Introduction

Lack of understanding of building tolerances is a major source of conflict on site. It increases construction costs and can lead to poor quality buildings or even failures if corrective measures are ill-conceived. This Technical Note discusses the issue of tolerance as it relates to cladding, in order to improve levels of understanding and awareness of how to achieve satisfactory fit and appearance. The guidance given in this Technical note is based on the principles described in BS 5606 and BS 6954.

Definitions

Fit is not merely being able to, for instance, insert one component within another, but also requires that the assembly functions as intended. Satisfactory fit is rarely achieved by accident - it is the result of good planning by all participants. This requires an understanding of some fundamental concepts, which are defined and described below.

Deviation

The difference between a specified nominal value and an actual measured value.

There are two types of deviation.

Induced deviations

The inevitable result of variations in the manufacturing process and the inability of human operatives and instrumentation to measure with absolute precision.

Induced deviations are permanent and whilst the design needs to take account of their presence at the time of construction, it is not necessary to allow for further induced deviations in service.

Inherent deviations

Inevitable inaccuracies due to the physical properties of materials.

Inherent deviations are post-installation dimensional changes and movements in both the structure and the cladding. Sources of inherent deviations include moisture and thermal movement, elastic deformations, concrete creep and shrinkage and foundation settlement. Guidance on estimation of inherent deviations is given in BRE Digests 227-9.

Cladding can absorb inherent deviations through allowing freedom of movement, by incorporating discontinuities and designing some fixings to slide. Alternatively, fixings and panels can be designed to resist the forces induced by restraining movement. Conversely, movement of the structure may in some instances have to be limited to a level that can be accommodated by the cladding fixings and joints.

Tolerance

Tolerances define the limits of induced deviation for which allowance should be made in design, and within which actual sizes are acceptable.

Tolerances therefore describe how much variability is allowable; not how much is present which is termed deviation (see above). Tolerances may be specified with equal deviation either side of the stated size but can also be specified as the maximum deviation from an absolute maximum or minimum value.

Why do we need accuracy?

Absolute accuracy is not achievable although the level of inaccuracy can be reduced by greater care and more refined construction techniques. The reduction in inaccuracy will
generally be accompanied by increased cost and specifying unnecessarily tight tolerances is therefore undesirable. It is necessary to achieve a balance between the cost of achieving accuracy and the costs resulting from inaccuracy. These arise from the effects of inaccuracy on:

- Structural behaviour,
- Weathertightness,
- Durability,
- Appearance,
- Buildability,
- Legal requirements.

**Structural behaviour**

Deviations in the shape of building components, and the assembled structural frame, potentially have a significant effect on structural behaviour. Hence the tolerances specified in BS 5950: Part 2 for structural steelwork are intended to ensure compliance with the design assumptions that underlie the design procedures in Part 1 of the standard.

On lightweight structural frames, tolerances may be affected by torsional rotation of edge beams. Care therefore needs to be taken at the outset to ensure that edge beams are designed with sufficient rigidity and any anticipated torsional rotation is duly quantified.

The effect of tolerances on the design of brackets may be much greater than for normal structural design and design calculations should therefore be carried out with forces and bending moments derived for the most adverse arrangement of dimensions.

**Weathertightness**

Variability in building components will lead to variation in width of joints, which may lead to ineffective seals. Joints that are too narrow may be impossible to seal properly due to restricted access. If joints are too wide, excessive quantities of sealant may be required and problems of slumping are likely to be experienced. Large variations in joint width over short distances lead to stress concentrations in the seal.

**Durability**

Lack of weathertightness resulting from excessive variability will have an adverse effect on durability. Durability may also be affected if unforeseen or increased stresses are induced as a result of excessive variability.

**Appearance**

The appearance of the completed structure will be affected by the variability of components and construction. These effects are subjective and may be disguised to some extent by careful detailing. Conversely when design features which emphasise defects are required by the designer greater accuracy may be required.

**Buildability**

Buildability relates to the ease with which a building can be constructed. In respect of fixing cladding it requires connections which have sufficient adjustment to overcome variations in both the supporting frame and the cladding. The connections should be simple to install and adjust at all stages of the cladding erection sequence.

Excessive variations arising from out of tolerance components or construction of the frame may require special fixings to be fabricated increasing cost and delaying the erection programme.

**Legal requirements**

Some dimensions are set by legal requirements, for example the height of handrails. Excessive variability may result in these legal requirements not being met.
Design requirements

Traditional cladding, such as brick-, block- or stonework, is flexible in terms of building layout for two reasons. Firstly, the construction process occurs on site and therefore provides the opportunity to accommodate actual irregularities. Secondly, the product comprises a large number of small components with relatively wide joints which provides the means to accommodate in-plane deviations and therefore to fit between or enclose the building frame. However, both these features reduce the level of accuracy and rate of construction of the cladding.

Modern forms of cladding involve the rapid enclosure of a site-erected frame with a factory-made skin. Lead times for cladding do not allow the cladding contractor to take actual measurements of the structure before proceeding with manufacture or fabrication. Prior to detailed design work commencing, it is essential that the tolerances to which the structure will be built are reconciled with those that the cladding specialists have planned to accommodate. It is commonplace for such coordination to be overlooked, with serious implications.

Satisfactory fit of modern cladding therefore has to be planned. There are two issues to be considered:

- Specification of tolerances for the completed cladding,
- Accommodation of tolerances in the supporting structure and cladding components to achieve fit.

Tolerances for cladding

The tolerances on the completed cladding are generally governed by the need to achieve satisfactory appearance. Tolerances for curtain walling are given in the CWCT Standard as follows:

- Line +/- 2mm in any one storey height, or structural bay width, and +/- 5mm overall;
- Level +/- 2mm in any one structural bay, and +/- 5mm overall;
- Plumb +/- 2mm in any one storey height, and +/- 5mm overall;
- Plane +/- 2mm in any one structural bay, and +/- 5mm overall;
- Widths of fixed joints should not vary by more than 10% of the minimum joint width;
- Offsets at joints should not exceed 10% of the joint width in plane, or out of plane.

These tolerances are intended to give satisfactory appearance, which is affected by relative positions of the visible cladding elements rather than absolute position in space. They should therefore be measured with respect to the plane of the cladding or in more practical terms a series of adjacent reference lines. There will be an additional deviation in the setting out of the reference lines with respect to the basic reference points for the site.

These tolerances are intended to be applied to curtain walling which is made up from smooth straight and flat elements and therefore the permitted deviations are relatively small. The tolerances for other types of cladding will vary according to the nature of the material involved. References to appropriate standards or guidance documents are given in Table 1.

Techniques that may be used to reduce the visual impact of variations include:

- Placing the least satisfactory cladding panels in less conspicuous locations such as the top or back of the building,
- Lack of straightness in horizontal features is most noticeable when viewed at an
angle. Landscaping may be used to restrict viewing angles,

- Deviations in the alignment of profiled metal sheets are more noticeable when the sheets are laid horizontally rather than vertically,

<table>
<thead>
<tr>
<th>Cladding type</th>
<th>Standard of manufacture</th>
<th>Standard of erection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick/concrete masonry</td>
<td>BS 3921, BS 6073: Part 1</td>
<td>BS 8000: Part 3</td>
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<tr>
<td>Stone masonry</td>
<td>BS EN 485: Part 4, BS EN 10131</td>
<td>Stone Federation Data Information Leaflet</td>
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<tr>
<td>Composite panel</td>
<td>BS 8297</td>
<td>BS 8297</td>
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<td>Stone panel</td>
<td>BS 1474, BS 952: Part 1, BS 5713</td>
<td>Standard for Curtain Walling</td>
</tr>
<tr>
<td>Curtain walling</td>
<td>BS 1474</td>
<td>A guide for specification of Patent Glazing</td>
</tr>
</tbody>
</table>

Table 1: Sources of information on the permissible accuracy of manufacture and erection of cladding components/systems

- Coarse or irregular panel finishes with less definite edges hide misaligned joints
- Chamfered edges at joints help to hide variations,
- Where joint widths change at intersections of horizontal and vertical joints, ensuring that there are equal offsets on both sides of the joint.

Achieving fit

It is a basic requirement for achieving fit that there is sufficient space for the various components. This can be achieved by using overlapping components so that variations in size can be accommodated by changing the amount of overlap but for most elements this is not possible and specified sizes must be chosen to avoid overlap or conflict. For example if a window frame is to be installed in an opening the maximum size of the window should not be greater than the minimum size of the opening.

This process involves a number of steps.

Identifying critical dimensions

A critical dimension is defined as one in which normal permissible deviations may subsequently prevent the fit of related components. Achieving fit requires the critical dimensions to be identified. The likely deviations associated with these dimensions can then be evaluated and allowed for in the design.

Difficulties of assembly are related to the degree of dimensional control required, that is, the number of critical dimensions. Reducing the number of critical dimensions will therefore reduce problems of lack of fit. For example a structure in which the external cladding fits within the frame of the building is more likely to give problems of lack of fit than one in which the cladding is fixed outside the frame with the only contact at fixing points.

In the example of the window above the critical dimensions are the height, width and squareness of the opening and frame.
Evaluation of induced deviations

The values of induced deviations will, in many cases, follow a normal statistical distribution around the mean size or position. Randomly occurring induced deviations may be treated according to statistical principles, so that account can be taken of the relative probability of small and large values, and may be expressed in terms of the standard deviation, as a measure of variability.

Values may also exhibit a bias reflecting systematic, rather than random, variability, such as a fixed deviation due to maladjustment of measuring instruments. Systematically occurring deviations apply to batches or groups of components or measurements and must generally be treated as definite, recurring values.

BS 5606 provides guidance on the accuracy that can be achieved in masonry, concrete, steel and timber members and structures based on measured and estimated survey data. This reflects the standards of construction/erection and manufacture achieved by industry in 1979 and 1990 respectively. For example, BS5606 indicates that the edge of a suspended concrete floor slab may vary from its intended position by +/-15 mm in plan and +/-25mm in level. These values have a probability of 1 in 22 of being exceeded and to reduce this probability to 1 in 80 the deviation would be increased to +/-19mm and +/-31mm respectively. For a probability of 1 in 370 the tolerances would be 22.5mm and 37.5mm.

A multitude of standards cover the accuracy of cladding components (Table 1)

Joint width

The interface between components constitutes a joint and in most cases it will be necessary to allow a space for the joint. The design joint width will depend on both the width necessary to construct the joint satisfactorily and the width necessary to allow the joint to function as intended. For example the joint must have sufficient width to be able to accommodate inherent deviations. One of the main functions of the joint is to compensate for the tolerances in the adjacent components and it will be necessary to determine the range of widths over which the joint will be satisfactory. Requirements for joints are described in further detail in Technical Note 16 Joints in the building envelope.

Assessment of specified dimensions

To ensure that components fit, the specified values for the critical dimensions must take account of both induced deviations and the width of the joint.

One approach would be to specify maximum and minimum values rather than mean values. In the example of the window, the size of the opening would be specified as a minimum value and the size of the frame would have maximum values specified. To ensure fit these values would have to differ by the minimum width of the joint and the overall variation in permissible joint width would have to equal or exceed the combined tolerance on the opening and frame.

Thus if the width of the opening is W with a tolerance of +2w and -0, the width of the frame is F +0/-2f and the width of the joint is J +/-j then:

\[ W \geq F + (J - j) \quad \text{and} \]
\[ f + w \leq j \]

If it is not possible to satisfy these conditions simultaneously it will be necessary to modify the design by for example requiring tighter tolerances, using a joint with greater range of acceptable width or increasing the number of joints.

In practice the method given above will be conservative as it allows for the possibility of the extreme deviations occurring in both critical dimensions simultaneously. Due to the statistical distribution of the deviations this is unlikely to occur. To give a more economical result the overall tolerance on a dimension made up from a series of components each
with an associated tolerance is given by the square root of the sum of the squares of the individual tolerances. Thus in the above example the required range of joint width is determined from

\[ \sqrt{f^2 + w^2} \leq j \]

It should also be recognised that the statistical distribution of deviations means that there will be a small chance of the actual deviation being greater than the stated tolerance. Values of tolerances are often quoted with a chance of approximately 1 in 22 of being exceeded. This may give an unacceptable risk of lack of fit and it may therefore be necessary to allow for greater tolerances, which will have a lower risk of being exceeded.

**Buffer zones**

In some situations the risk of lack of fit can be reduced by incorporating a buffer zone in addition to the allowance for normal tolerances. The buffer zone then provides a contingency for cases where the specified tolerance is exceeded. Buffer zones are most commonly used between the building frame and the cladding.

**Design of fixings**

Fixings must also be designed to accommodate tolerances. For example if a curtain wall is fixed to the edges of the floor slabs, the brackets must be able to adjust to accommodate the tolerances on the construction of the floors described above. The required adjustment can be determined in the same way as the range in joint width.

Adjustment provision can be incorporated by one or more of the following features:

- Oversize or slotted holes;
- Site-drilling or welding after positioning of components;
- Shims, packing pieces or washers (low friction for movement provision);
- Sliding/serrated connections or adjustable bolts.

Where the adjustment is provided in steps as in the case of serrated surfaces it is important to ensure that the size of the steps is smaller than the tolerance on the erected cladding.

Requirements for brackets are described in greater detail in Technical Note 28 *Performance requirements for curtain wall brackets*.

**Construction procedures**

Even where the cladding has been designed to take account of tolerances, the erected cladding will only be satisfactory if the erection of the cladding is carried out in accordance with good practice.

- A fundamental requirement is to ensure that all setting out is carried out from defined datums using equipment of the required accuracy. Setting out fixing locations from the edge of the floor slab rather than reference grid lines is unlikely to lead to a satisfactory result.
- The maximum number of shims/packing pieces should be specified. Excessive shimming, which is usually the result of a structure being out of tolerance laterally, can lead to inadequate penetration of fixing bolts and to both a reduction in pull-out strength and an increase in the bending stresses in the anchors/bolts. It may also prompt the substitution of longer bolts, again inducing unforeseen bending loads.
- The final position of a bolt in a slotted hole may need to be specified so as not to restrict post-installation movement.
- Panel-to-panel butt joints must be kept within the practical (installation) and physical (working range) of the joint seal.
- Minimum lengths of overlap must be maintained for weathertightness.
Lateral adjustment (of masonry or concrete cladding panels) should not lead to a loss of bearing of the seating.

Summary

This note is intended to provide a first step towards addressing the general lack of understanding of tolerances. Permissible deviations in the structure and cladding should be agreed between the architect, contractor and cladding contractor at the design stage and marked on drawings and specifications, maintained during erection of the frame and planned for in the cladding fixing arrangement. Each sub-contractor should set out from the same datum and levels and be accountable for their element of the work.

References and bibliography

BS 644 British Standard Wood Windows

BS 952 Glass for glazing, Part 1, 1978, Classification, British Standards Institution.


BS 3921, 1985, Specification for clay bricks, British Standards Institution.


BS 5713, 1979, Specification for Hermetically sealed flat double glazing units, British Standards Institution.


BS 6954 Tolerances for building, British Standards Institution.


BS 8297, 1995, Design and installation of non-loadbearing precast concrete cladding, British Standards Institution.


BS EN 10131, 1991, Cold-rolled uncoated low carbon and high yield strength steel flat products for cold forming. Tolerances on dimensions and shape, British Standards Institution.


