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THE REPEATABILITY AND REPRODUCEABILITY OF TEST RESULTS ON WINDOWS AND WALL SPAN ELEMENTS AND THE EXPECTED RESULTS

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The variations in the test results which occur with the laboratory procedures for assessing the air and water penetration attributes of windows are discussed. Data are presented for windows examined under British Standard BS 4315 : Part 1 'Methods of test for resistance to air and water penetration – windows and gasket glazing systems'. The implications of these tests for the development of performance levels for use in standards and procurement documents are considered and a two-stage statistical procedure is proposed, based in the first instance on tests on five windows. The use of such a procedure will permit the acceptance with confidence of test results as being a correct interpretation of the performance of a window type under the assessment procedure. However it is emphasised that before meaningful performance levels can be set there is need to correlate the performance of windows as established under the laboratory assessment procedure with the actual performance of windows installed and in use in buildings.

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INTRODUCTION

For many years, individual manufacturers, specifiers and research organisations have been concerned with applying the performance concept to the specification of windows and other wall elements. National standards based on the constructional details of the products involved are being gradually replaced either totally or in part by standards which define only the performance required; this trend is also becoming evident at the international level through the work of CEN[1] and ISO[2]. Of the performance attributes of windows and associated wall elements that need to be considered by designers and others concerned with building performance, those for air and water penetration are among the most important. Various laboratory tests have been developed over the years in an attempt to simulate the conditions of exposure to wind and rain that pertain in buildings and on a national basis performance levels have been defined and related to the required degree of exposure. Most of the available test methods employ a pressure box into one face of which the window or wall element is inserted. The air pressure in the box is increased to simulate wind pressure, though with many test systems not wind movement, and water is applied to the window or wall element by a variety of methods, many of which have been defined in the recently proposed CEN Standard EN86. Although one method, the area spray technique in which water jets in a grid are directed at the component under test, is the 'preferred' method, there is some evidence from the work of CIB Commission W61 – Joints – that the various water application methods give different results and there are few data relating the performance under the various tests to the actual performance of the joints between and within components in use in buildings. This is a subject that is currently being investigated at the Princes Risborough Laboratory of the Building Research Establishment in England.

An important aspect of any laboratory tests for air and water penetration is the variability that arises in the test results because, without data on the variability, it is impossible to define meaningful performance levels under the test. This paper discusses this variability and describes an investigation recently completed at the Princes Risborough Laboratory which was aimed at assessing the variation implicit in the current British Standard BS 4315 : Part 1 'Methods of test for resistance to air and water penetration – Windows and gasket glazing systems'. The implications of the results are assessed for the future development of meaningful performance-based standards for windows and other wall elements.

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[1] Comité Européen de Normalisation

[2] International Standards Organisation

TEST METHOD VARIABILITY

Apart from the differences in performance under air and water penetration tests of the different types of windows available to the building designer and specifier, the following sources of variability within a type can be identified:

(a) Variation between individual windows of the same type
Despite care in manufacture, individual windows of the same type will vary. Slight differences in the dimensions of the constituent parts will occur and, even under the most carefully controlled assembly procedures, the spatial relationships between the parts after assembly will be such that the joint dimensions will not be constant. In addition, any slight distortion, particularly of opening lights, induced subsequent to manufacture by movement of the material of which the window is made can affect the performance. Thus there will be a measurable variation in performance between windows of the same type that is associated with the windows themselves.

(b) Variation between test apparatus
Although the essential characteristics of the test apparatus can be defined, individual designs of equipment will vary. Apart from the physical dimensions, the care with which equipment is made will be reflected in the air leakage from equipment itself though attempts are made to take this into account in most tests. In addition the method of measuring the entering air, its point of entry, and any baffle arrangement could affect the operation. The accuracy of the manufacture of the water spray system and the precision with which it can be and is set will also affect to some degree the results achieved in the water penetration test. Thus there will be a variation between individual test apparati.

(c) Variation between test operators
Although air leakage from the test apparatus and air penetration through the window joints can be quantified, the precision with which the readings are taken will be dependent partly on the skill of the operator. In addition, under the water penetration test the operator is required to decide at what pressure 'gross' leakage occurs. This at present is only defined in general terms and much depends on the experience of the operator in interpreting the meaning of 'gross'. Thus there will be a variation between operators that must be recognised.

(d) Residual variation
Even when the sources of variation due to the window, the test apparatus and the operators are separated there will inevitably be a residual variation that cannot be accounted for precisely, for example the care with which the window is mounted in the test apparatus, and this must also be recognised. Indeed the level of this residual variation is to some extent a measure of the stage of development and of the validity of the test method.

Few authoritative data are available on the extent of these variations and indeed in most standards for air and water penetration they are ignored. Without the recognition of these variations however any performance levels set against the laboratory tests have little real meaning.

THE DEGREE OF TEST METHOD VARIABILITY ASSOCIATED WITH BS 4315 : PART 1 METHODS OF TEST FOR RESISTANCE TO AIR AND WATER PENETRATION

x designs of window covering the five configurations detailed in Table 1 and commonly in use in the UK were identified and a number of windows of such type were secured from the stocks of the normal production of the manufacturers concerned.

The windows were tested in accordance with the method detailed in BS 4315 : Part 1 using two pressure boxes and two different but experienced operators. The experimental procedure was arranged to separate as far as possible the effects of the various sources of variability.

RESULTS OF AIR PENETRATION TESTS

The results of the air penetration tests are given in Table 2. The mean air penetration varied from 2.2 $m^3/h/m$ to 25 $m^3/h/m$ and there was a considerable spread of results about the mean which tended to increase with the mean level. For a mean of between 2 and 4 $m^3/h/m$, 95per cent of the windows tested were within the range 0 to 7 $m^3/h/m$ while for a mean of 24 $m^3/h/m$, 95 per cent of the windows tested were within the range 16 to 32 $m^3/h/m$. This wide range is built up from a number of individual variations considered earlier in this paper and quantified in Table 3. The variation due to the windows themselves was represented by a standard deviation of between 0.9 and 3.5 $m^3/h/m$.

Thus 95 per cent ie ± 2 standard deviations of the windows of the most variable type tested occurred within the range ± 7.0 $m^3/h/m$. There were statistically significant differences between the two box/operator combinations employed, even although the boxes were within the requirements of BS 4315 : Part 1, and both operators were considered 'experienced'. One box/operator combination gave consistently higher values than the other, the difference in the means of ten windows of each type varying from 1.3 $m^3/h/m$ to 3.3 $m^3/h/m$. The reason for this variation has not been identified though it is believed to be due to the method of measuring the air introduced into the box and the baffle system used at the entry.

Table 1 Details of windows examined

Type		Material and finish	Draught stripping	Number obtained for testing
Designation	Description			
IA	Horizontal slider in timber sub-frame One opening light one fixed light	Aluminium mill finish	Brush and neo- prene seals	30
IB	Horizontal slider in timber sub-frame One opening light one fixed light	Aluminium mill finish	Brush seal	5
II	Side-hung casement in timber sub-frame One opening light one fixed light Weather bar at head	Aluminium mill finish	Neoprene seal	40
III	Vertical slider in timber sub-frame Two sliding lights	Aluminium mill finish	Brush and neo- prene foam seal	20
IV	Side-hung casement and vent light Two opening lights one fixed light Weather bar at head	Timber Gloss paint finish	None	30
V	Side-hung casement and vent light in timber sub-frame Two opening lights one fixed light Weather bar at head	Steel Gloss paint	None	6

Table 2 Air penetration at 100 Pa of windows tested using two boxes and two operators

Type designation	Number of windows tested	Mean air penetration ($m^3/h/m$)*	Standard deviation ($m^3/h/m$)*	Range within which 95% of window tests occur ($m^3/h/m$)*
IA	30	3.6	1.6	0.4 – 6.8
IB	5	13.8	1.8	10.2 – 17.4
II	40	2.2	1.3	0 – 4.8
III	20	11.1	1.6	7.9 – 14.3
IV (a) whole window	30	7.9	3.2	1.5 – 14.3
(b) side-hung casement only	30	8.7	4.2	0.3 – 17.1
(c) vent light only	30	6.4	3.1	0.2 – 12.6
V (a) whole window	6	23.8	3.8	16.2 – 31.4
(b) side-hung casement only	6	25.0	4.5	16.0 – 34.0
(c) vent light only	6	21.8	4.1	13.6 – 30.0

*The rate of air penetration is expressed at m^3/h per metre length of opening light

As shown by Table 3 when the effect of the box/operator combination is removed and the variation between individual windows of a type taken into account by testing the same window a number of times in one box and with one operator there is a residual variation which has not been identified in detail but which is associated with the test procedure itself. With the exception of Type V all the types of window tested for air penetration gave a residual standard deviation of about 1.0 $m^3/h/m$. That is, the test procedure itself generated a variation such that 95 per cent of the results were within the range of ± 2.0 $m^3/h/m$ of the mean value. With the Type V window the standard deviation for the six windows examined was 2.5 $m^3/h/m$.

There is thus no single source of the wide variation found in the test results. Indeed the difference between individual windows of a type, between box/operator combinations and associated with the test procedure as such appeared to contribute to a similar extent to the total variation experienced.

RESULTS OF WATER PENETRATION TESTS

The results of the water penetration tests are shown in Table 4. The mean level for 'gross' water penetration varied from 160Pa to 630Pa for the window types tested and there was a very considerable spread of results about the mean which tended to increase with the mean level. For a mean leakage pressure of 100 to 200Pa, 95 per cent of the results were within the range ± 200Pa while with a mean of 300 to 650Pa the range increased to about ± 500Pa. As with air penetration this variation was built up from a number of individual variations considered earlier in this paper and quantified in Table 5.

The variation due to the windows themselves gave standard deviations between 10 and 89Pa with the exceptions of Type II which gave a high level of 253Pa and Type IV for which no statistically significant variation was identified. Thus, apart from these types, 95 per cent of the windows examined were within the range ± 178Pa of the mean. Again there was a difference due to both the operator and the box used but this was only statistically significant on window Types III and IV. With these window types a difference in the means between operators varied between 63 and 130Pa, with one opening light showing no significant difference. That due to the boxes alone varied between 40 and 144Pa with again one comparison giving a difference which was not statistically significant.

As shown by Table 5, when the effects of the box, the operator and window variation were eliminated by retesting an individual window a number of times, the residual standard deviation due to the test procedure alone varied between 20 and 209Pa depending on the window type. Thus the test procedure itself generated a variation such that 95 per cent of the results were within the range of up to ± 418Pa of the mean. By retaining the window in the box between tests this variation was reduced by about a third of the standard deviation showing the effect of the mounting procedure on the test result.

With water penetration as with air penetration therefore there was no single source of the wide variation found in the test results. Indeed, the differences between individual windows of a type, between boxes, between operators and associated with the test procedure as such appeared to contribute to a similar extent to the total variation experienced.

Table 3 Source and extent of variation in the air penetration of windows

Type designation	Source and extent of variation					
	Between windows		Between two box/ operator combinations		Associated with test procedure	
	Number of windows examined	Standard deviation ($m^3/h/m$)	Number of windows examined	Difference in mean value ($m^3/h/m$)	Number of windows examined	Standard deviation ($m^3/h/m$)
IA	20	0.9	10	1.3	20	1.3
IB	5	1.3	–	–	5	0.8
II	20	1.3	10	1.3	20	0.8
III	20	0.9	10	1.4	20	1.1
IV (a) whole window	20	2.1	10	1.3	20	1.3
(b) side-hung casement only	10	3.5	10	3.3	10	0.8
(c) vent light only	10	2.7	10	2.0	10	0.9
V (a) whole window	6	*	–	–	6	2.5
(b) side-hung casement only	6	} *	–	–	6	3.7
(c) vent light only	6					

*No statistically significant difference at the 5% level
–No test carried out

Table 4 Water penetration (pressure at which 'gross' leakage occurred) tests on windows using two boxes and two operators

Type designation	Number of windows tested	Mean pressure for 'gross' leakage (Pa)	Standard deviation (Pa)	Range within which 95% of window tests occur (Pa)
IA	30	160	55	50 – 270
IB	5	190	22	146 – 234
II	40	360	241	0 – 842
III	20	630	184	262 – 998
IV (a) whole window	30	200	102	0 – 404
(b) side-hung casement only	30	230	101	28 – 432
(c) vent light only	30	310	259	0 – 828
V (a) whole window	5	260	22	216 – 304
(b) side-hung casement only	5	280	27	246 – 314
(c) vent light only	5	260	22	216 – 304

Table 5 Source and extent of variation in water penetration of windows

Type designation	Source and extent of variation							
	Between windows		Between two operators		Between two boxes		Associated with test procedure	
	Number of windows	Standard deviation (Pa)	Number of windows	Difference in mean value (Pa)	Number of windows	Difference in mean value (Pa)	Number of windows	Standard deviation (Pa)
IA	6	10	10	*(1)	10	*(1)	6	29
IB	5	19	–	–	–	–	5	25
II	5	253	10	*(1)	10	*(1)	5	209
III	5	70	8	63	8	144	5	125
IV (a) whole window	5	*	5	80	5	*	5	97
(b) side-hung casement only	5	*	5	130	5	40	5	50
(c) vent light only	5	89	5	*	5	95	5	114
V (a) whole window	5	23	–		–		5	24
(b) side-hung casement only	5	22					5	20
(c) vent light only	5	23					5	24

*No statistically significant difference at the 5% level
–No test carried out

(1) For window types IA and II differences between operators and between boxes were not isolated. The result given for the window types refers to the difference between two box/operator combinations.

THE IMPLICATIONS OF THE TEST PROGRAMME ON AIR AND WATER PENETRATION FOR WINDOW SPECIFICATION

It is apparent from the test programme described above that considerable variation occurs in the testing of the air and water penetration attributes of windows to BS 4315 : Part 1 and it is probable that an equivalent variation will exist with other similar test methods especially those based on the use of a pressure box. This variation is dependent on window type but does tend to increase with the mean value of samples tested. Thus it is not possible to predetermine without an extensive background of test results the variation that could occur with a particular design and type of window and, as a result, it becomes difficult to set realistic performance levels for specification and procurement purposes. One approach is simply to assume a maximum variation and apply it to all windows in setting performance levels. This approach however could penalise windows of good performance especially in the case of water penetration. A second alternative is to adopt a two-stage statistical procedure that can accomodate the variation associated with the actual group of windows tested; this is the procedure recommended in the paper.

SUGGESTED TEST PROCEDURES

It is suggested that the criteria for acceptance should be such that there is a 75 per cent chance that the group of windows tested are drawn from a population of which 95 per cent of the windows have a higher test result than the specified level. It can be shown[3] that this criterion is met when the mean of five results is more than 2.46 times the standard deviation of those 5 results above the specified level. With fewer test samples the multiplying factor is increased, for example for four windows it is 2.68, and for more test samples the multiplying factor is decreased, for example for 6 windows it is 2.33. The use of five samples is suggested in this paper as being appropriate taking into account, on the one hand, the need to minimise the cost incurred by testing and, on the other, the benefits obtained from testing a larger number of windows.

If the five windows tested fail this initial coarse assessment, it is permissible to examine another five windows. The tests on these ten windows are then repeated to remove the effect of the variability of the test procedure and the mean result when reduced by 2.1 standard deviations should then be above the specified level for a 'pass' to be accepted.

The proposed method is detailed and an example of the calculation for the water penetration attribute is given in the appendix to this paper.

[3] A note on performance testing and the use of statistics – G Christensen, Danish Building Research Institute, Paper 10/10 CIB W60 meeting, Oslo, March 1977.

CONCLUSIONS

The main sources of variation in the testing of windows to BS 4315 : Part 1 'Methods of test for resistance to air and water penetration', have been identified and quantified. It is apparent that this overall variation is built up from the variation that occurs within a batch of windows of the same design, from the variation in the test equipment, from operator variation and from the variation that arises from the test procedure; no one source predominates. The extent of the overall variation depends on the type and design of windows being considered and for a group of windows it tends to increase with the mean test level. Thus the variation that can be expected for a particular group of windows cannot be pre-determined and setting meaningful performance levels for specification and procurement purposes becomes difficult. However a two-stage statistical procedure has been devised for this situation, which takes into account the actual variation of the sample examined. As the variation experienced with the BS 4315 : Part 1 test method is likely to be reflected in other test techniques, especially those employing a pressure box, the suggested procedure merits consideration by all those concerned with the development of performance-based standards for the weathertightness of windows and indeed for other external components.

However it should be emphasised that before performance levels determined under test using these recommended procedures can be accepted it is essential that these levels and the test procedure on which they are based be correlated with the actual performance of windows in use and with the conditions to which the windows are subjected in a building. It is only with the establishment of such a correlation based on authoritative data that performance-based standards will be accepted with confidence by those concerned with the selection and procurement of windows.

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APPENDIX

SUGGESTED ASSESSMENT PROCEDURE FOR AIR AND WATER PENETRATION TESTS

Stage 1 Calculation of characteristic test performance from results of testing five windows once each.

Let $x_1\ x_2\ \ldots\ldots\ x_5$ be individual results

$$\text{the mean } \bar{x} = \frac{\Sigma x}{5}$$

$$\text{and standard deviation } s = \sqrt{\frac{x^2 - \dfrac{(\Sigma x)^2}{5}}{4}}$$

With a 75 per cent chance that this group of windows is drawn from a population of which 95 per cent of the windows have a higher or lower test result than the specified level then:

the characteristic test performance = $\bar{x} \pm 2.46s$

For example if five windows gave the following results for the water penetration test:

150 200 150 200 250 Pa

$\Sigma x = 950, \bar{x} = 190$ and $\Sigma(x^2) = 187500$

$$s = \sqrt{\frac{187500 - \dfrac{950^2}{5}}{4}} = 41.8$$

Therefore characteristic water test performance = 190 − (2.46 x 41.8) Pa

= 87 Pa

If the specification pass level is 50 Pa the windows would pass. However if it was 100 Pa they would just fail and stage 2 of the assessment procedure could be invoked especially as the characteristic water test performance approaches the pass level required.

Stage 2 Calculation of characteristic test performance from results of testing ten windows twice each:

Let $x_{1.1}\ x_{1.2}\ \ldots\ldots\ldots\ x_{1.10}$ be first test results

and let $x_{2.1}\ x_{2.2}\ \ldots\ldots\ldots\ x_{2.10}$ be second test results

Then to use the analysis of variance techniques to identify the window variance:

(a) square each test result and sum, ie $\Sigma(x^2)$

(b) add together two test results for each window, square these totals, sum the squares and divide by 2, ie

$$\frac{(x_{1.1} + x_{2.1})^2 + (x_{1.2} + x_{2.2})^2 + \cdots (x_{1.10} + x_{2.10})^2}{2}$$

(c) add together all twenty test results, square this total and divide by 20 ie

$$\frac{(\Sigma x)^2}{20}$$

Then test variance $$s_t^2 = \frac{(a) - (b)}{10}$$

As the variance between results for different windows

$$2s_w^2 + s_t^2 = \frac{(b) - (c)}{9} \quad \text{where } s_w \text{ is the window variance}$$

then window variance alone $$s_w^2 = \frac{\dfrac{(b) - (c)}{9} - \dfrac{(a) - (b)}{10}}{2}$$

and characteristic performance now $= \bar{x} \pm 2.1\, s_w$

For example if two water penetration tests on each of ten windows give the following results

1st test	150	200	150	200	250	150	150	200	150	200 Pa
2nd test	150	150	200	200	200	200	100	150	150	100 Pa
then $(x_1 + x_2)$	300	350	350	400	450	350	250	350	300	300 and $\bar{x}$ = 170 Pa

(a) $\Sigma(x^2) = 605\,000$

(b) $\dfrac{\Sigma(x_1 + x_2)^2}{2} = 592\,500$

(c) $\dfrac{(\Sigma x)^2}{20} = 578\,000$

Therefore test variance $$s_t^2 = \frac{605\,000 - 592\,500}{10} = 1250$$

As variance between results for different windows

$$2s_w^2 + s_t^2 = \frac{592\,500 - 57\,800}{9} = 1611.1$$

Then window variance alone $$s_w^2 = \frac{1611.1 - 1250}{2} = 180$$

and $s_w = 13.4$

Therefore characteristic performance $= 170 - (2.1 \times 13.4)$
$= 142$ Pa

The windows now pass the 100 Pa specified level.