Window form in deep walls
- the affect on light and solar transmittance.

Matt Bloom MSc
Graduate School of the Environment, Centre for Alternative Technology (CAT)
Email: mattrvb@yahoo.co.uk

Abstract: Increases in requisite levels of insulation typically result in deeper walls and deeper window reveals, which affect daylighting and solar gains - but the literature is limited. This research investigates window form in deep walls - varying the aperture shape, glazing position and the angle of the window reveals, while controlling the glazing area, window head height, and orientation. A scale-model is tested; for daylight from daylight-factor readings taken under an 'artificial overcast sky'; and for sunlight by recording sunpatches (introducing digital photographic software) on a 'heliodon'. Deep reveals reduce mean daylight-factors by 13-18%, although internal splayed reveals can mitigate this loss. Window shape can vary mean daylight-factors by 20%. Glazing position is found to be negligible to daylighting. Deep reveals prevent 73-94% of unwelcome summer solar gains, while permitting 52-65% of useful winter solar gains. Tall windows, and external splayed reveals, perform poorly. The paper concludes that deep reveals can effectively regulate natural light and seasonal solar gains, thereby reducing energy loads, as an integrated and cost-effective element of current building design.

Keywords; window form, deep walls, daylight, solar gains.

1. INTRODUCTION

Natural light is vital to human health and can largely preempt artificial light during the day [Boyle 2004]. Diffuse light - from the sky or reflected sunlight - yields quality illumination. Direct sunlight produces significant solar gains which can provide a third of heat demands in winter [Feist et al 2001] but present an over-heating risk in summer [BR PtL1A 2010; BR PtL2A 2010].

As buildings become more insulated, the heating season is shortened, but the over-heating risk can rise [Persson et al 2005]. Climate change is expected to aggravate this. Insulation obstructs external heat gains conducted from building surfaces [Hastings & Wall 2007], but unshaded glazing will magnify solar radiation and peak space temperatures [CIBSE Guide A 2006]. Increased insulation typically increases wall depth. Deep window reveals provide shade when glazing is positioned internally, but feasibly involve daylighting losses.

Window shape is less significant to daylighting than glazing height and glazing area [Baker & Steemers 2002; BS 8206-2 2008]. However, Bonaiuti & Wilson [2007] find that window shape affects daylight distribution and average illuminances by ±20%, but that this is not accounted for by the established design tool, the average daylight-factor equation.

Window frames are conventionally fixed towards the external face of the window aperture, or currently, towards the insulation layer (internal, within a cavity, or external) [Feist et al 2001]. The orthodoxy sets out that glazing positioned toward the external face of the aperture maximizes the visible sky angle and daylighting [Littlefair 1988].

Deep reveals with internal glazing markedly reduce irradiation and solar gains, for south facing windows in particular. Littlefair [2005] provides an extensive range of correction-factors to estimate a summer seasons risk of overheating for three window shapes.

Splayed window reveals are very relevant to deep walled structures. Internal splays reduce glare and contrast, and enhance daylight distribution and penetration [Hopkinson & Kay 1974]. External splays barely alter the daylighting and solar gains performance of internally glazed 'box' reveals [Mardaljevic & Lomas 2005].

The variables of this research are window shape (fig.1), glazing position and splayed reveals in deep walls. All other parameters - most importantly window head height and glazing area - are constant.

Fig.1: Square, wide, tall, round, arch, inverted arch, and 'T' window shapes are tested, with equal glazing area.

2. DAYLIGHT EXPERIMENT

2.1 The Method

'Radiance' daylighting computer simulation was used for the pilot study of this research to evaluate room and window parameters, and can be very accurate with expertise. However, a scale-model is inherently accurate for daylight studies as the behaviour of light is indistinguishable at all practical scales [Phillips 1997], and was considered most appropriate to compare numerous window forms for all tests in this paper.

The scale-model was tested in a mirror-type 'artificial sky' which reproduces a 'standard overcast sky' - where the zenith is three times brighter than the horizon – validated for cloudy maritime regions like the UK.

The calibrated and cosine-corrected light-meter was error-free. The lightcell was fixed to a sliding platform to measure a working-plane height ≡700mm (fig.2). The model was enclosed. Recording grid-point illuminances simultaneously visualized results, improving error detection (fig.3). The unobstructed illuminance was taken before and after each gridline and the average used to calculate daylight-factors *viz.*, the percentage of daylight reaching the working-plane from the unobstructed sky. This method reduced the margin of error due to sky luminance fluctuations to <1%, and was used for all daylight tests in this paper.

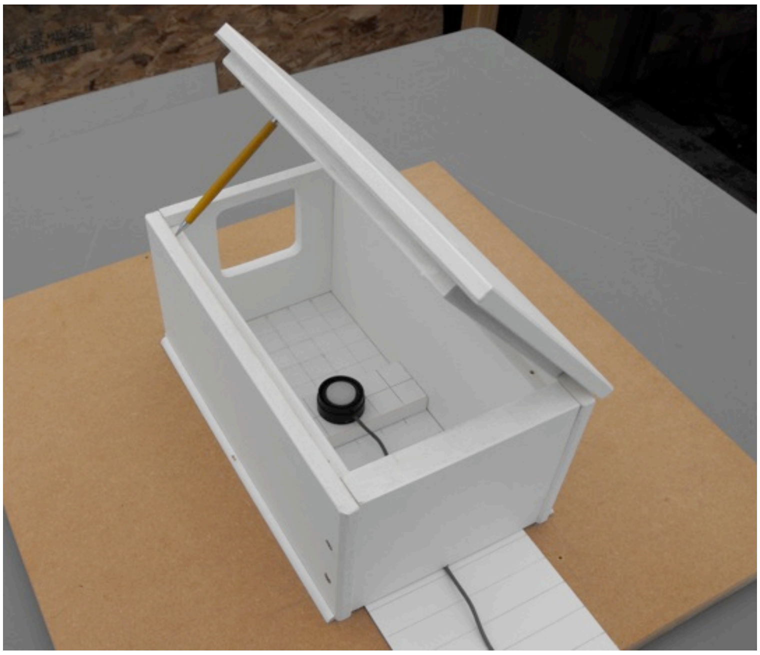
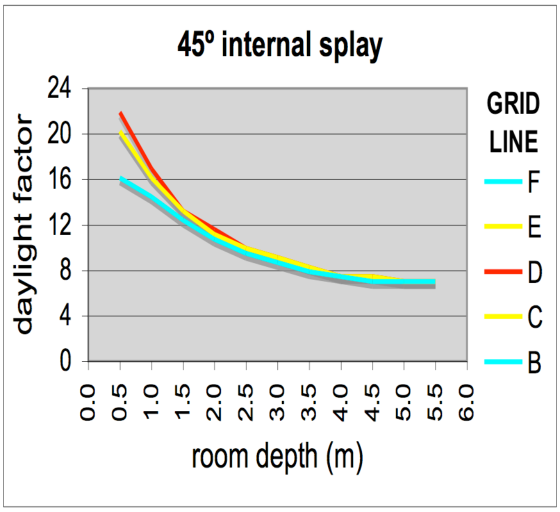


Fig.2: 1:20 scale-model. 30% glazing-to-wall area and 15% glazing-to-floor area observe recommendations and Building Regulations. Internal room geometry (6m deep/3m wide/3m high) compares to sidelit rooms in architecture and architectural modelling.



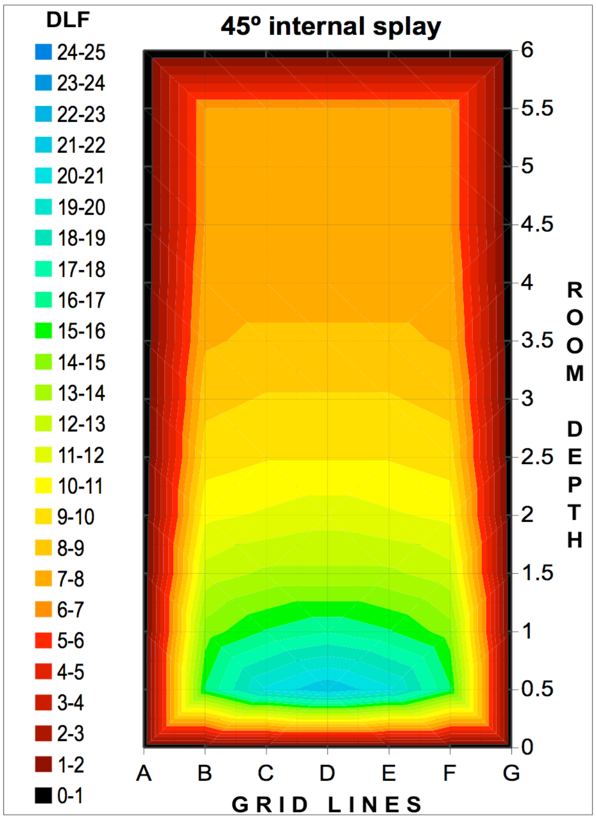


Fig.3: Example of a daylight-factor profile (above) and a daylight-factor contour plan (right). It was not physically possible to take readings at the very perimeter of the room with this lightcell. Daylight-factors were taken for grid-points along B, C and D, and replicated for E and F, producing 'symmetrical' results valid for a precisely symmetrical building.

2.2 Daylight Results and Analysis

Test A) 250mm 'standard' reveals are compared to 500mm 'deep' reveals.

Minimum daylight-factors (mindlf) are higher for more 'open' window shapes (round and square) than less open window shapes ('T', tall and wide) (table.1). Doubling the reveals depth reduces mindlf's by 11% on average.

Mean daylight-factors (meandlf) vary 15% in standard reveals - between otherwise equal window shapes - equivalent to a 15% variation in glazing area. Window shape is even more significant in deep reveals (20%), which reduce meandlf's by 13-18%. More open window shapes produce higher meandlf's, and reduce meandlf's less as reveals become deeper.

Uniformity ratios (the consistency of light throughout the room) vary 11-14% between window shapes. Less open window shapes produce higher uniformity. Deep reveals increase uniformity.

Daylight distribution varies most in the front half of the room, and greatly between window shapes. Generally speaking, wider window shapes, wider sills, and deep reveals produce more even distribution.

Daylight penetration is by definition more relevant towards the rear of the room. More open window shapes produce deeper penetration. Deep reveals reduce penetration, particularly for less open window shapes.

Meandlf's and daylight distribution are seen to be dependent on window shape. Overall, daylighting levels increase with the openess of the window shape. Deep reveals always reduce daylight; particularly at the front of the room, providing more uniform and even illumination; and especially for less open window shapes, increasing the significance of window shape.

		square	wide	tall	round	' T '	% var.
maximum daylight-factor	standard reveal	19.2	12.6	22.1	22.4	15.9	*44*
	deep reveal	15.5	9.5	17.8	18.8	12.9	*49*
	% change	*19*	*25*	*20*	*16*	*19*	
minimum daylight-factor	standard reveal	7.3	6.9	6.9	7.2	6.8	*7*
	deep reveal	6.4	6.1	6.1	6.8	5.7	*16*
	% change	*12*	*12*	*12*	*6*	*17*	
mean daylight-factor	standard reveal	10.8	9.3	9.6	10.9	9.3	*15*
	deep reveal	9.4	7.6	8.1	9.5	7.6	*20*
	% change	*13*	*18*	*16*	*13*	*18*	
uniformity ratio (min daylight-factor / mean daylight-factor)	standard reveal	0.68	0.74	0.72	0.66	0.73	*11*
	deep reveal	0.69	0.8	0.75	0.71	0.75	*14*
daylight distribution (mean range of daylight-factor's)	standard reveal	0.98	0.24	1.5	1.08	1.02	*84*
	deep reveal	0.76	0.23	1.46	1.13	0.96	*84*
daylight penetration (mean daylight-factor in rear half of room)	standard reveal	7.8	7.5	7.3	7.8	7.3	*7*
	deep reveal	7	6.5	6.4	7	6.2	*11*
	% change	*11*	*13*	*13*	*10*	*15*	

Table.1: Window shape vs reveal depth results, including percentage variation (% var.) between shapes.

Test B) Three glazing positions are compared for the square window with 500mm deep reveals.

A single pane of clear 6mm float glass fitted into the square aperture reduces diffuse illuminance - but results vary <3% due to glazing position (table.2). This defies the orthodoxy, yet no errors are apparent.

frame position	maximum daylight-factor	minimum daylight-factor	mean daylight-factor	uniformity ratio	daylight distribution	daylight penetration
internal glazing	13.5	5.9	8.2	0.72	0.84	6.1
mid glazing	13.8	5.9	8.4	0.70	0.84	6.2
external glazing	13.7	5.8	8.2	0.71	0.75	6.1
no glazing	*15.5*	*6.4*	*9.4*	*0.69*	*0.76*	*7.0*

Table.2: Glazing position results for square window

The average daylight-factors by equation (fig.4) are very different per glazing position - relative to the only changing variable here; the visible sky angle (fig.5). This accounts for the obstruction of the window head, but ignores the reflectance of the reveals, which - when equal - will absorb and reflect light to the same degree whether inside or outside the glazing (fig.6). The equation increasingly underestimates average dlf's as the glazing is positioned back from the external face of the window aperture. This research finds deep reveals reduce meandlf's, but glazing position does not.

adlf = Ag x T x q x M / Ai [1 – (R x R)]

where **Ag** = glazing area,
Ai = internal surface area,
R = average internal reflectance,
T = glazing transmittance,
q = vertical angle subtended by visible sky from centre of window,
M = glazing maintenance factor [CIBSE LG10 1999].

Fig.4: Average daylight-factor (**adlf**) equation.

Whatever the glazing position, the aperture has the same view of the sky (fig.7). This suggests it maybe more appropriate to take the angle of visible sky from the plane of the internal face of the aperture, while also representing the depth and reflectance of the reveals. The reveals reflectance is increasingly significant in deeper walls, and influential where floor reflectance is low.

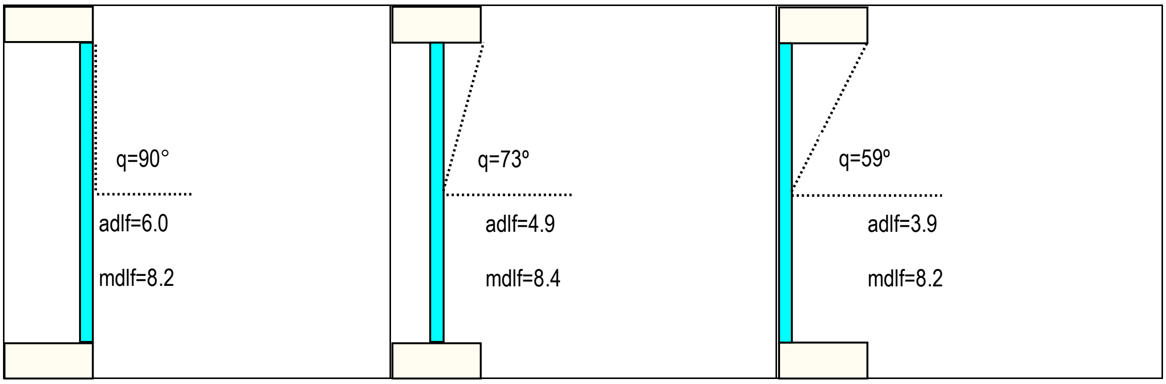


Fig.5: Visible sky angle *q* used by *adlf* equation (fig.4) vs. actual mean daylight-factor *mdlf* (table.2).

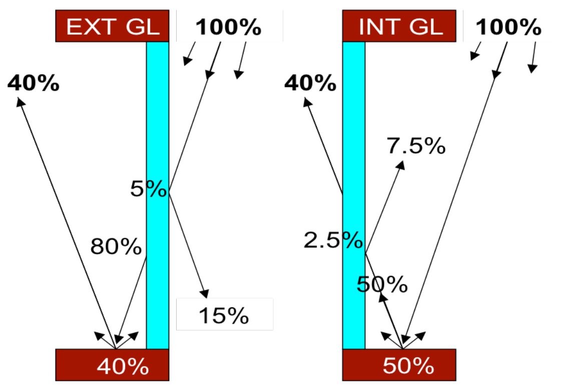


Fig.6: Example of how percentage of zenithal daylight (from an overcast sky (2.1)) is reflected, absorbed and transmitted by glazing with transmittance 0.8, and reveals with reflectance 0.5.

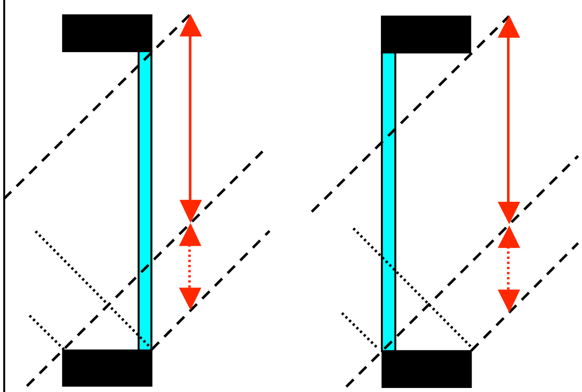


Fig.7: Example of how an aperture receives the same daylight irrespective of glazing position.

Test C) Internal and external splayed reveals are compared to box reveals, for the square window with 500mm deep reveals.

The internal splayed reveals increase min and meandlf's (≈9%), and penetration (4%), while retaining uniformity and similar distribution (table.3). The external splays produce comparable dlf's to the box reveal, but less uniformity and distribution. The combined splay performs more akin to internal splays.

splayed reveal type	maximum daylight-factor	minimum daylight-factor	mean daylight-factor	uniformity ratio	daylight distribution	daylight penetration
box reveal	*15.5*	*6.4*	*9.4*	*0.69*	*0.90*	*7.0*
30º internal splay	20.1	7.0	10.2	0.69	1.04	7.3
45º internal splay	20.6	6.7	10.2	0.66	1.18	7.3
30º external splay	16.5	6.2	9.5	0.65	1.42	6.9
45º external splay	16.8	6.3	9.5	0.66	1.26	6.9
45º internal and external splay	19.7	6.6	10.0	0.66	1.19	7.1

Table.3: Splayed reveals results for square window

Internal splays permit brighter daylight at the front of the room, broadcasting it across the width, and reflecting it to penetrate the back. External splays however, focus the daylight to the centre of the room, and do not enhance conventional daylighting.

Test D) Internal splayed reveals are compared to box reveals, for all window shapes, with 500mm deep reveals.

45º internal splayed reveals increase dlf's for all windows at most points (table.4). Windows with wide horizontal sills increase meandlf's and penetration more. Less open shapes increase mindlf's the most. The 'T' window makes the greater gains in general. However, more open window shapes still permit more light overall. Uniformity is typically reduced, as is distribution for windows with larger gains in maxdlf's. The performance of the tall window is moderated by internal splays.

45° internal splayed reveals	square	wide	tall	round	'T'
maximum daylight-factor	20.6	13.1	17.6	21.9	16.0
% change	*33*	*37*	*-1*	*17*	*24*
minimum daylight-factor	6.7	6.5	6.5	7.0	6.6
% change	*4*	*7*	*8*	*4*	*15*
mean daylight-factor	10.2	8.7	8.4	10.4	9.1
% change	*9*	*14*	*4*	*9*	*19*
uniformity ratio	0.66	0.75	0.78	0.68	0.72
daylight distribution	1.18	0.52	1.15	1.05	0.89
daylight penetration	7.3	6.9	6.7	7.4	7.1
% change	*5*	*6*	*5*	*5*	*13*

Table.4: 45º internal splays results for all windows

On average, internal splays regained ⅔ of the meandlf's that standard box reveals lost to deep box reveals. These are structurally-integrated daylight redirecting systems.

3. SUNLIGHT EXPERIMENT

3.1 The Method

The sunlight study was performed on a heliodon, with the same scale-model (fig.8). Solar gains are relative to the glazing area exposed to radiation (fig.9), which changes with shade cast due to the sun altitude and azimuth. The sunpatch area can be calculated manually, but the method trialled here used Photoshop computer software to count the pixels in the sunpatch (3.3).

Firstly, the windows whole sunpatch, at normal incidence, without shading, was photographed. For all tests, the orientation was south being the most significant aspect for passive solar design, and the latitude was 51° (London) based on available climate data and research. With the date set, the time was 'rotated' and recorded for solar sunrise, and when the light first struck the glazing (to account for the irradiation of the sunrise hour). The heliodon was then turned to each following whole hour and the sunpatch photographed.

This method was replicated at monthly intervals for 500mm deep walls with internal 'glazing' for; box reveals in the seven window shapes (fig.1); and external splays in the square window.

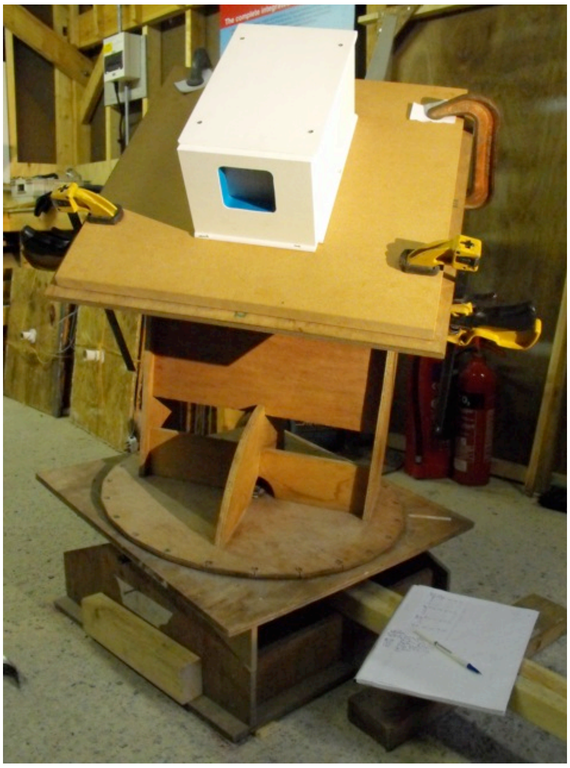


Fig.8: Using a slide projector as a fixed 'sun', the heliodon emulates the tilt and rotation of the earth for any given latitude, solar time, and orientation, for the solstices and equinoxes.

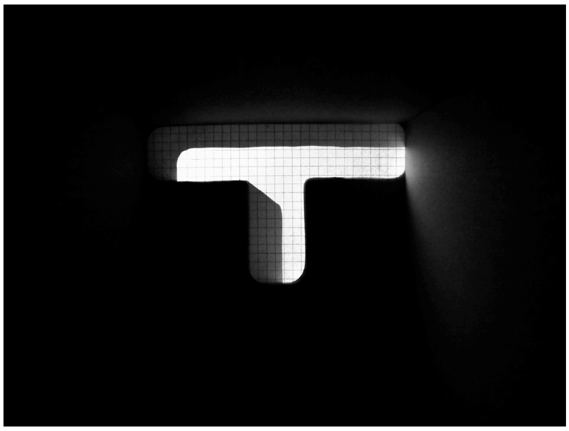


Fig.9: The sunpatch can be recorded on tracing-paper 'glazing' fixed to the internal face of the window wall in the scale-model. This was efficiently achieved in this experiment by black and white digital photography, from a lens aperture in the back wall. The room and reveal surfaces must be of low reflectance.

3.2 Limitations

The monthly settings did not produce regular monthly results, which would have improved linear interpolation (3.5). The mass of the model exaggerated sunrise times by 10-16 minutes at the solstices. However, the dates are corrected using recognized solar sunrise times, and being consistent to every window are not considered to invalidate a comparative experiment such as this.

3.3 Counting the pixels

The sunpatch photographs were converted to numerical data in Photoshop. Preliminary tests honed the technique: Set 'units' to 'pixels', and the grayscale photograph to full contrast (-50). Use the 'magic wand tool' to automatically select the consistently coloured sunpatch, then nominate a grid-square, and focusing on its centre, fine-tune the 'tolerance' to the most representative sun-patch. Refresh the histogram to give the pixel-count. The highest pixel-count in this 0.4% range was used, minimizing deviation. Pixel-counts aren't numerically comparable.

3.4 The climate data

Solar gains are calculated from hourly direct irradiances at normal incidence, composed of up to 20years recordings for London. Monthly-mean results use the CIBSE [2005] Test Reference Year - a composite year providing 'typical' weather conditions to estimate a buildings energy performance. Clear-day results use the 97.5 percentile tables which provide near-extreme global irradiation to assess overheating risk-based design [CIBSE Guide J 2002]. Appropriate design dates are employed.

3.5 Calculating the solar gains

The sunpatch pixel-count is divided by the whole window pixel-count to convert to a shading-correction-factor (SCF). SCFs represent the effectiveness of a shading device (the lower the better) and can be compared quantitatively. By applying the SCFs to the dates with astronomical daylengths equal to the recorded daylengths, the SCFs for the intermediate design dates can be calculated by linear interpolation (fig.10).

The g-value is the fraction of irradiation that is transmitted through glazing at normal incidence. (0.68 is used here for low-e double glazing). However, the transmission and reflection of light varies with the angle of incidence. The angle of incidence is computed from the sun altitude and azimuth (fig.11). Therefore, the angle dependent g-value is derived from the formula in fig.12. The solar gains per m^2 of glazing are a product of window specific SCF,

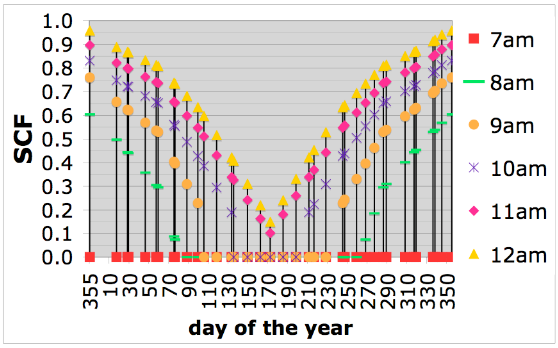


Fig.10: Example of square windows recorded SCFs (days 28, 59, 76, 99, 133, 172, 211, 245, 268, 286, 317, & 336), and intermediate design day SCFs calculated by linear interpolation. The resulting pattern is slightly tangential, with a 2% maximum estimated deviation, but is equally applied to all tests, and considered valid for this comparative experiment.

$$v(\beta,\alpha) = \cos^{-1} (\cos \gamma s \cos \alpha f \sin \beta + \sin \gamma s \cos \beta)$$

Fig.11: The angle of incidence of the solar radiation, $v(\beta,\alpha)$, on a surface of tilt β and surface azimuth angle α is calculated from the solar altitude (γs) and azimuth (αs) using the wall–solar azimuth angle (αf) where $\alpha f = \alpha s - \alpha$, as set out by CIBSE [2002].

$$g\angle = gn\,(1 - az\alpha - bz\beta) - czy)$$

Fig.12: The formula to simulate the angle dependent g-value ($g\angle$) is calculated from the g-value of glazing at 0º normal incidence (gn), the angle of incidence (v), and the number of glazing panes (p), where a = 8, $b = 0.25/q$, $c = (1 - a - b)$, $z = v/90°$, α = 5.2 +0.7q, β = 2, y = (5.26 +0.06p) + (0.73 + 0.04p)q, and q = 3.5 for low-e double glazing [Karlsson & Roos 1999, cited by Littlefair 2005].

the solar irradiation and angle dependent g-value, which vary constantly. It is therefore most accurate to compare solar gains of different window forms over a longer period, such as the heating season, or ‘overheating season’ [CIBSE Guide A 2006].

3.7 Season results and analysis

The performance of the window forms are ranked for best to worst performance, for four heating seasons (table.5); and three overheating seasons (table.6). Monthly mean and clear day design dates produce identical ranking and very close percentages.

- The wide window prevents the most solar gains over summer, and permits practically as much as the best window shapes during the heating seasons - and is the optimal all-round window form.
- The “T” window is very protective during the overheating seasons, but also for the rest of the year, permitting the least solar gains in winter - and is most suitable for high summer overheating risks and low winter heating demands, such as a building with high internal heat gains.
- The square and round windows do not perform as well during the overheating seasons, but are among the best windows over the heating seasons - and are therefore best suited to a low over-heating risk, and some heating demands.
- The tall window is the least effective window shape during the overheating season, and would not be a good choice for winter heating, or overall if selected on solar gain performance alone.
- The external splayed reveals magnify solar gains all year – suited to buildings with no risk of overheating - possibly due to thermal mass, night cooling, adaptive thermal comfort strategies, or a high internal design temperature.

ranking	1st	2nd		1st	2nd	3rd	4th	5th	6th	7th
october-april	45°SPLAY 73%	30°SPLAY 72%		ROUND 65%	ARCH 64%	INV.ARCH 63%	SQUARE 63%	WIDE 62%	TALL 55%	"T" 52%
november-march	45°SPLAY 80%	30°SPLAY 79%		ROUND 72%	ARCH 71%	INV.ARCH 71%	WIDE 70%	SQUARE 69%	TALL 61%	"T" 60%
december-february	45°SPLAY 86%	30°SPLAY 86%		ROUND 78%	ARCH 78%	INV.ARCH 78%	WIDE 77%	SQUARE 76%	"T" 68%	TALL 67%
january	45°SPLAY 87%	30°SPLAY 87%		ROUND 82%	ARCH 78%	INV.ARCH 78%	WIDE 77%	SQUARE 77%	TALL 69%	"T" 68%

Table.5: Ranking of; mean percentage of solar gains received by unshaded external glazing that is *permitted* by deep reveals with internal glazing, during four heating seasons, for monthly mean design dates.

ranking	1st	2nd	3rd	4th	5th	6th	7th		2nd	3rd
july-august	WIDE 90%	"T" 89%	INV.ARCH 84%	ARCH 83%	SQUARE 77%	ROUND 76%	TALL 71%		30°SPLAY 70%	45°SPLAY 69%
may-august	WIDE 94%	"T" 91%	INV.ARCH 89%	ARCH 87%	SQUARE 81%	ROUND 80%	TALL 73%		45°SPLAY 74%	30°SPLAY 74%
april-october	"T" 80%	WIDE 78%	INV.ARCH 74%	ARCH 73%	SQUARE 69%	ROUND 68%	TALL 66%		30°SPLAY 62%	45°SPLAY 61%

Table.6: Ranking of; mean percentage of solar gains received by unshaded external glazing that is *prevented* by deep reveals with internal glazing, during three overheating seasons, for clear day design dates.

4. CONCLUSION

This research studies the affect of window shape, glazing position and splayed reveals in deep walls, on internal daylight levels and seasonal solar gains. Window shape varies mean daylight-factors by 15% in standard walls, rising to 20% in deep walls, and solar gains range even more widely. These variations in window performance are as significant as the same variation in glazing area. Doubling the depth of the window reveals invariably reduces daylighting, by 13-18% on average, but improves uniformity. However, internal splayed reveals regain most of these losses, and are a particular improvement for less 'open' window shapes – the 'T', wide and tall windows. South-facing deep reveals with internal glazing effectively reduce the risk of overheating by blocking 73-94% of solar gains in summer, while allowing 52-65% of useful solar gains in winter - compared to unshaded external glazing. The low sill-to-head height of the wide window is most effective for summer shading, and delivers uniform though lower daylight levels. More 'open' window shapes - particularly the round window - admit more solar gains all year, and strong but uneven daylighting. The tall window prevents the least summer solar gains, permits the least winter solar gains, and provides uneven illuminance. The external splays increase solar gains at all times, but do not improve daylighting. Of course, glazing position is fundamental to shading and solar gains - but has little affect on daylighting, in this study; reveals obstruct and reflect as much daylight whether internal or external to the glazing.

Deep reveals are integral to the building fabric, enabling the building to shade itself seasonally while also redirecting light and allowing the usual functions of windows. Deep reveals are fixed shading devices, but can be fitted with blinds that afford adaptive lighting control while permitting useful solar gains. Formed by the requisite insulation layer, deep reveals can be simple, cost-effective, and multifunctional by reducing primary energy use and CO_2 emissions from heating, and from electrical lighting and cooling in particular.

The sunlight experiment introduces the 'pixel count method' which combines routine scale-modelling with common digital photo-graphy and software to efficiently record and process sunpatch data.

This research provides an insight and comparison of specific window forms that might inform early stage design or further research. However, it is clear that window forms in *deep* walls are even more critical to the lighting and thermal demands of buildings, and require a different approach, but with good specification can be an asset to contemporary building design.

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