required to give a stable solution. Solution times ranged from about 30 minutes for gasket E, to nearly 10 hours for gasket B, depending upon the level of friction required.

This approach does not undertake a true dynamic solution of the mechanical equations, but instead takes a series of snap-shots of the gasket for different positions of the contact surface. A dynamic simulation would require values for other material properties, and is beyond the scope of this report.

A.3 Analysing the results

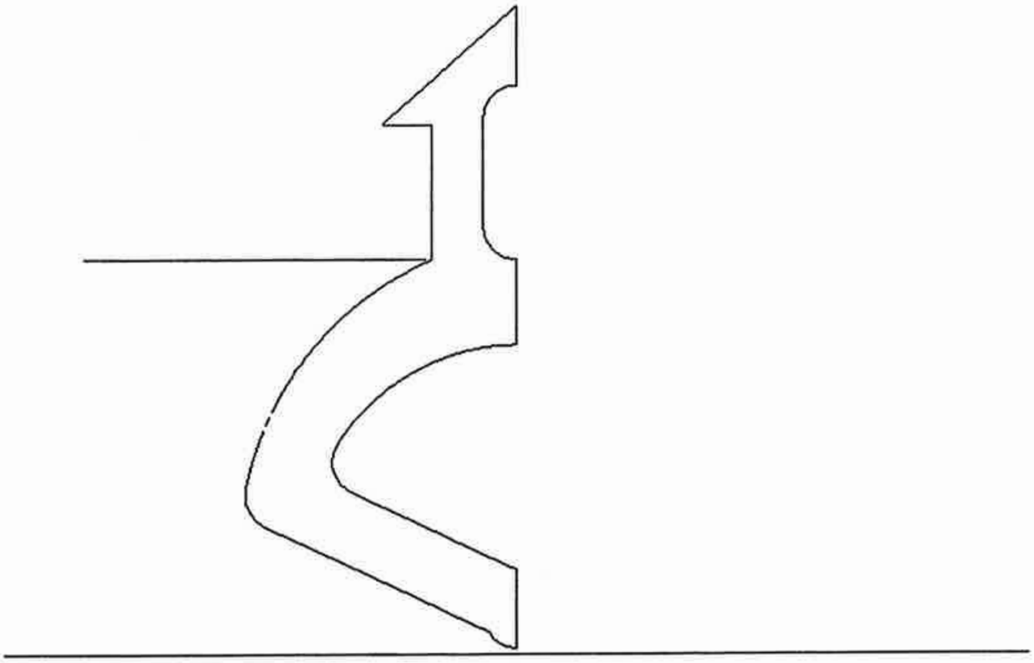
At a number of intermittent time-steps a set of results is stored and can be retrieved and analysed. For each set of results there is a time value (which can be converted to a deflection of the gasket, because the rate of movement of the contact surface is constant) and a set of stresses, strains and forces. The contact force can be added together for all of the contact elements, and this is the force required to compress the gasket by the given amount (note that because a two-dimensional simulation has been performed the force is given per metre length of the gasket). It is then possible to plot the predicted force-compression characteristic for each gasket. It is also possible to plot the deflected shape of the gasket at each time-step, and to plot the stresses and strains in the gasket at each time-step.

The simulations can be run as many times as required, changing one or more material property for each run.

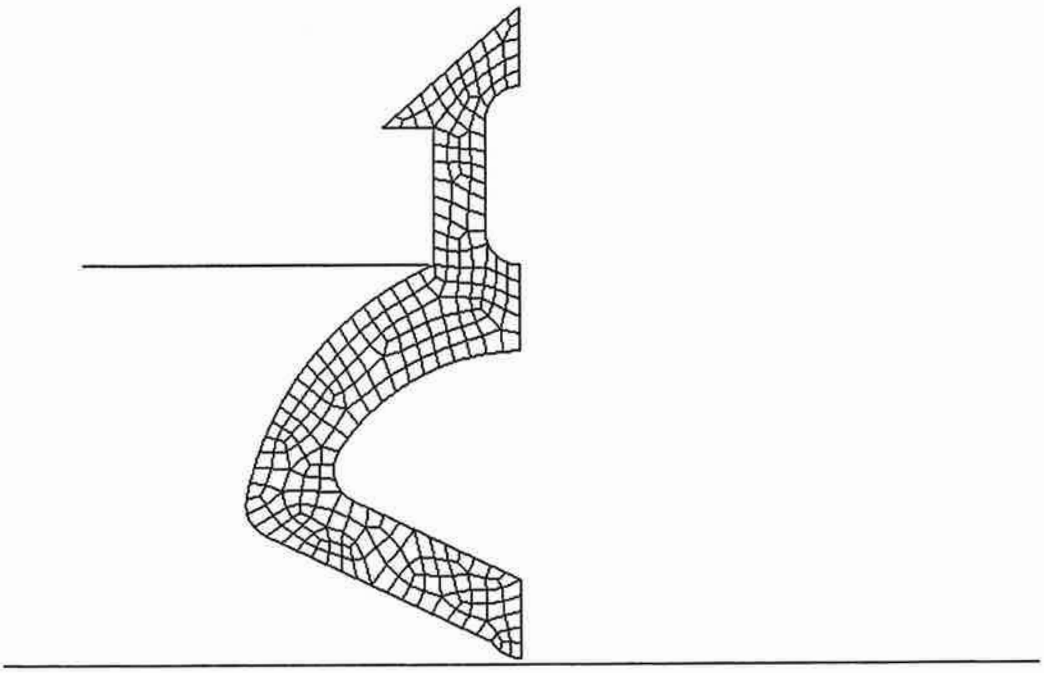
A.4 Closure

Finite element analysis is a specialist form of analysis, and requires specialist computer software. The description above is by no means comprehensive, and the method by which the simulation software solves the various equations established by the analysis is also beyond the scope of this report. However, this type of software is used extensively in many fields of engineering, and providing suitable experimental data is available for comparison, computer simulation is a valuable tool in the design of many components.

Figure A.1 The simulation of gasket A



a) the simulation drawing



b) the finite element mesh