Optimizing the Architectural Layouts of Curtain Walls to Minimize Use of Aluminium

Adam D. Lee[a,b,*], Paul Shepherd[a], Mark C. Evernden[a], David Metcalfe[c]

[a] *Department of Architecture and Civil Engineering, University of Bath, Claverton Down, Bath, BA2 7AY, U.K.*
[b] *PTCC Facade Design, Telecom Plaza, 316 Senator Gil Puyat Ave., Makati City, Metro Manila, 1200, Philippines.*
[c] *Centre for Window and Cladding Technology (CWCT), The Studio, Entry Hill, Bath, BA2 5LY, U.K.*

Abstract

During recent decades it has become common to enclose large buildings with lightweight, weathertight walls that hang, like curtains, from the floor edges. The frames of these curtain walls are, usually, extruded aluminium – a material whose production is highly energy-intensive. Although means of enhancing the thermal performance of building envelopes have been scrutinized, comparatively little attention has been given to the cost and embodied energy savings that can be achieved through efficient structural design. No guidelines for efficient use of aluminium in a curtain wall have been published, and architects therefore have not known the impact that their decisions have upon the facade's material content.

In this study more than 1,000 unique curtain wall systems have been optimized numerically, each one to a different set of design criteria, and the results show the extent to which aluminium content is influenced by floor height, locations of supports, number of horizontal members per panel, width of the extrusions, spacing between mullions, design wind pressure, and the minimum allowable thickness of aluminium. The conditions in which the amount of metal

*Corresponding Author
Email addresses: adamlee@torstencalvi.com (Adam D. Lee), p.shepherd@bath.ac.uk (Paul Shepherd), m.evernden@bath.ac.uk (Mark C. Evernden), david.metcalfe@cwct.co.uk (David Metcalfe)

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required to construct a window wall (glazing spanning between two floors) might be less than that required for a curtain wall (an uninterrupted, multi-floor shroud), also have been explored. The results show that substantial metal savings – reductions of 40 % or more – can be realized by making modest changes to the layout geometries and specifications that are in common use. The value of the corresponding construction cost reductions is significant: in the worldwide construction market, the potential savings are in billions of dollars per year.

The practical steps that an architect and specifier should take in order to reduce metal content in a curtain wall are set out in a list. These savings are separate from, and in addition to, any that might be attained by optimizing the cross-sectional shapes of extrusion profiles.

Unlike improvements in a facade's thermal performance, which usually require capital investment in insulating materials for returns that accrue over decades, material-efficient design methods are free to apply, and the benefits can be enjoyed immediately.

Keywords: curtain wall, facade design, structural optimization, layout optimization, topology optimization, embodied energy, green building

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1. Introduction

At the start of the last century, when the world's tallest skyscraper was not much more than 100 m high [1], it was still common to design tower buildings with thick masonry walls that served not only to protect occupants from the weather, but also to support the weight of the floors and to resist lateral forces [2]. There is however a practical limit [3] to the height of these load-bearing walls. To create taller towers, another construction technique evolved in two cities – New York and Chicago – which were already the largest in America, and which were still growing rapidly [4, p. 492,504]. There, it became the norm to construct a freestanding structural frame made up of beams and columns, and then use that frame to carry the floors and walls. By moving away from masonry enclosures, it was possible to build to much greater heights and, partly for this reason, by the mid-1920s New York had become the worlds' most populous city [4, p. 505]. In the process, a market had been established for lightweight exterior walls that could be suspended, like curtains, from the edges of a tower's floors [5].

In the earliest of these *curtain walls*, the main structural component – the vertical member, or *mullion*, spanning from floor to floor – was a simple steel section. At those locations where windows were needed, the glass was carried by a separate metal frame fixed mechanically to the mullion [6, p. 108]. For decades this was the dominant design approach and, in the late 1950s, it was the method used to create the facades of the first fully-glazed towers. It was however in these early "glass box" buildings that the limitations of a curtain wall made up of window frames supported by steel verticals, particularly difficulties in achieving an effective weather barrier, were revealed [7, p. 17]. Higher performance standards were attained as facade engineers exploited the freedom afforded by the aluminium extrusion process to create mullions with more complex cross-sectional shapes. Conventional structural forms – I-sections, T-sections and boxes – were combined with features such as gasket keyways, so that a separate frame for glass was no longer required [e.g. 6, p. 111; 8].

During the ensuing period of innovation there emerged a new type or variety of curtain wall, the *unitized* systems, the first of which was patented in America in 1962 [9]. Facades of this type are made up of discrete panels, each one being, typically, one floor in height, prefabricated and preglazed away from the building site. The anatomy of such a panel is shown in Figure 1. Because of the advantages conferred by factory fabrication [10 p. 4-5; 11 p. 86], today the majority of the world's new curtain wall is unitized [12, p. 82].

When two unitized panels are brought together, side by side at the exterior of a building [13, in photos, p. 69], their extruded aluminium frames engage to create a two-piece mullion – the *split-mullion* – within which the joints are weatherproofed by rubber gaskets. Each of the two profiles in a modern split mullion is, usually, shaped like the letter E, and many extrusions of this sort

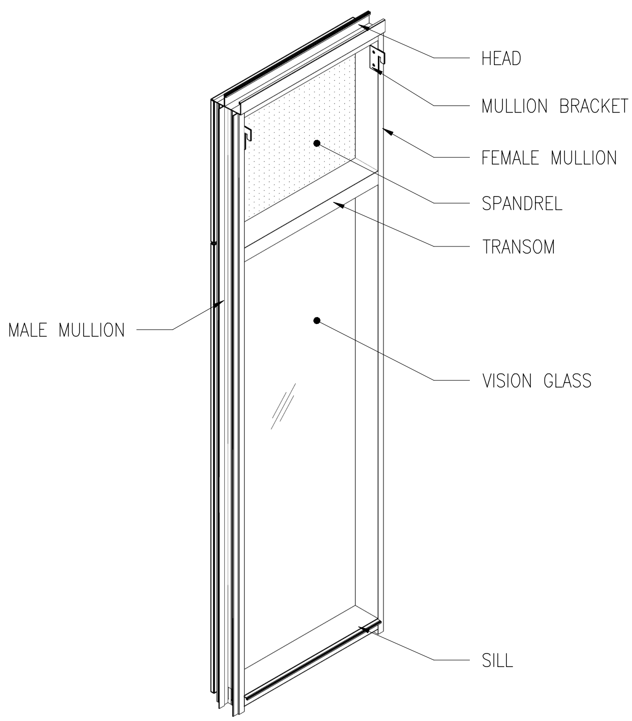


Figure 1: Parts of a unitized curtain wall panel for a flat facade, viewed from the side facing the interior of the building. For clarity, cosmetic trims, insulation, and barriers preventing the spread of fire and smoke, are omitted from this diagram.

may be found in the industry's technical literature [e.g. 14, p. 6-51; 15, p. 90; 16, p. 52; 17 pp. 6-11; 18]. In the particular example shown in Figure 2, the base shape of both the male and female profile is E-shaped, but an additional web has been added to create a box in the exterior part of the female side.

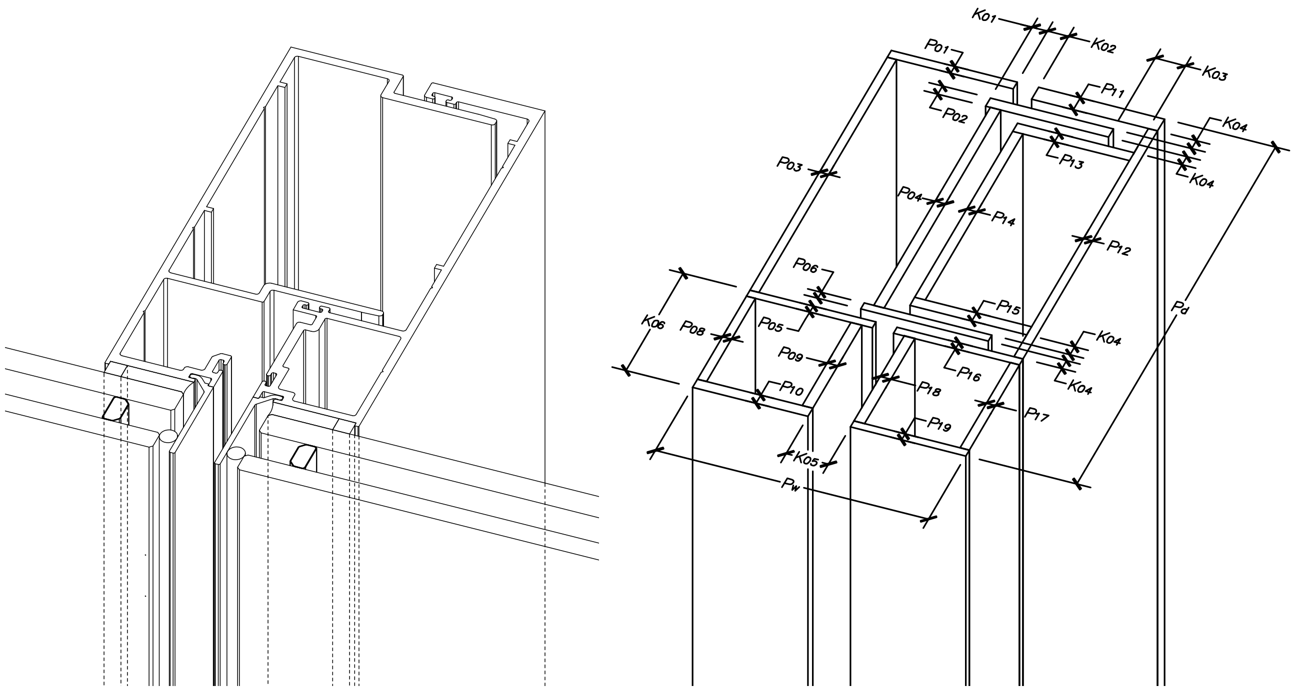


Figure 2: The male and female extrusions (Left), together, form a unitized curtain wall's split mullion. In the idealized model of the mullion extrusions (Right), the P series of dimensions can be modified parametrically. Other input parameters control whether the elements labelled P_{04} , P_{09} , and P_{18} , as well as the group of elements labelled P_{13} , P_{14} , and P_{15} , are included in the model.

In this paper, curtain wall has been introduced in its historical context in order to emphasize that, by the standards of the construction industry, the technology is still young. It was only in the 1980s that unitized building techniques entered the mainstream [14, p. 2-4]. The first structurally-glazed tower facade – using sealant to secure the glass to the aluminium frame, as shown in Figure 2 and discussed in Section 3.9 – was completed as recently as 1986 [13, p. 53]. Design know-how has had to propagate rapidly between contractors, especially during the period between 2005 and 2012, when the global market for unitized curtain wall doubled in value, to around US $ 12 billion per year [12, p. 82]. It would therefore be unsurprising to find that opportunities for further technical refinement exist within this relatively new field.

The authors of this paper have previously examined the efficiency with which aluminium is used in bespoke curtain walls conceived, by respected specialists, for real facades [19]. The mass of aluminium in twenty-four existing unitized wall systems, each one custom-designed for a specific building, was compared with the mass of metal in a numerically optimized design complying with the same performance criteria. The solutions obtained numerically were found to be consistently superior to those conceived by experienced facade designers. It proved to be easy to identify cases in which metal savings of 20 % or more could have been achieved through better optimization of the extrusion shapes. This finding is of interest for at least two reasons. One, most obviously, is that material savings bring cost savings. The other is that, of all the materials used in significant quantity in construction, aluminium has the highest embodied energy per unit mass (approximately 80 times that of reinforced concrete [20]), so there is an environmental incentive to use this metal sparingly.

This past investigation demonstrated that the task usually undertaken by a curtain wall contractor's designers – finding the most efficient cross-sectional shapes for extruded framing members capable of satisfying a given set of performance requirements – can be handled effectively, or more effectively, by computational algorithms. The research described in this present paper goes further: it investigates the effects that decisions made by architects and their consultants – regarding the facades' layout, and its performance criteria – have upon the mass of metal in a building's curtain wall.

The method of investigation has been to consider, initially, the geometric layout and specifications for an archetypal curtain wall – a wall typical of the sort used to enclose large numbers of modern buildings – and then, by varying one design constraint at a time, it has been possible to quantify the extent to which each of the variables influences the mass of metal in the wall system.

In this paper, the specifications for a total of more than 1,000 unique curtain walls have been defined. In each case the wall system's extrusion shapes have been optimized using numerical algorithms implemented in the software whose workings are outlined, briefly, in Sections 1.1, 1.2 and 1.3. Results are set out in Section 2: these show the extent to which the mass of aluminium is affected by changes in floor-to-floor height, mullion bracket location, number of transoms, mullion width, mullion spacing, and also by the magnitude of the design wind pressure. The implications of these results, which are presented in Section 3, are formulated as a set of practical guidelines for those architects and facade engineers whose aim it is to make efficient use of material in their buildings' facades.

1.1. ACWEDS *Software for Curtain Wall Optimization*

For each unique combination of facade layout and performance specification, the shapes of the extrusions in an optimized curtain wall system have been found numerically. The optimization software, named ACWEDS, was written for this purpose. The program's features and complexities – it is made up of 5,000 lines of C++ code – are not detailed here, but a description of its workings, as well as the steps taken to test its efficacy, has been published separately [19]. Its four main operative parts are:

(a) A parameterized geometric model of a unitized curtain wall system's extrusions.

(b) A set of procedures by which to evaluate whether proposed extrusions are structurally viable, and whether they can in practice be manufactured. One of the verifications made during these analyses ensures that the magnitude of the mullion's deflection is not greater than the specified allowable. Also, stresses are computed in each inter-transom span, for each of the panel's mullion profiles, for each specified wind load condition: these values are checked, using the algebraic rules given in the Aluminum Design Manual (ADM) [21], to ensure that they do not exceed the allowable proportion of the extrusion's yield strength or local buckling limit or lateral torsional buckling limit.

(c) A numerical search function, a genetic algorithm (GA), programmed to look for that set of dimensions that, when applied to the parametric model, produces a curtain wall design satisfying the constraints using the minimum possible quantity of aluminium.

(d) Computer code capable of converting the program's data into human-readable format. Output includes structural calculation reports, drawings of optimized extrusions, and statistics with which to track the search algorithm's progress.

1.2. Structural Design of Glass

In order to admit light to a building, and in order to allow the occupants to see outside, it is usual that the sheet material used to cover a large proportion of a curtain wall's surface area – sometimes the entire surface area – will be glass. Although the central goal of this research is to find effective means by which to minimize the mass of aluminium in a curtain wall, it is desirable to understand also the way in which those strategies influence the thickness of the glass. This information is of interest because the amount of energy required to create architectural glass, by melting silica sand and subsequently heat treating the cut panes, is energy intensive. The finished material's embodied energy, and hence its cost, is significant, although in a typical curtain wall glass contributes less than aluminium to the total embodied energy and total cost. So that these contributions may be assessed, ACWEDS has been programmed to calculate the minimum required thickness of each glass pane in the curtain wall panels that it analyzes.

The load resistance of a glass pane is determined using a closed-form algebraic expression deduced from the British Standard for glazing in buildings [22]. Glass deflections, on the other hand, are computed by the algebraic method set out in of ASTM E1300 [23, Appendix X1]. The reason for mixing the design rules published in two different countries is simply that the British standard does not provide a method for finding deflections, and the ASTM's procedure for estimating load resistance relies on graphs whose data are not readily incorporated within a computer program. So, where glass thicknesses are presented in this paper, they should be considered to be approximate.

1.3. Material Cost and Embodied Energy

For the purpose of estimating the combined cost of glass and aluminium in a given curtain wall design, the price of extruded and painted aluminium has been taken to be US $ 3 per kg. The cost of tinted, heat strengthened, monolithic glass with a single coating of metal oxide, has been assumed to vary linearly with the thickness of the pane. Based on a review of current "factory gate" prices – that is to say, without transportation fees, taxes or duties – for high-volume glass purchases [24, 25], the authors have developed the following algebraic expression to describe glass costs: -

$$c_{gl} = 4 + 3100 \cdot t_{gl} \tag{1}$$

where, c_{gl} is the cost of glass in US \$ per m^2, and,

t_{gl} is the thickness of the pane, in m.

The embodied energy in extruded aluminium and tempered glass is taken to be 154 MJ/kg [20, p. 74] and 36 MJ/kg [mean value, 20, p. 16] respectively.

2. Numerical Optimization Studies

Throughout the history of the "glass box" architectural style, critics have complained that the curtain wall facades of many of the world's large buildings are similar to one another in appearance. There is some truth in this allegation. Because of practical constraints, different architects arrive at similar design solutions: floor-to-floor heights vary only within a narrow range; a rectilinear grid is the most practical arrangement for the facade's skeletal frame; transportation logistics limit the sizes of curtain wall panels; the building's occupants will expect to see out of windows positioned at eye level; and so on. In the context of this study, it is an interesting observation that so many curtain walls are alike: metal optimization heuristics revealed by studying one building's curtain wall are likely to be effective when applied to the large numbers of walls having similar geometric layouts and performance requirements. The layout configurations of a selection of common curtain walls in the real world, and their performance specifications, have been examined, and popular values for dimensions and design constraints have been determined. A reference layout, following the popular dimensions, is shown in Figure 4, and the reference set of performance targets is given in Table 1. The shapes of a set of weight-minimized curtain wall extrusion profiles for a curtain wall system having this grid geometry, and designed to these performance criteria, was determined using ACWEDS. The optimized mullion profiles are shown in Figure 3.

Having established this benchmark, one design constraint at a time was selected – initially, the distance between the top of the curtain wall panel and its attachment bracket – and the value of the constraint was varied in discreet steps through a wide range. The effect that these changes have upon the optimized wall system's aluminium content were observed. The same process was repeated to investigate the effect of changing other design constraints, and the results are described in the following sub-sections.

In plots of data points, some of the noise or scatter is attributable to the stochastic nature of the genetic algorithm: the best solutions identified during successive curtain wall optimization runs are not necessarily uniformly close to the global optimum. The extent of the spread could be reduced by, say, running ACWEDS more than once for each set of design criteria, and then presenting the best of the solutions found. Alternatively it would be possible to allow evolution to occur in a larger population, or for more generations. Such strategies would however be more costly in terms of computational resources. The authors have taken the view that, as all of the algorithmically-found designs are known to comply with the structural code, slightly sub-optimal results are still adequate for practical engineering purposes.

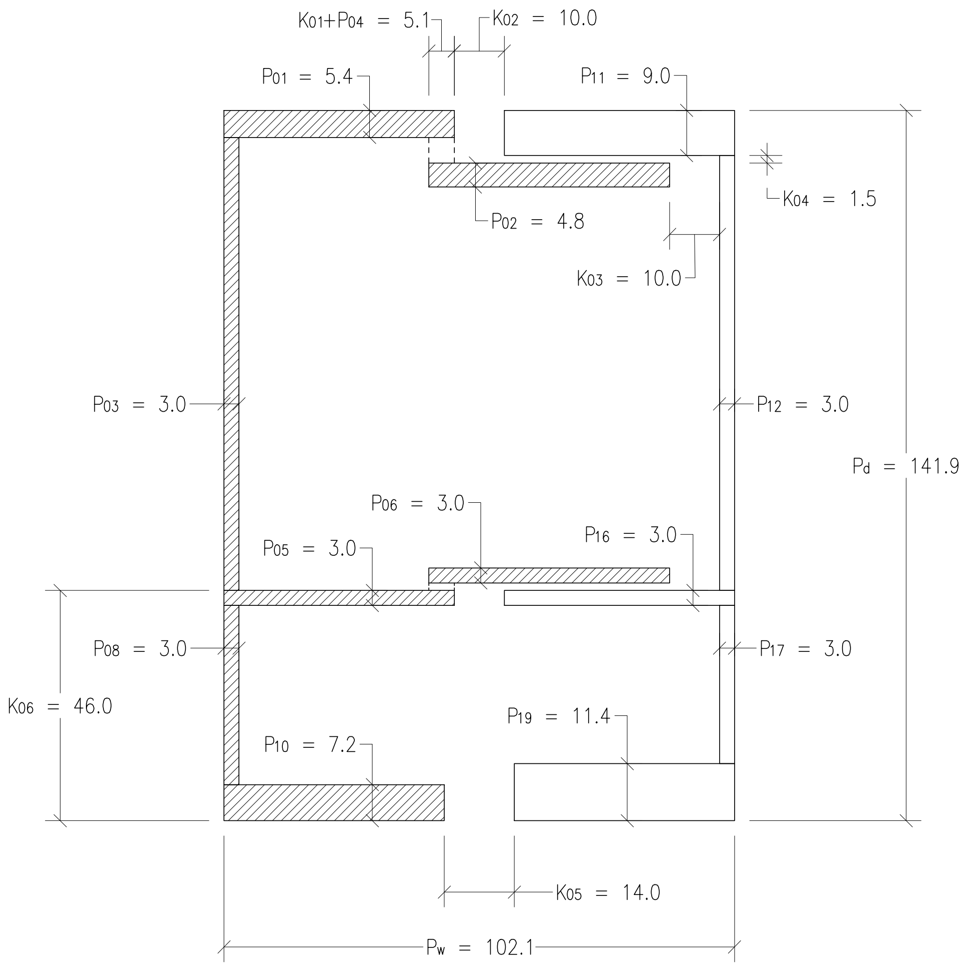


Figure 3: Shapes of the mullion profiles optimized to meet the performance criteria set out in Table 1, and the facade layout geometry shown in Figure 4. Dimensions are in millimeters.

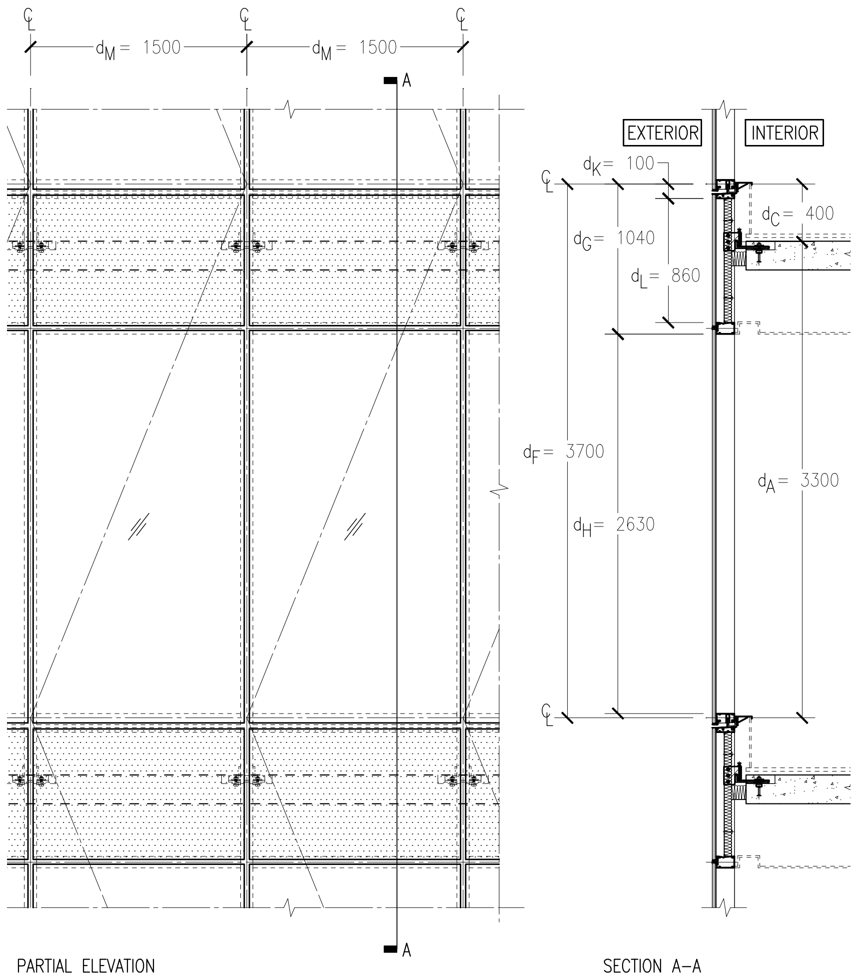


Figure 4: Dimensioned elevation and section views showing the layout of the normative reference curtain wall considered in the numerical optimization studies. The vertical distance between the fulcrum of the bracket and the fulcrum of the stack joint, d_C, is the "stack-height".

Table 1: Layout dimensions, alloy type and performance criteria for normative standard curtain wall system considered in numerical analysis.

Constraint	**Value**	**Comment**
Extruded metal thickness:	$3\,\text{mm} \leq P_i \leq 12\,\text{mm}$.	[19, Fig. 5]
Front-to-back mullion depth:	$60\,\text{mm} \leq P_d \leq 240\,\text{mm}$.	See Figure 2.
Mullion width:	$60\,\text{mm} \leq P_w \leq 120\,\text{mm}$.	See Figure 2.
Interior flange separation:	$K_{02} = 10\,\text{mm}$.	See Figure 2.
Gasket clearance:	$K_{04} = 1.5\,\text{mm}$.	See Figure 2.
Exterior flange separation:	$K_{05} = 14\,\text{mm}$.	See Figure 2.
Outer face to rainscreen:	$K_{06} = 46\,\text{mm}$.	See Figure 2.
Sum of transom web thicknesses:	15 mm.	*See note below.
Total area of reference transoms:	4965 mm^2.	*See note below.
Reference transom depth:	150 mm.	*See note below.
Panel width:	$d_M = 1{,}500\,\text{mm}$.	See Figure 4.
Bracket to bottom of panel:	$d_A = 3{,}300\,\text{mm}$.	See Figure 4.
Vertical distance between brackets:	$d_B = 0\,\text{mm}$. (Only one bracket per floor.)	See Figure 4.
Stack height:	$d_C = 400\,\text{mm}$.	See Figure 4.
Top of vision span to top of panel:	$d_G = 1{,}040\,\text{mm}$.	See Figure 4.
Height of unbraced vision span:	$d_H = 2{,}630\,\text{mm}$.	See Figure 4.
Top of spandrel to top of panel:	$d_K = 100\,\text{mm}$.	See Figure 4.
Height of spandrel:	$d_L = 860\,\text{mm}$.	See Figure 4.
Maximum deflection:	$\min\{20\,\text{mm}, \text{Span}/175\}$.	
Wind pressure:	+2.8 kPa and -3.5 kPa.	
Aluminium alloy:	6063-T5.	

*A selection of different existing unitized curtain wall systems have been examined, and the mass of metal in a typical set of horizontal structural members has been determined for the case in which the front-to-back depth of the sections – P_d in Figure 2 – is 150 mm. In order to estimate the mass of metal in the horizontal profiles in other conditions, it has been assumed that the lengths of their webs change so that the depth of the section matches the depth of the mullion.

2.1. Floor Height

If the design of the reference curtain wall is modified to suit a new floor-to-floor height, then the amount of metal in the facade will change as shown in Figure 5. The plot shows the variation in mass of metal per unit area of facade. When quantifying the consequence of an increase in floor height, it should be remembered that not only will the mass per area rise, but also, assuming that the number of building floors remains constant, the total facade area will increase.

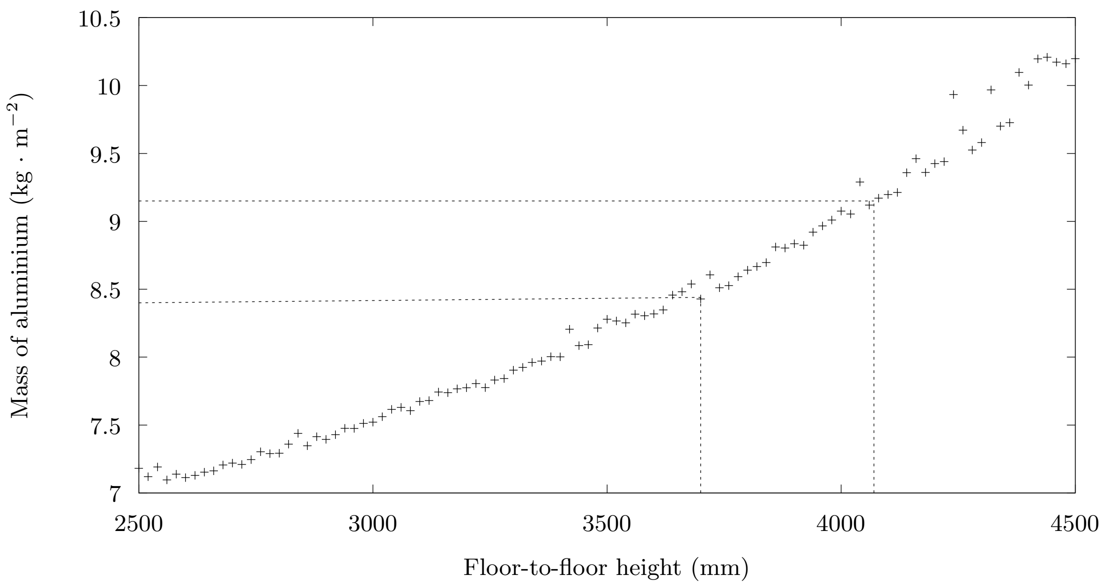


Figure 5: Influence of floor-to-floor height upon the mass of metal per unit area of optimized curtain wall.

From these results it can be seen that changes in floor-to-floor span affect strongly the facade's aluminium content. If the number of floors in the building remains constant and the height of each floor is increased by 10 % – from 3700 mm to 4070 mm – then the total mass of metal in the structurally-optimzied facade will rise by 19.3 %. An architectural team wishing to use material efficiently should therefore ensure that floor-to-floor spans are no larger than necessary.

2.2. Stack Height

Figure 6 plots the weight of metal in the members of a family of curtain walls. The geometric arrangement of these walls is matched to that shown in Figure 4 except that, in each member of the group, the distance between the top of the panel and the attachment bracket, the "stack height", is different. Figure 6 shows that, if the bracket connection point is not at the very top of the panel, which is the location often chosen by architects, but is moved down by approximately 17 % of panel height, then the weight of metal in the curtain wall can be reduced by more than 25 %. The importance of this observation is worth emphasizing: simply by moving the mullion's support bracket away from the very top of the panel, the magnitude of bending moment in the main span is lessened [bending moment shown in 19, Figure 4], and the mass of aluminium in the facade may be reduced by one quarter.

2.3. Unbraced Length & Mullion Width

The cross-sectional shapes of mullions optimized for the different curtain wall panels in Figure 7, having between one and four transoms, are presented in Figure 8. The graph in Figure 7 shows that, if the number of transoms is two or more, then in the common range of unitized mullion widths – between, say, 75 mm and 105 mm – changes in the width of the mullion have little effect upon the system's aluminium content. If the number of transoms in the panel is increased above two, each extra transom increases the metal mass by approximately $0.8\,\mathrm{kg/m^2}$.

If the panel has only one transom, and if the mullion is narrow, then the governing structural design consideration is the stability of the slender vertical members. In this situation the amount of metal needed to make the slender mullions resistant to buckling is greater than the amount of metal needed to reduce the mullion's unbraced span by introducing an additional transom.

2.4. Minimum Extruded Thickness

Figure 9 shows the effect that the value of the specified minimum metal thickness has upon the mass of aluminium in this study's reference curtain wall

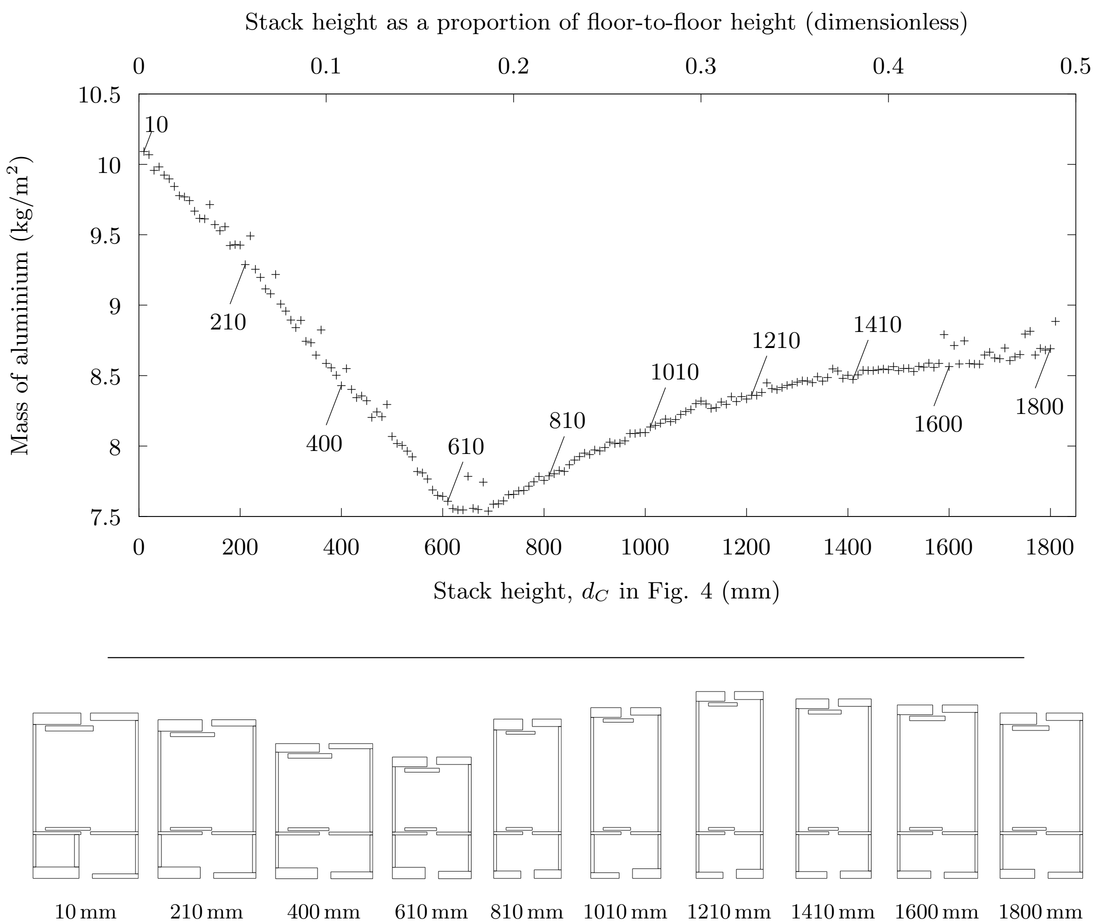


Figure 6: The graph shows the mass of aluminium in the members of a family of optimized curtain wall designs, each with a different stack height (d_c in Figure 4).

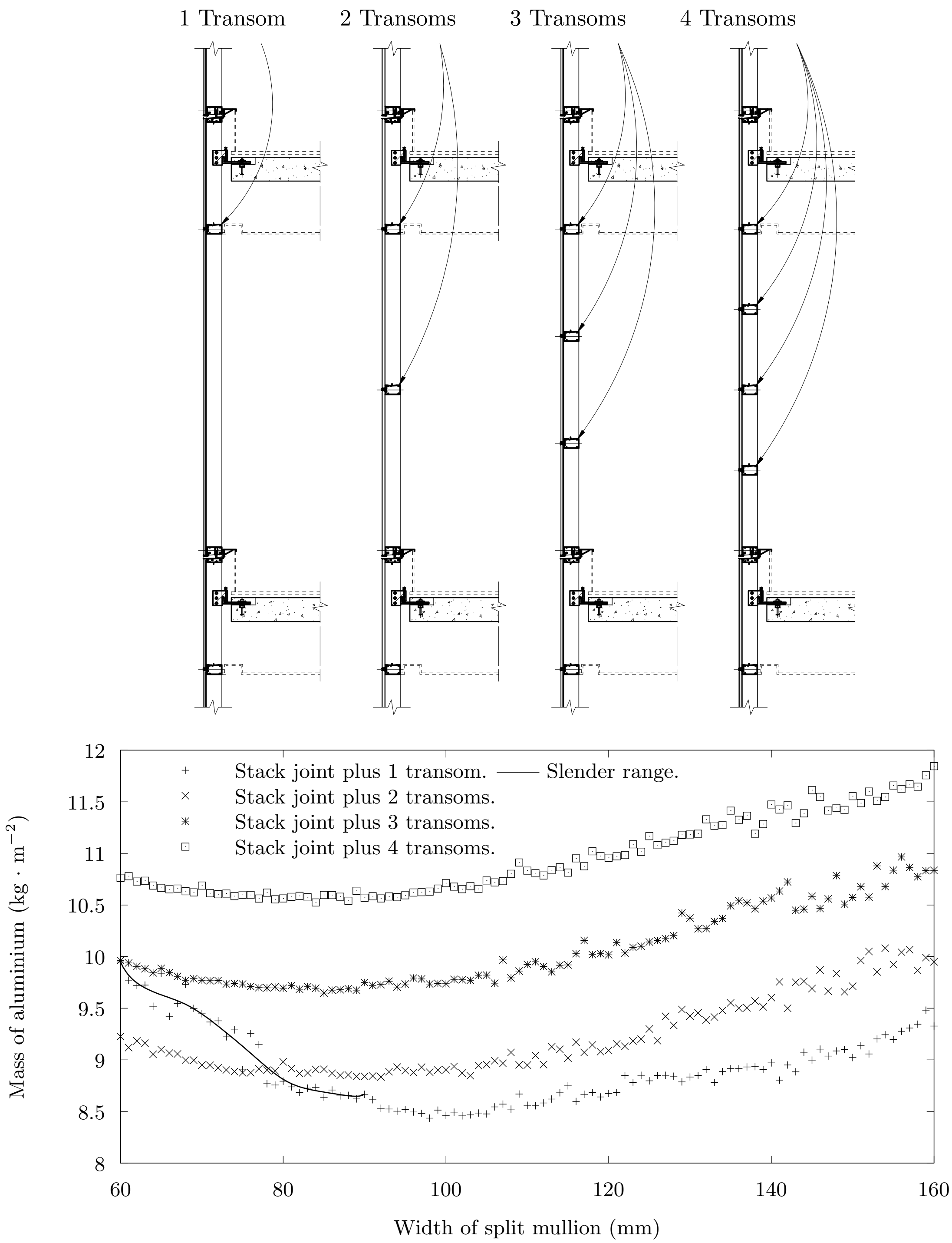


Figure 7: Plot (bottom) shows variation in mass of aluminium with mullion width, for four different curtain wall panel configurations (above). Other than the number of their transoms, panels are the same as those shown in Figure 4. The solid line on the graph is a moving mean mass of metal for panels with one transom, in which the mullion is slender and lateral torsional buckling is the governing structural design consideration. At high slenderness ratios, the mullion cross-sections are inefficient: if mullion width is narrower than 80 mm then a panel with two transoms requires less aluminium than in a panel with one transom.

system. The shapes of four different pairs of optimized mullion profiles, created by ACWEDS to meet minimum metal thickness requirements of 1, 2, 3 and 4 mm, are shown. All of the profiles meet the structural design criteria – for resistance to local buckling, lateral torsional buckling and so on – and they are drawn to the same scale. It can be seen that the optimal depth of the profiles decreases as the specified minimum extrusion thickness increases, and at the same time the mass of metal in the wall system rises. Based on this analysis it appears that a change in minimum thickness from 3.2 mm (or 1/8 inch), a figure that is frequently found in the technical specifications for facades of buildings in North America, to 2.2 mm, causes the overall mass of aluminium in the curtain wall system to fall by approximately 18 %. Therefore, the specifier's choice of minimum thickness will have a significant effect upon the amount of metal in the optimized design. Although it is currently impractical to extrude or to handle curtain wall extrusions with webs or flanges as thin as 1 mm, the data from this study show that if new technologies were to be developed – for example, lightweight composite framing members created by bonding thin aluminium sheets to a low-modulus filler material – then more efficient designs could be realised.

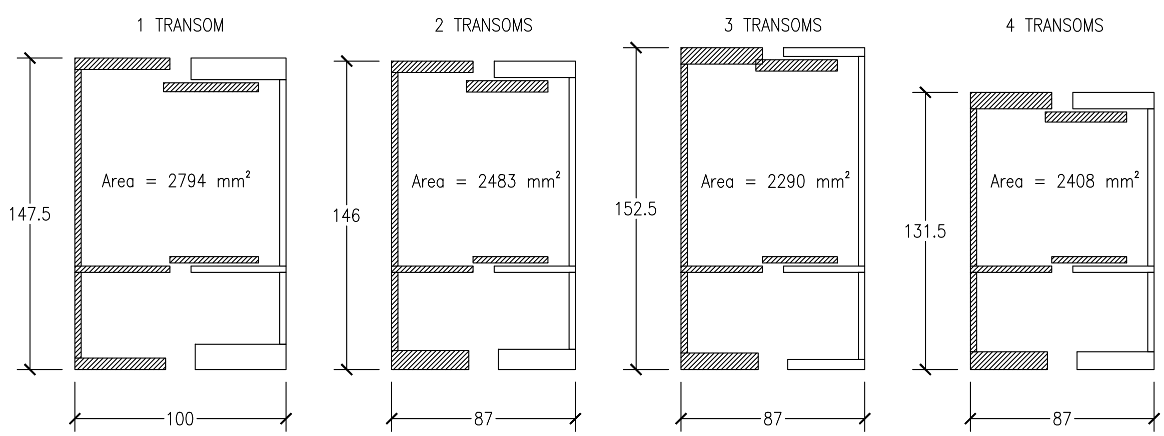
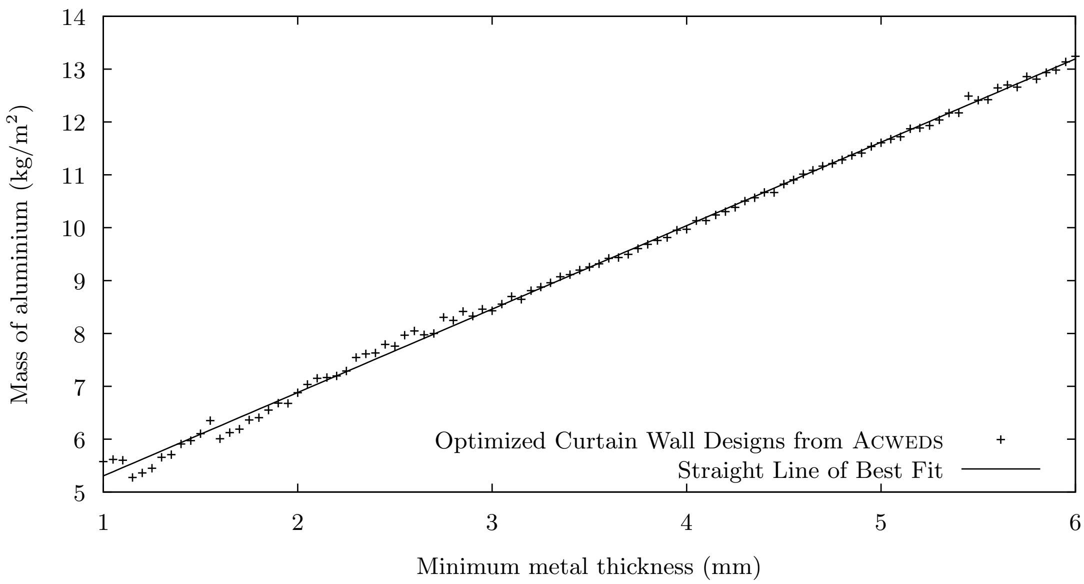


Figure 8: Mullions optimized for four different curtain wall panels – those shown in the upper diagram of Figure 7 – each with a different number of transoms.



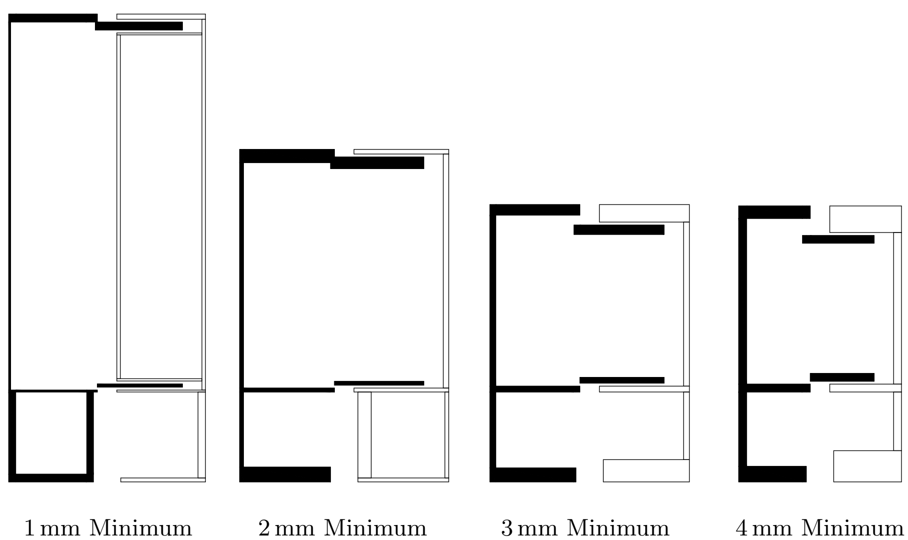


Figure 9: (Top) Weight of aluminium in the curtain wall shown in Figure 4, plotted against minimum allowable metal thickness. (Bottom) Shapes of mullions optimized for metal thickness minima of 1 mm, 2 mm, 3 mm and 4 mm. Male mullions are drawn with fill, while female mullions are drawn in outline.

2.5. Mullion Spacing

Figure 10 shows the influence that the curtain wall's module width – the horizontal distance between mullions – has upon metal content.

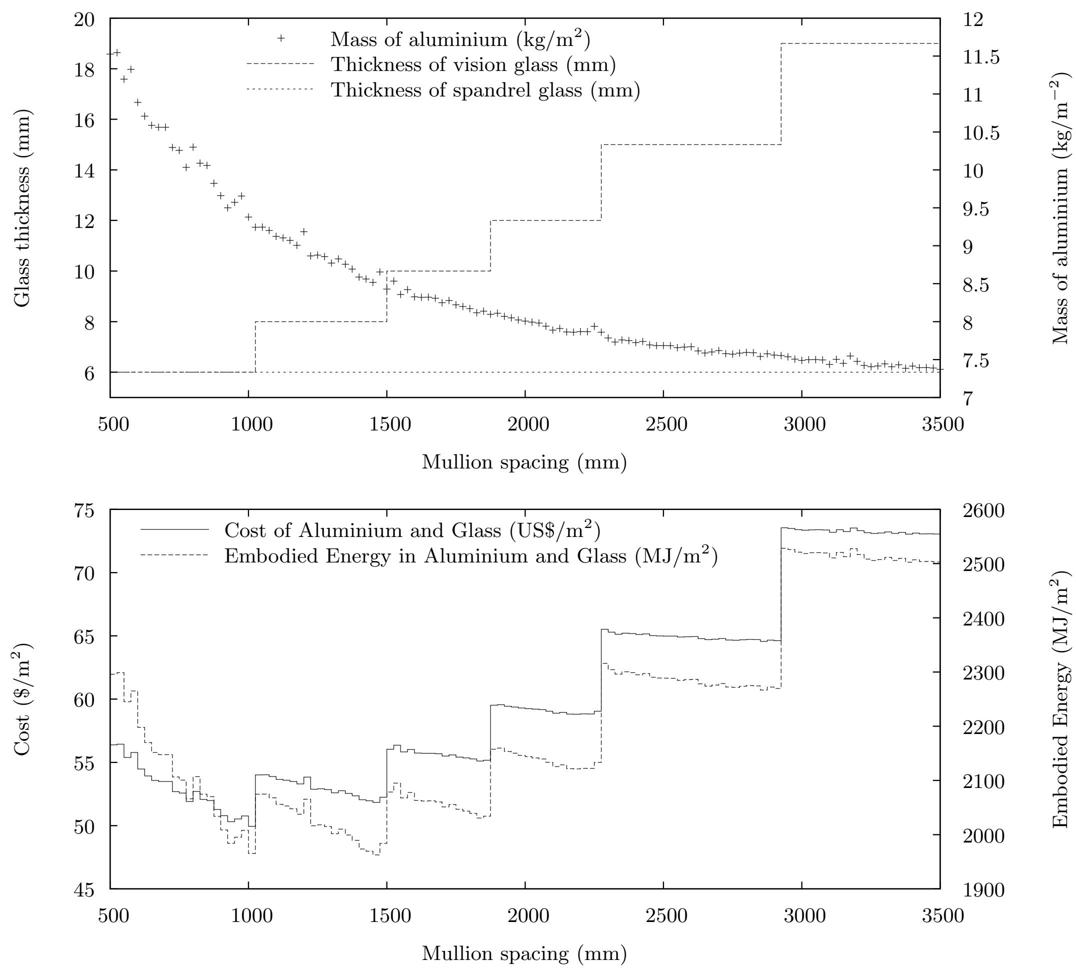


Figure 10: The upper graph shows how the mass of aluminium in an optimized curtain wall, and the thickness of its vision and spandrel glass, change with the horizontal spacing between mullions. The lower graph shows the approximate combined cost, and the approximate combined embodied energy, of the aluminium and glass.

The plot shows panels of up to 3.5 m in width but, in practice, because of transportation and handling constraints, panels of so wide are unusual.

As panel width increases, so the mass of aluminium in the wall falls. At the same time however, if the panel is glazed, then the thickness of glass must increase. The combined cost of aluminium and glass, as well as the combined embodied energy, are shown in Figure 10. Both cost and embodied energy are at a minimum when one of the common architectural glass thicknesses – 6 mm or 8 mm – is chosen, and when the separation between mullions is as wide as is possible without causing excessive stress or deflection in the glass.

2.6. Wind Pressure

The forces resulting from the action of wind upon a building's facades may be predicted by testing a scale model in an atmospheric wind tunnel. This method has been widely used for many decades, and its fundamental technical aspects are well documented [26, 27, 28]. Most of the world's building codes allow a facade's design wind loads to be determined either by wind tunnel testing or, alternatively, using formulas that take account of the building's location, its shape and the topography of its surroundings. Architects and their consultants usually are advised that the costs associated with a wind tunnel study are outweighed by the resulting material savings [29, pp. 88-89; 26, p. 4]. This assertion, that wind tunnel testing results in cost savings, appears often in the marketing materials of wind engineering firms. To quote phrases used on the internet by three of these firms: there are "massive cost-saving implications"; wind tunnel testing "generally results in significant savings in the cost of the facade"; and there may be "a cost to benefit ratio of 1:30 in carrying out a cladding pressure study".

While various authors, [e.g. 28], have compared the magnitudes of the design pressures obtained by wind tunnel modelling with those calculated using the construction codes, until now little information has been available to describe the relationship between a facade's design pressure and its material content. It has therefore been difficult for architects and building owners, the parties who commission wind tunnel studies, to evaluate the sort of cost-saving claims made in the quotations above.

Figure 11 shows, for a range of different design wind pressures, the minimum mass of metal required to construct this study's reference curtain wall system. It is usually the case that the magnitude of the positive, or inward-acting, pressure is less than that of the negative, or outward-acting, load. So, for each of the cases considered in this design pressure study, the magnitude of the positive wind load has been maintained at 80 % of the magnitude of negative wind load. These results may be used to estimate the metal savings associated with a given reduction in design wind pressure, assuming that the structural design of each wall panel is optimized to match its nominal design pressure. In practice however, as discussed in Section 3.6, if a wind tunnel study results in a pressure zoning scheme that is more complex than that which would have been obtained from a construction code, then it may be impractical to create different curtain wall panels for each of the design pressure conditions. Consequently, the magnitude of the metal saving indicated in Figure 11 should be considered to be an upper bound.

2.7. Comparison Between Curtain Wall & Window Wall

Amongst other popular types of exterior envelope system, an architect might choose a *curtain wall* – a continuous multi-storey envelope mounted outside the building structure – or a *window wall*, which spans only from the upper side of one floor slab to the underside of the floor above [30, p. 32]. The sections in Figure 12 show these two different types of construction.

While it might at first seem that, since a curtain wall must cover a greater area it will contain more material than a window wall, this argument neglects a difference in the bending moment distribution in the mullions of the two systems. The vertical members of the curtain wall behave as continuous beams spanning multiple storeys [19, Fig. 4], while vertical members of the window wall are simply supported at the head and sill. The result is that the magnitude of the moments in mullions, and hence also the required mass of aluminium, may be greater in a window wall than in a curtain wall.

Acweds was used to create a family of unitized window wall designs, each

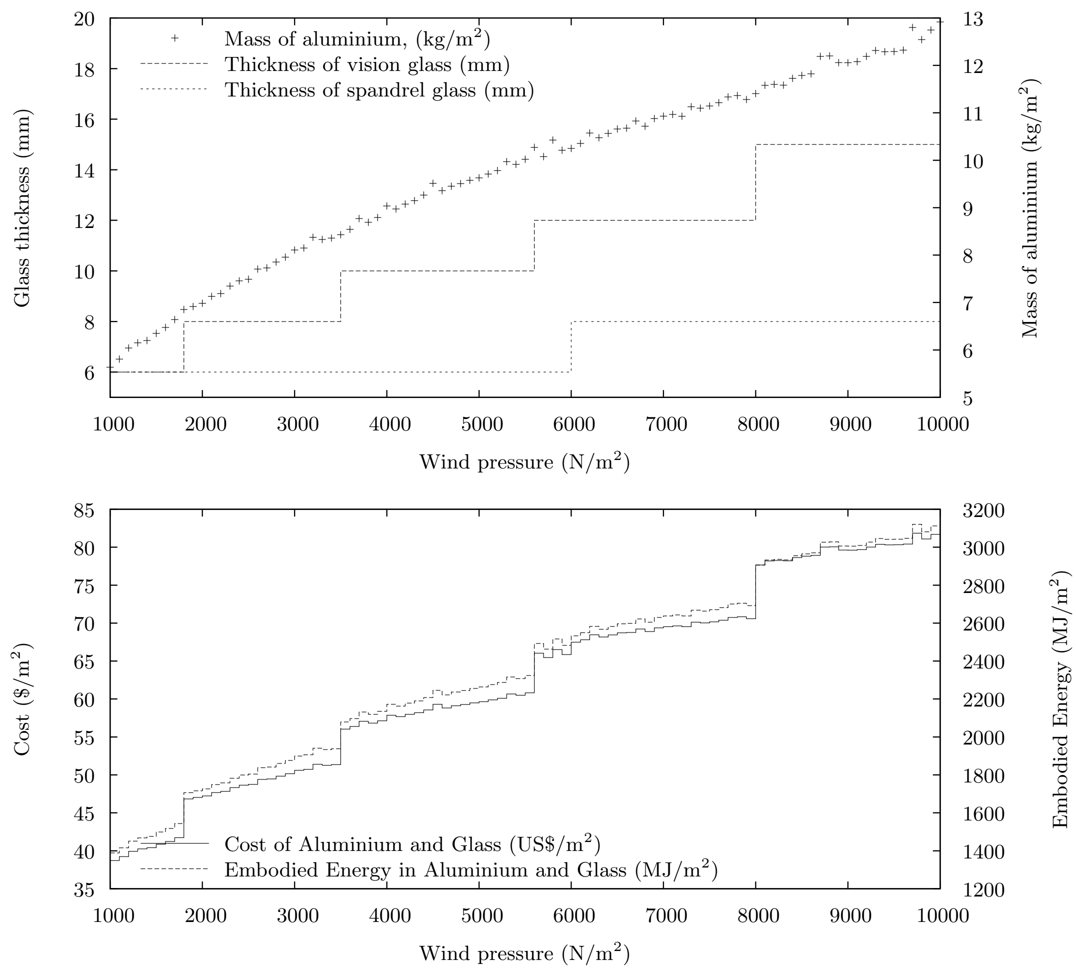


Figure 11: Upper graph shows the effect that variation in design wind load has upon weight of aluminium and thickness of glass in an optimized curtain wall system. Lower graph shows the effect upon and material cost and embodied energy.

of a different vertical span, and each optimized for minimum metal weight. The frames of the window wall panels were simple rectangles without any transom between the head and sill members, and the vertical height of the panels varied between 2.1 and 3.7 m. The front-to-back depth of each panel's horizontal members was set to match the depth of its mullion: for a mullion depth 150 mm the sum total cross-sectional area of the sub-head, head, head clip, sill and sub-sill, as shown in Figure 13, is 4865 mm^2. Other aspects of the specification of the window wall were set to match the curtain wall specification summarized in Table 1. Figure 13 shows the cross-sectional form of a window wall's head and sill. The system shown in these diagrams has extruded caps at the perimeter of the glass, but, as for the previous studies of curtain walls, such caps are ignored in the computation of metal weight.

Figure 14 shows the way in which metal mass varies with the height of the window wall. Also marked on this graph are the masses of metal in two curtain wall systems designed to the same performance specifications: one is the reference curtain wall shown in Figure 4, and the other is similar but with a distance of 640 mm between stack joint and bracket. These two curtain wall layouts have been chosen for comparison because they are the common and

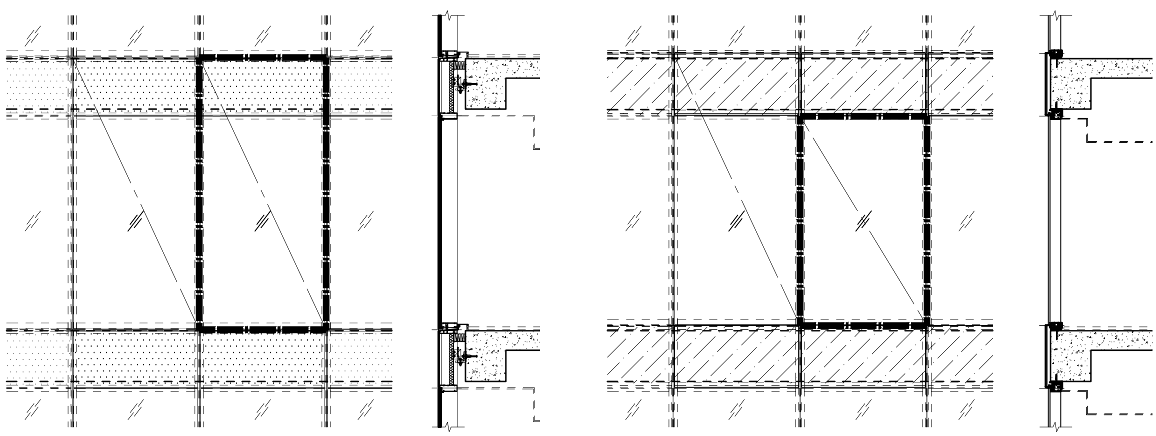


Figure 12: Elevation and section views of a curtain wall (left), and a window wall (right). In the elevation views, panel sizes are indicated with a heavy, broken line.

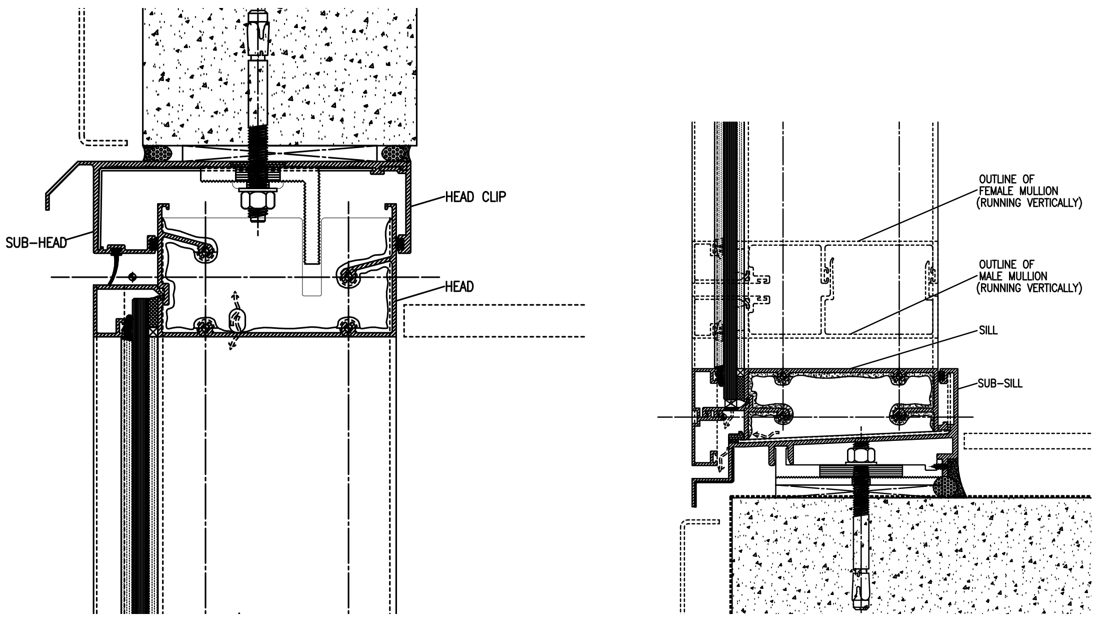


Figure 13: Cross-sectional form of horizontal members in a window wall: the sub-head and head (left), and the sill and sub-sill (right). An outline of the vertical mullion is shown above the sill.

geometrically optimized geometries that an architect might reasonably consider as alternatives to the window wall facade.

The results indicate that, for this set of design criteria, if the height of an optimized window wall is greater than approximately 80% of the vertical distance between floors, then it will contain more aluminium than an optimized curtain wall, even though the curtain wall covers a greater area.

In order to make a fair comparison between the two different types of wall system, the material used to create those parts of a facade that exist between the horizontal bands of window wall also should be taken into consideration. If construction costs are to be compared, then it should be noted that the window wall requires site-applied waterproofing and coordination between trades. For all of these reasons a window wall is unlikely to be more economical than a curtain wall unless its span is considerably less than 80 % of the floor-to-floor height.

3. Research-Based Heuristics for Efficient Curtain Wall Design

Metal-saving strategies that might be used by the different members of a building's facade design team – the architect, the specialist consultant and the facade contractor – are presented below. These recommendations follow from the numerical studies described in this paper.

3.1. Floor Height

As a building's floor-to-floor height rises, the mullions in its facade must be made stronger and stiffer in order to span a greater distance, and so the mass of metal per unit area of facade will increase. If the number of floors remains constant then, because the building becomes taller, the total area of facade also will increase.

The data presented in Figure 5 shows that a 10 % increase in floor-to-floor height – from 3700 mm to 4070 mm – adds 19.3 % to the total mass of metal in the facade. For this reason the vertical distance between a building's floors should be no larger than necessary.

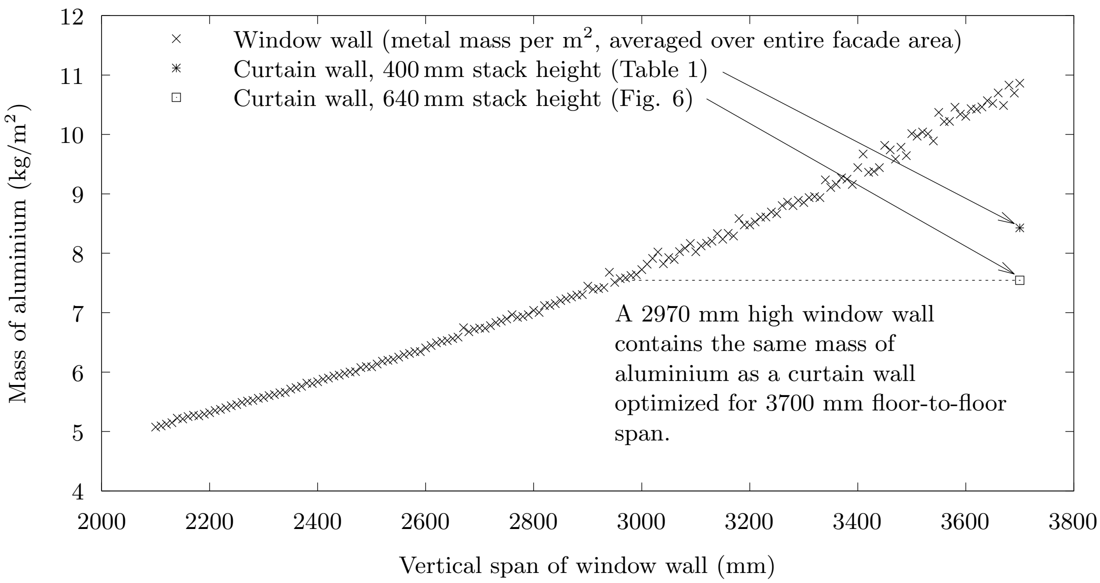


Figure 14: Relationship between mass of aluminium and height of window wall. The mass of metal in this study's reference curtain wall system (Figure 4) is shown for comparison. Also shown is the mass of metal in a modified version of the reference wall, in which the mullion's support bracket is positioned at the optimal distance from the top of the panel.

3.2. Location of Mullion Brackets

It has been shown in Section 2.2 that, when deciding upon the layout for a unitized curtain wall, considerable metal savings can be achieved if each mullion's support bracket is moved downward, away from the end of the mullion – that is to say, away from the top of the panel. In the results presented in Figure 6, the optimum distance between bracket and stack joint is approximately 17 % of floor-to-floor span.

If, as is commonly the case, mullion brackets are attached to the building's structure at the upper side of the floor slab, as shown in the left hand side of Figure 15, then the structurally optimal position for the stack joint will be close to knee height. On the other hand, if an architect wishes to align the bottom of the curtain wall's panels with the top of the floor, as show at the right hand side of Figure 15, then, in order to achieve the optimal stack-to-bracket distance, the mullion bracket will need to be positioned at the underside of the floor slab, or at the face of the beam below. While the placement of brackets below floor level might be considered to be unconventional, the lead author has developed attachments of this sort, which have been used successfully in high-rise building facades. The curtain wall contractors who have used these designs report that any additional costs associated with the installation process are by far outweighed by the value of the metal savings made possible by this design approach.

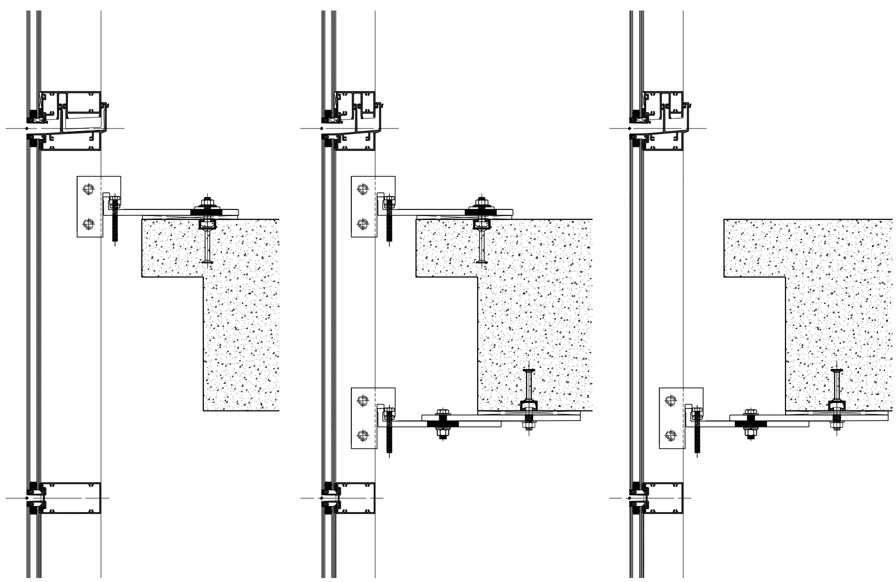


Figure 15: A top-of-slab mullion bracket (left), double bracket (centre) and underside bracket (right).

Changing the design so that the stack joint is not immediately above the bracket has a secondary benefit. Not only does the required mullion strength diminish, but also, because the magnitude of the shear force between the bottom of one panel and the top of another is lower, so the amount of metal in the stack joint profiles can be reduced as well.

3.3. Number of Transoms

In order to minimize the extent to which a curtain wall's structural lattice interferes with the building's occupants' view of the world outside, an architect might have a preference for designs in which the size and number of framing elements is kept to a minimum. Panels might be designed with a single pane of glass spanning from floor to ceiling, and mullions might be made as narrow as possible. However, such an approach is likely to result in inefficient use of aluminium. If the structural analysis of mullions is carried out in accordance with the curtain wall industry's current guidelines for best practice [for example 31], ignoring any lateral support provided by glass or other infill materials then, as shown in Figure 7, an optimized curtain wall panel with floor-to-ceiling glass and mullions narrower than about 80 mm will contain more metal than an optimized design in which the vision glass is divided by one additional horizontal member.

Efficient designs can be achieved in panels with floor-to-ceiling glass, providing the mullion is not too slender. For the curtain wall layout studied here, in which the floor height is 3700,mm, the use of split mullions of around 100 mm in width was found to minimize the mass of metal in the facade.

3.4. Minimum Metal Thickness

The model specifications and design commentaries prepared by the curtain wall industry's technical bodies [32, 14, 30] place no restrictions upon the thickness of aluminium in extruded structural profiles, except of course that the metal thickness should be sufficient to ensure satisfactory structural performance. However, many technical specifications for the construction projects of governments and private developers stipulate that extrusions in which the thickness of metal is less than a certain minimum are either forbidden or that they require special approval [e.g. 33, p. 16-9]. A specifier might, for instance, insist that in all structural extrusions the thickness of metal is not less than 3 mm or 3.2 mm. Section 2.4 of this this present study shows that the overall size of an optimized framing member increases as the minimum allowable metal thickness is decreased. However, even if the profiles become larger, the total mass of metal in the wall system can be reduced. The results presented in Figure 9 indicate that simply by changing the allowable minimum metal thickness from 3.2 mm to 2.2 mm, the curtain wall's metal content falls by 18 %.

The recommendation arising from these findings is that architectural teams should question whether it is really necessary to stipulate a minimum metal thickness. Instead, metal can be saved if curtain wall contractors are allowed to develop their extrusion profiles without geometric restrictions, other than that the shapes must be shown to comply with the prevailing structural design rules.

Specifiers may, hypothetically, have been imposing minimum metal thicknesses as an indirect means of controlling another aspect of a curtain wall's performance. It might be that a requirement for thicker metal has been introduced to tighten dimensional control during the extrusion process, or to increase a curtain wall's capacity to attenuate noise. Perhaps specifiers believe that an extrusion will be weak if its plate elements are thin, even if the profile complies with prescriptions of the structural design codes. The authors of this paper argue however that it is preferable to specify the desired criteria directly. In the case of these examples, rather than use metal thickness as a proxy, it would be better to set geometric tolerance limits, or to indicate the required standard of acoustic performance.

3.5. Horizontal Distance Between Mullions

It has been shown, in Section 2.5, that as a curtain wall system's mullions are moved apart, so the mass of metal in the optimized facade will decrease, but at the same time the mass of glass will increase. Some guideline is needed to achieve an efficient compromise. Whether it is the objective to minimize embodied energy or to minimize cost of metal and glass, and whether the curtain wall is to be glazed with monolithic or insulated glass, Figure 10 suggests a reasonable optimization strategy. First, one of the common architectural glass ply thicknesses, 6 mm or 8 mm, should be chosen; next, the horizontal spacing between mullions should be set to the maximum at which the chosen glass is structurally adequate. Also a check should be made to ensure that the facade's typical panes can be cut from "jumbo" sheets, which are approximately 3 m by 6 m [34, p. 226], without excessive wastage.

If a wall's design wind loads are determined using a code, rather than by wind tunnel testing, then a large facade will, typically, be divided into a small number of simple rectangular zones, and each zone will have a different wind pressure. Because the optimal mullion spacing depends upon the design load, in order to make the most efficient use of material, an architect might, for example, choose a wider mullion spacing in the central part of a facade, where the magnitude of the design load is lower, and a closer spacing in the proximity of corners, where the magnitude of wind pressure is greater.

Maximizing the horizontal separation between mullions not only lowers the mass of metal in the curtain wall, but also benefits thermal performance because less heat passes through insulated glass than through the frame [35, p. 32].

3.6. Wind Tunnel Testing

If a building's design loads are calculated using the rules given in a code, then each of its facades will be divided into a small number of simple, rectangular zones, and a different design wind pressure will be assigned to each zone [26, p. 11]. If, on the other hand, facade wind loads are determined by wind tunnel testing, although the results may, on average, be lower than those found using construction codes [e.g. 28, 26], it is likely that the facade pressure maps will be geometrically more complex [26, pp. 24 & 29] and that they will span a greater pressure range than the codified predictions. The cost of additional work in the design of the facade, and well as the expenses associated with an increase in logistical complexity – in procurement, fabrication and installation – should therefore be taken into consideration when evaluating the net cost impact of a wind tunnel test.

Aside from the pursuit of savings, there may be sound reasons for carrying out a facade pressure study in a wind tunnel. Not least of these is that routine project-specific wind tunnel testing helps to train and support wind engineers whose specialists technical knowledge is of certain benefit to the building design community. It is for each building's design team to weigh the pros and cons of a wind tunnel study, and the only advice given here is that the cost benefits indicated in wind laboratories' marketing literature, such as those quoted in Section **??**, should be treated in the same way as any other business' advertising claims: with some measure of caution. The data in Figure 11 may help architects and their consultants to estimate the upper bound to the cost saving associated with a given reduction in design wind pressure.

3.7. Curtain Wall or Window Wall?

The study presented in Section 2.7 suggests that, for facades of conventional geometry and performance, a window wall design will require less metal than an optimized curtain wall only if the window wall's vertical span, as a proportion of floor-to-floor height, is 80 % or less. After taking into consideration all of the practicalities of window wall construction, such as the need to provide extended floor slabs and the cost of coordinating between trades, it is likely that a window wall will be the more economical option only when its vertical span is much less than 80 % of floor height.

3.8. Transom Depth

In many curtain wall systems, horizontal members are sized to match the mullions. This configuration is shown at the left hand side of Figure 16. In comparison with the mullions, usually a facade's transoms will have shorter spans and will carry less bending moment, and so it is possible to make the transoms smaller in size, as at the right hand side of Figure 16. If the curtain wall contractor is permitted to size transoms and mullions independently then more efficient designs, containing less metal, may be achieved.

3.9. Glazing Caps

Glass may be secured to a curtain wall panel's metal frame in one of two ways. Either the perimeter of the pane can be bonded to the metal using a

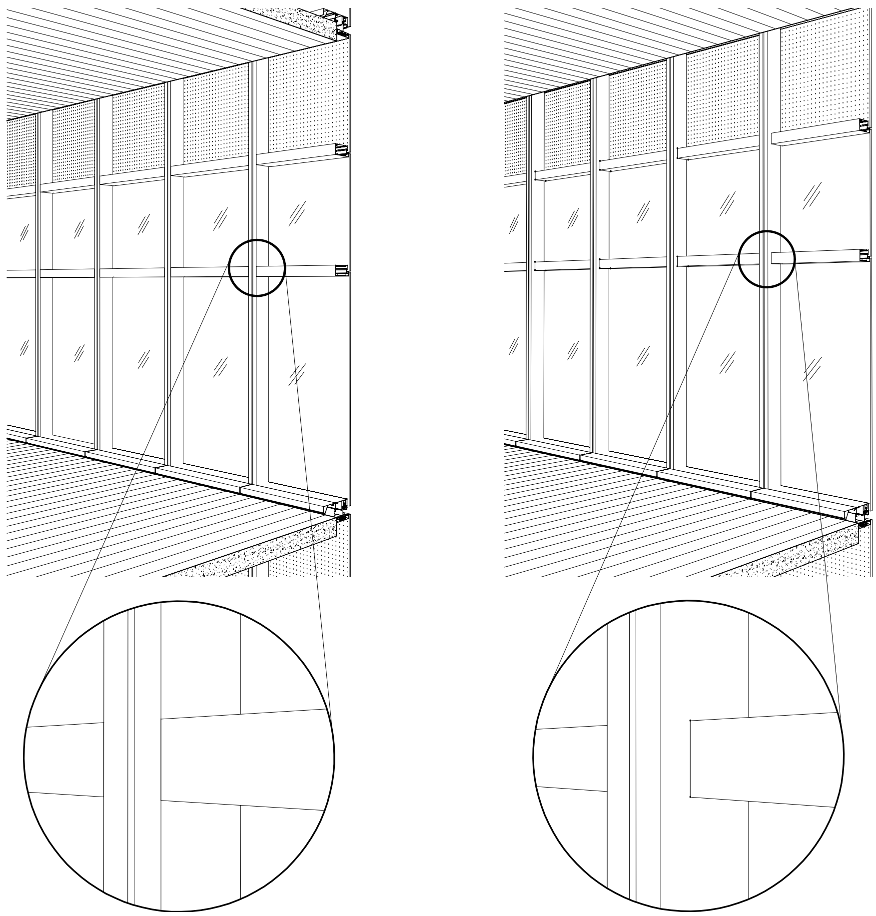


Figure 16: Two unitized curtain walls viewed from the interior side. In one (left), mullions and transoms are of uniform size, in the other (right) transoms are recessed. Aesthetically, the difference between the two designs is minor. Suspended ceilings, spandrel insulation and fire barriers have been omitted from the drawing for clarity.

structural adhesive or, alternatively, the glass edge can be retained mechanically using an extruded metal cap. These design options are shown in Figure 17.

If glass is attached using a structural sealant then the width of the joint, or bite – marked 'b' in Figure 17 – must be of a certain minimum size. The minimum bite dimension is a function of the glass pane's width and the design wind pressure [36].

If an architect were to choose to change from a capped mullion to a structurally glazed mullion, then the width of the member might need to increase in order to provide space for the structural silicone bite. Using the results presented in Figure 7, it is possible to assess the effect that such a change would have upon metal content. Within the range of common split mullion widths, from about 70 mm and 110 mm, if the unbraced spans between transoms are sufficiently small that structural design is not governed by buckling, the mass of aluminium in an optimized curtain wall is not sensitive to changes in mullion width. It follows that, providing the mullion is not slender, the mass of metal in a curtain wall with capped glazing can be reduced by removing the caps and, if necessary, making the mullions wider in order to accommodate structural sealant.

Changes to the shapes and locations of glazing caps can have a marked effect upon the exterior appearance of a facade, and hence upon the character of a building. The choice of glass retention method therefore has an aesthetic impact that should be evaluated for each specific building project, but this study indicates that a structurally optimized curtain wall system with seamless structural silicone glazing will use less metal than an optimized curtain wall with glazing caps.

4. Further Metal-Saving Strategies

The rules of thumb set out above, in Section 3, follow directly from the numerical studies described in Section 2. The list below contains further suggestions that are not based upon the research results, but may nonetheless be of help to those building designers and code committees who have an interest in minimizing the mass of aluminium in curtain wall facades.

4.1. Choice of Alloy and Temper

If the structural design of a particular curtain wall is governed by the yield strength of the aluminium, then an optimized solution containing less metal can be found if a higher strength alloy or temper is selected. So, metal savings might be associated with a change from 6063-T5 to 6063-T6. The change in material type will bring no benefit however if the dominant constraint is deflection or if the members are so slender that lateral torsional buckling is possible.

4.2. Additional Safety Factors

If a curtain wall's technical specification requires that structural analysis be carried out in a way that is more conservative than the methods described in the design codes then, naturally, those directives will increase the amount of metal needed to construct the facade.

A building design team seeking to make efficient use of material should check whether its specifications make structural performance demands that are

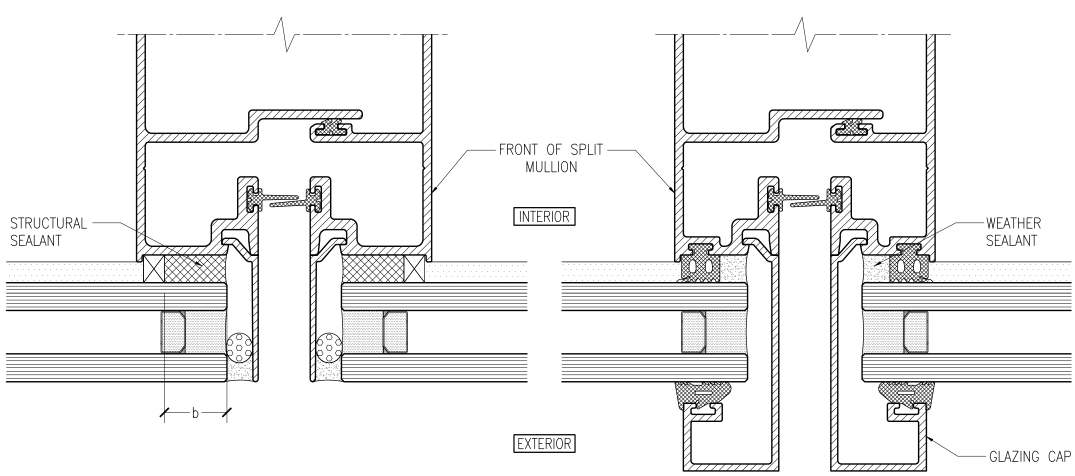


Figure 17: A split mullion with seamless, structural silicone glazing (left), and with capped glazing (right).

over and above those found in the structural design standards. The costs and the benefits associated with any increased factor of safety should be evaluated critically.

4.3. Transom Webs

By convention, transoms are box sections having two webs, as shown on the left hand side of Figure 18. In those locations where a transom is wholly or partially concealed – typically at the ceiling line or within a spandrel area – a curtain wall's designer might save metal by creating a profile with only one web, as shown at the right of Figure 18.

4.4. Whole-Facade Optimization Strategy

The numerical studies described in this paper have considered curtain walls subjected to uniform wind load, but the facades of a real building, particularly if they are large, may be divided into different zones, each having its own design pressure. To minimize metal weight in a multi-pressure facade, the following strategies are rational.

A curtain wall design should be developed and optimized for the facade's most common design load – that which applies to the greatest area of facade. In buildings of conventional geometry it is invariably the most economic solution to use only one bracket per mullion, as shown in the right or left hand diagrams in Figure 15.

For aesthetic reasons it will usually be necessary to maintain, throughout the facade, the same external dimensions for framing members, and in this case one set of common horizontal profiles can be used throughout. If the area of an atypical wind load zone is sufficiently large then it becomes economically rational to create a pair of atypical mullion extrusions specifically for that facade zone. The atypical mullion can be of the same width and depth as the typical mullion, but its internal form is adjusted to satisfy the atypical design criteria.

To cope with "hotspots" – small areas that must be designed to withstand a greater wind load – the wall can be strengthened locally by placing a metal

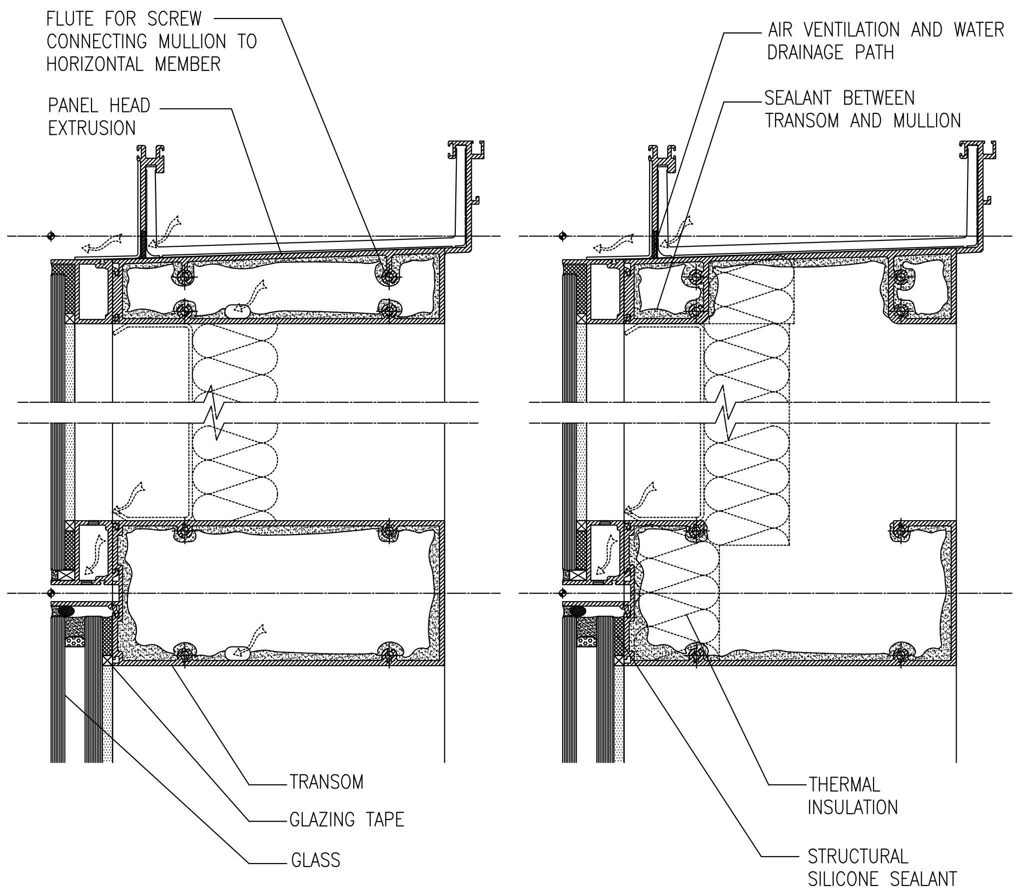


Figure 18: The unitized curtain wall head and transom members on the left are conventional, boxed designs. Those on the right are open sections, requiring less metal.

stiffener inside the standard mullion extrusions or, alternatively, the standard mullions can be supported by two brackets, as shown in the centre of Figure 15.

4.5. Coordinating Building Structure with the Facade

Some of the factors influencing the quantity of material in a curtain wall, such as the locations of its attachment brackets, are affected by the design of the building's structural frame. If there is cooperative interaction between the designers of the facade and the designers of the building's structure, there is more opportunity to develop efficient solutions [37]. For this reason, if economical design solutions are to be found, then consideration should be given to the timing of the appointment of a project's curtain wall contractor.

4.6. Energy-Efficiency Codes

Amongst the existing design codes written with the intention of improving efficiency in the usage of energy – be it embodied energy or thermal energy – performance targets most commonly scale with the area of facade [e.g. 35]. When goals are formulated in this way, developers and their architects are given no incentive to create buildings that are inherently efficient in shape. The facades of different buildings might achieve a uniform energy performance rating, but it would be the building with the smallest ratio of wall to floor area that would serve its occupants' needs with the lowest energy expenditure. Greater benefit might be obtained if construction codes were to be formulated so that allowable limits for a facade's thermal or embodied energy scale with the area of the building's floor, rather than the area of the facade itself.

4.7. Architectural Guidelines

A study of the world's towers taller than 300 m [38] found that the "vanity component" – the proportion of a building, by height, that is decorative rather than functional – correlated with the date and the location of construction. The more recent buildings have higher vanity components. In one country, amongst 19 of these tall buildings, the mean vanity component was 19 %.

An oversized facade, used to exaggerate the apparent size of one building, may influence the design of future buildings in the locality, and a trend or architectural fashion may emerge. The use of curtain wall for purely decorative purpose is, viewed from the standpoint of material usage, wasteful. Officials with a say in construction planning, as well as the authors of architectural guidelines, might therefore aim to limit the extent to which material is used for purely artistic effect.

5. Quantifying Material Optimization's Benefits

This study has shown that, just by moving the mullion's support point away from the top of the panel (Sections 2.2 and 3.2) and relaxing the allowable minimum metal thickness (Sections 2.4 and 3.4), the mass of metal in a unitized curtain wall may be reduced by more than 40 %. Other small deviations from current common practice, such as adjustment of the spacings between members (Sections 2.3, 2.5, 3.3 and 3.5) and modification of transom profiles (Section 4.3), can result in yet further savings. These techniques may be applied together, in combination, to greater benefit.

Because the embodied energy per unit mass of extruded aluminium – 154 MJ/kg [20, p. 10] – is greater than that in any other construction material used in bulk, there is good reason to seek the savings that design optimization can bring. The figures that follow place the potential energy savings from facade optimization in the context of a building's total embodied energy.

If all of the materials and processes needed to put up a new building are considered, the total embodied energy in a typical, newly-built, mid-rise office tower is in the region of 6 GJ per square meter of floor area [39]. Wall-to-floor area ratios easily can be estimated by looking at the shapes of existing buildings, and values around 0.4 are common. Therefore, if this paper's guidelines for the creation of efficient architectural layouts and specifications will reduce the mass of aluminium in facades by 40 %, from 12.0 to 7.2 kg/m^2, the corresponding embodied energy saving will be 744 MJ/m^2 of facade, or 298 MJ/m^2 of floor, so the total embodied energy in new buildings will fall by about 5 %. Further, if extrusion shape optimization techniques [19] are applied in addition, then the total of all embodied energy in newly constructed office buildings could be cut by 8 %.

Using published statistics it is possible to estimate, albeit crudely, the magnitude of the commercial returns that can be realized by applying material optimization strategies during the design of unitized curtain walls. The global construction industry's demand for extruded aluminium exceeds 8 billion kg per year [40, p. 64] and, extrapolating from American usage data [41], about a quarter, or 2 billion kg per year, is for curtain walls and storefronts. Of this metal, approximately 60 %, or 1.2 billion kg per year, will go into unitized curtain walls [12, p. 82]. If efficient designs can reduce this total by 40 %, saving US $ 3 per kg [25], then the annual worldwide reward will be US $ 1.44 billion.

6. Conclusions

In the course of this study, the designs of more than 1,000 curtain wall facades have been optimized numerically, using a cluster of high-performance computers. Analysis of the results has revealed that the criteria defined by an architectural team – for example, the distances between framing members, the positioning of attachment brackets, and any requirement for a minimum thickness of metal in extrusions – have a marked influence upon the quantity of aluminium in a unitized curtain wall. It has been demonstrated that, just by making small changes to the popular panel geometry (Sections 2.2 and 3.2) and specification (Sections 2.4 and 3.4), the mass of metal in a unitized curtain wall may be reduced by more than 40 %. In many cases it will be possible to obtain still greater savings by applying all of the practical guidelines set out in Sections 3 and 4, and it is known [19] that metal mass can be reduced yet further, typically by 20 % or more, if facade contractors optimize the shapes of their extrusion profiles for each individual building.

There are sound environmental reasons [42] and economic motives [43] for every country to curb its energy consumption. The results of this present research are therefore important because they highlight an energy-reduction opportunity that has, to date, been overlooked. National governments and energy policy bodies have emphasized the need to improve the thermal performance of building envelopes [e.g. 35], they have developed thermal analysis tools for facade designers [e.g. 44], and in building codes they have mandated minimum standards of thermal performance for exterior walls, but almost no attention has been given to the possibility of reducing embodied energy by modifying the design of wall systems so that material is used more efficiently.

In this document it has been shown that, by optimizing curtain wall designs to use less aluminium, the total embodied energy in a new building can be lowered by as much as 8 % (Section 5). This embodied energy reduction is of the same order of magnitude as the operational energy saving that an architectural team might obtain, over the lifespan of the building, by enhancing the thermal performance of the exterior envelope. While the pursuit of thermal improvements is not to be discouraged, thermal energy savings can, usually, be enjoyed only after making an initial capital expenditure and embodied energy investment in shading or insulating material, and the returns accrue slowly, during future decades. The cost of material optimization, on the other hand, is negligible – it requires little more than the design team's awareness – and the payoff, in terms of both cost and greenhouse gas emissions, is immediate.

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