STRUCTURAL SKIN

Integrating structure and cladding

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ABSTRACT

Many prominent, recent buildings feature forms suggesting structural surface while their enclosures are really non-load-bearing curtain wall. At the same time, we instinctively read the increasing proportion of opaque area on the facade required by the energy codes as solid, an opportunity to augment the primary building frame with perimeter structure. We have evident aesthetic desire to see structural form, and technical incentive in the form of increased opaque surface area to use the exterior enclosure as structural skin to make buildings more efficient, and more sustainable.

Preliminary modeling of a 24-story braced moment-frame with a 90’ x 90’ floor plate shows that structural cladding occupying the same depth as a conventional curtain wall has the capacity to limit lateral drift and reduce tonnage of the primary steel frame. The study evaluates three different schemes of moment-connected mullions braced by infill plate or diagonal rods. Each version replaces conventional aluminum mullions with stronger and stiffer hybrid mullions of steel and aluminum cassette glazing frames.

The initial expectation was that the skin would allow reduction in tonnage of the primary frame, resulting in reduced embodied CO2. It turns out that the reduction of steel in the primary frame is more than offset by the amount of steel added to the cladding in each case, but the net result in the last iteration is a reduction of embodied CO2 in the frame and skin due to the relatively high embodied CO2 of the replaced aluminum.

Next steps include refining details and exploring the potential of shaped or corrugated surface and structural laminated glass to enhance structural skin. This preliminary investigation shows that integrating structure and cladding, and using steel instead of aluminum in the enclosure framing, can save embodied energy.

KEYWORDS

Façade- curtain wall, innovative; *Performance*- energy efficiency, carbon; *Sustainability*- energy and carbon; *Material*- steel and aluminum (metal); *Other*- future trends, structural cladding.

INTRODUCTION

> *We are given an area which is to be covered, a space which is to be enclosed. We know the movement conditions of the external forces. If we set ourselves the task of sustaining these forces by transferring the reactions to the supports in a simple manner, by using the space-enclosing surface itself to carry the load…this is a general, but, finally, the only interesting problem.*
>
> B. Lafaille, 1936.(Angerer).

Structure expressed on the building surface is often the most aesthetically important element of architecture. The figural masses and quality of repose of the classical orders, the mysterious spaces and seemingly tensile forms of Gothic masonry, and the bio-morphic shapes of recent sculptural buildings all show the animating power of apparently structural form. This suggests that aesthetics and structure should be conceived in concert. But in modern design practice and education, aesthetic and technical aspects of architecture are commonly dealt with by separate ‘design’ and ‘technical’ groups, and structure is usually concealed by the non-load-bearing veneer of the curtain wall. Although the extra effort required to integrate different types of construction has kept structure and cladding separate in most modern buildings, a desire to integrate them appears in many current high-profile projects. One example is the Broad Museum in Los Angeles. The minimally sculpted box appears to be a structural dia-grid shell, its light-controlling apertures shaped as if carved from solid concrete. But the ‘veil’ enclosure is made of thin, lightweight glass fiber reinforced concrete panels attached to a steel framework supported by the interior structure of the building (Vaillancourt) (Fig. 1, Broad).

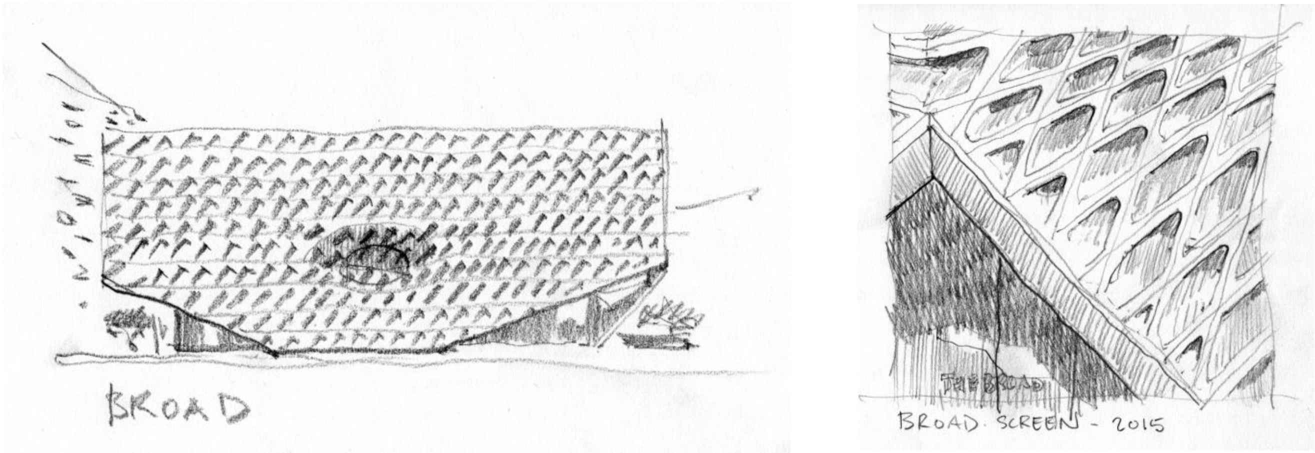

Figure 1: Broad Museum, Los Angeles, 2015, DS+R Architects. Elevation and close-up views. The façade reads as a perforated structural shell, but is made of thin GFRC panels on a curtain wall framing system.

The growing realization that climate change is accelerating is incentive to make building systems more efficient by integrating them, making material perform multiple functions in order to use less of it. Digital design technology makes analyzing hybrid frame and skin structure much easier than it once was. Meanwhile, evolving energy codes mandate a higher proportion of opaque surface on building exteriors. This is surface that we tend to read intuitively as mass or structure, and it could possibly be that in reality. The 2010 ASHRAE 90.1 prescriptive method for determining energy performance of exterior walls has decreased the baseline proportion of vision glass from 50%, previously, to 40% of total wall area, and the 2012 International Energy Conservation Code baseline is 30% (ASHRAE).

This study examines the potential for the enclosure framing to reduce wind drift in a high-rise structure, replacing steel tonnage in the primary frame. The curtain wall represents a significant amount of building mass, weighing 10 to 15 pounds-per-square-foot on the façade of an average mid- to high-rise building. In comparison, the primary structural frame weighs 15 to 20 pounds per square-foot of floor space.

The concept of structural surface is counter to the prevalence of the non-load-bearing curtain wall skin in the modern era, and some critics have dismissed it as impractical, or contrived. E. Ford, in The Details of Modern Architecture, credits Le Corbusier’s romantic infatuation with the airplane, an invention that only came into existence during the lifetime of the first modern architects, with being the source of a modernist fixation on exposed structure for appearance’s sake (Ford). The new incentives to explore integral structure and enclosure may help illuminate the underlying appeal of the airplane: it is a construct with almost all dead weight eliminated.

BACKGROUND

As buildings that account for no net CO2-equivalent emissions in operation of their heating and cooling systems become a practical reality, minimizing ‘embodied’ CO2—emissions caused by manufacturing and fabrication of material-- by getting rid of redundant or unnecessary components will be a big next step in improving the sustainability of the built environment. Studies have estimated that the CO2-equivalent emissions embodied in a high-performance building can range from between 40% to 300% of the amount resulting from energy used during operation in its lifespan (Airaksinen & Matilainen; Thormark). In a ‘net-zero’ energy-use building, the embodied energy theoretically accounts for 100% of related CO2 emissions.

EMBODIED CO2 IN ALUMINUM AND STEEL

Using less material would suggest less embodied CO2, but some materials require more energy to produce than others. According to two industry-published metrics, steel production results in .73 tons of CO2 per ton of steel, while aluminum production results in 2.2 tons of CO2 per ton of aluminum (American Institute of Steel Construction, Aluminum Association). Other sources give different values. The Bath University Inventory of Carbon and Energy lists aluminum, with international average of 33% recycled content, at 8.16 tons of embodied CO2 equivalent per ton. Steel, which averages 59% recycled content, compares at 1.37 tons embodied CO2 per ton in the Bath index (G. Hammond & C. Jones). The object of this study is not to advocate for a particular material, but rather to advocate questioning the conventions of construction systems to find more sustainable approaches, with estimates of embodied CO2 being a significant criterion.

CURTAIN WALL AND STRUCTURAL CLADDING

Ease of construction, minimal obstruction of view and light, minimal maintenance requirement, design flexibility and, after more than a century of evolution, familiarity to builders has made the curtain wall independent of the structural frame the standard mode of enclosure on modern buildings, and this basic approach is unlikely to change in the near future (Fig. 2, Curtain Wall).

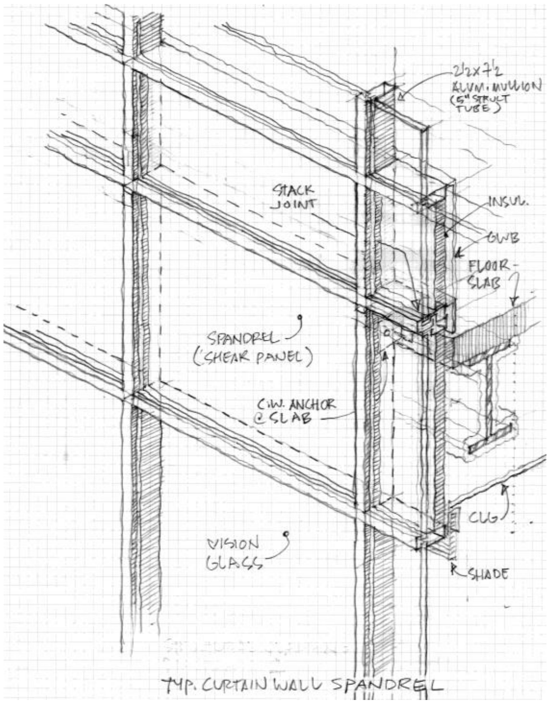

Figure 2: Typical Curtain Wall Panel Assembly.

Still, there is precedent for integrating structure and enclosure in recent and not so recent buildings. Early green houses, such as at Bicton Gardens, constructed in the 1820's, used the glass as a shell stiffening the frame of iron glazing bars (J.C. Loudon) (Fig. 3, Bicton).

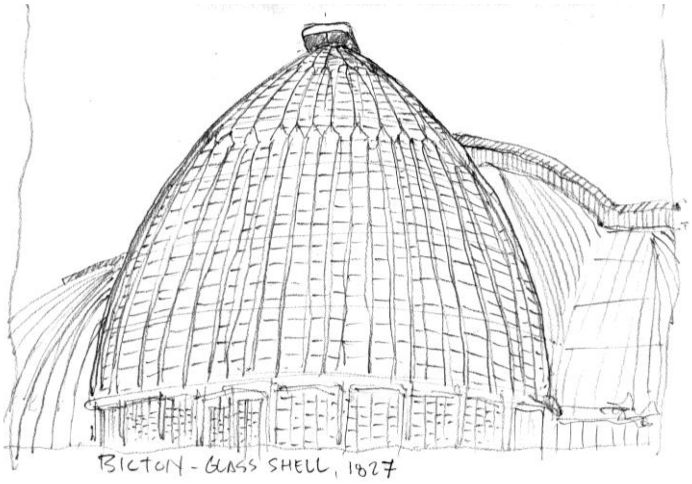

Figure 3: Palm House, Bicton Glasshouses, Bicton Botanical Gardens, Exeter Devon, England. 1820's. Thin wrought iron glazing bars form a flexible network supporting panes of glass which stiffen the enclosure by acting as a compressive shell.

There are projects from the latter half of the 20th century with facades integral to their primary structural frames, such as Corbusier's exposed concrete Unite d'habitation block (1952) and B. Fuller's Dymaxion House (1930), modeled after a grain bin of riveted sheet metal. Mies van der Rohe's steel facades of 860-880 Lake Shore Drive (1951) are engaged with the concrete and steel frame by welded studs, similar to the steel stressed-skin exterior of the Daley Center in Chicago designed by Jacques Brownson of C.F. Murphy (1964) (Fig. 4- Daley Center). During the design of the Daley Center, the structural engineers raised concerns that a continuous structural skin would have problems with thermal expansion and other building movements. Brownson argued correctly that the skin could absorb the stresses of these movements, just as welded railroad track does (Chicago Architects Oral History, and personal conversation c. 2004). The glazing frames 'float' to allow for drift and deflection of the structural wall around them.

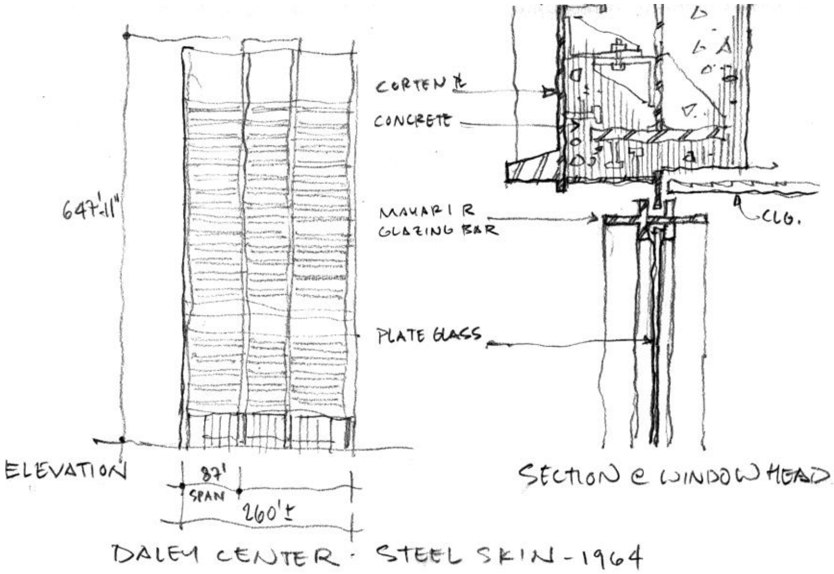

Figure 4. Daley Center, Chicago (orig. Chicago Civic Center), 1964. Joint venture C.F. Murphy Associates, Skidmore, Owings & Merrill and Loebl, Schlossman, Bennett & Dart. The Cor-Ten steel skin is structural, acting as formwork for the concrete encasing the steel frame, in an assembly similar to the steel cladding and composite frame of 860-880 Lakeshore Drive (1951), by Mies van der Rohe. The steel skin intentionally contributes to the stiffness of the tower against wind.

The structural tube concept employed in tall buildings since the 1960's uses the enclosure as lateral bracing and for gravity loads, creating what the engineer W. LeMessurier called the steel or concrete "bearing wall," (LeMessurier). This perimeter wall was thicker than the curtain wall, and had a much greater percentage of opaque surface than the normal frame enclosure.

The 54-story Dravo Tower, by Welton Becket and Lev Zetlin Associates, built in 1984 in Pittsburgh, is a perimeter-framed tube with unprotected painted steel plate cladding that forms a stressed skin limiting wind-induced sway. The steel skin is not relied upon for any code-required strength, but provides comfort-related limit of drift (Tomasetti). Port hole-like window openings in the steel plate were glazed with gaskets, and the 3-story by 10' plates were attached using neoprene seals. According to the designers, the stressed skin allowed reduction of the depth of spandrel beams.

In the last decade or so, a number of researchers have explored the potential for double façade armatures to become structural cages contributing to the stiffness of high-rise buildings, limiting wind-induced drift (Moon; Azad & Samali). There were studies published in the 1980's and 1990's on the idea of using cladding connections to dissipate seismic energy by using springs or friction devices in the anchors (Whole Building Design Guide; Cohen & Powell). However, this work has been mostly speculative. Double facades are expensive and it is difficult to quantify their performance. Shock absorbers for cladding connections may work, but they are, almost 50 years after viscous dampers were installed at the perimeter of the World Trade Center Towers, uncommon in buildings. The influence of these concepts on the conventions of commercial construction has been limited because of their complexity and high initial cost, the problems of exposing structure to the elements, and the floor-space they take up.

The framed-tube model that uses closely spaced columns to create a dense perimeter wall has drawbacks of limiting view and flexibility, and the few projects that employed steel stressed skin cladding had limited influence. Maintenance and thermal bridging are two common problems with exposed steel, along with fire-safing and initial cost. It could be more practical to make structural use of the material already typically in place on the building surface in the market's preferred construction model-- the long-span frame and the curtain wall-- if there is sufficient structural capacity in this thin layer.

METHOD

DESIGN INVESTIGATION

The current proposal adds a stiffening membrane over a moment frame with a braced core. The wall only limits drift for comfort's sake, which would improve serviceability—wear and tear—of the skin as well. This keeps the skin distinct from the primary structure, with the advantages of separating design and construction of different types of assemblies: heavy primary structure can be built to a different set of tolerances and finish standards than surface, and design of the primary frame can be developed for beginning construction without finishing the skin design. Gravity members, columns as well as elements that brace them against buckling, are separate from lateral bracing, consistent with the way the building code has historically not required fire protection for structural members designed to take only lateral wind or seismic force. The concept could be expanded to include primary structure, and in construction temporary lateral bracing of the frame could be removed when the structural skin is put on. The spandrel and column-cover area of the façade could easily incorporate fire protection if necessary (**Fig. 5**, Opaque Assemblies on Spandrel & Column Cover).

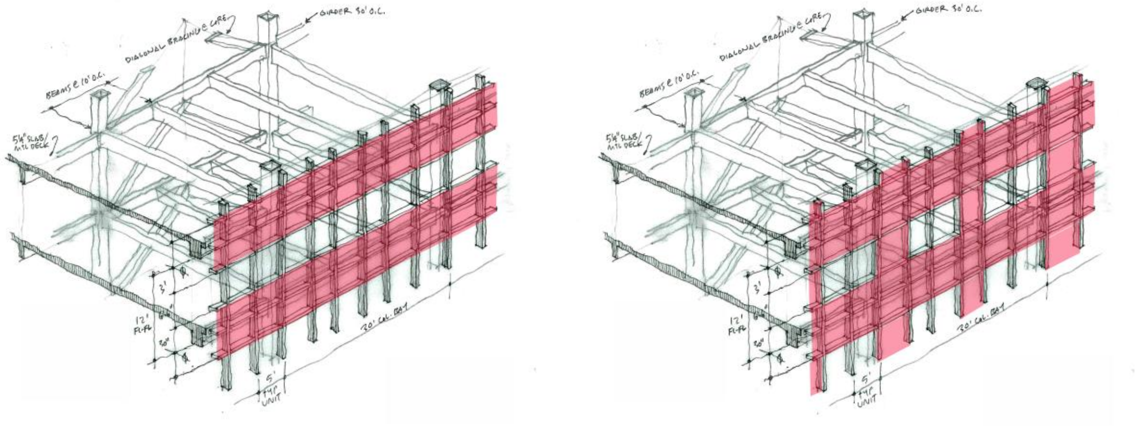

Figure 5: Varying degrees of opacity and structural potential on the elevation correlate to spandrel area; spandrel and column area.

The aluminum mullions in the façade would be too flexible to control inter-story displacement adequately, so the structural body of them is replaced with steel. With the column covers included in the diaphragm area, only two mullions per bay are exposed. With intumescent paint or other cover for fire protection, if necessary, these could contribute to the façade stiffening.

A 2x5x5/16 HSS (8.15 plf) is used for the mullion, and a ¼" steel plate infill occupies the spandrel area in the first iterations of the structural model. Lighter ½"-diameter rods replace the plate in the final scheme. The rods could extend to the vison area, which would increase the strength of the system. The HSS is about 50% heavier than a standard aluminum mullion (which is about 5 plf).

The glazing frame part of the enclosure will still be aluminum (Fig. 6, aluminum mullion and aluminum-and-steel hybrid). This hybrid assembly uses the two materials for their respective advantages—aluminum for its malleability, facilitating extrusion into shapes that receive gaskets and fasteners, and for its corrosion resistance at the weather surface; steel on the interior for its stiffness and strength. This is in the spirit of recent developments in automobile manufacturing that employ steel and aluminum and other structural materials in combination according to their different properties in 'lightweighting' strategies for improving mileage and fuel efficiency, such as putting aluminum bodies on steel frames in small trucks. The assembly is similar to 'piggy-back' arrangements used on spaceframe enclosures and monumental façade systems for many years.

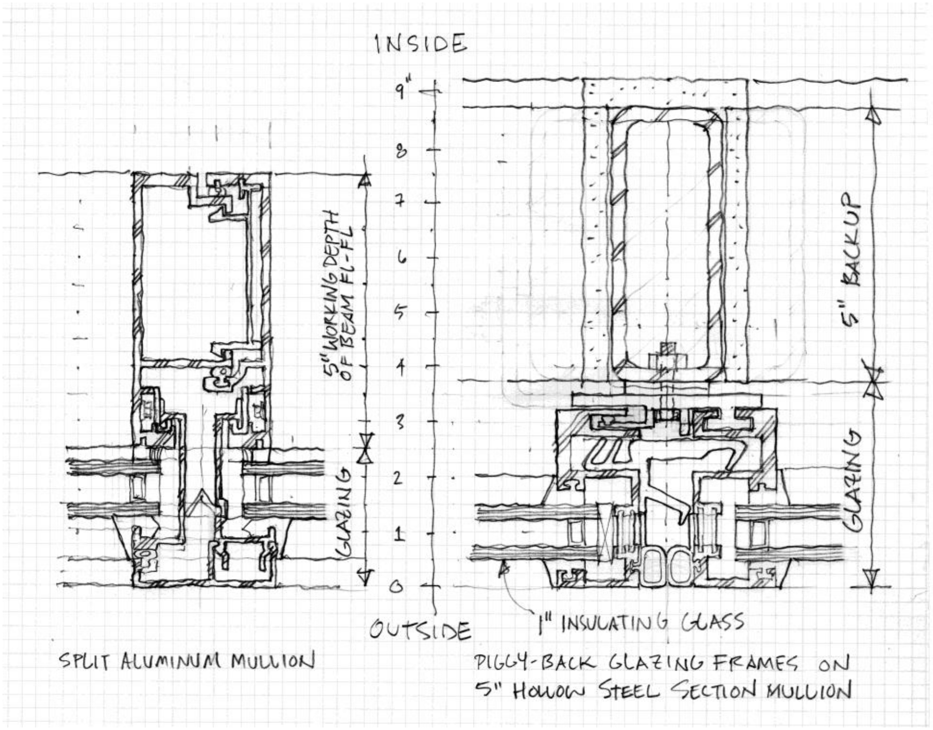

Figure 6: Plan of aluminum split mullion, and aluminum cassette frames on steel backup mullion.

Aluminum has been the default choice of material for framing in the non-load-bearing curtain wall. Aluminum has higher strength relative to weight than steel, is more corrosion resistant, and is easily worked and extruded to receive gaskets and fasteners. However, aluminum is only a third as stiff as steel, most aluminum alloys are not as strong as steel, it costs more per ton than steel, and it has more embodied carbon per ton than steel. It is also more conductive than steel, creating higher levels of thermal bridging. The smaller carbon footprint per ton of steel relative to aluminum is offset by the greater weight by volume of steel—a cubic foot of aluminum weighs about 170 pounds, a cubic foot of steel weighs 500 pounds.

The infill panel in the structural skin would occupy the same space as the conventional spandrel panel of glass or metal. Connections could be accomplished with stick-framed or unitized steel panels. The system proposed can function with a basic stack joint splice at each floor line designed to accommodate live-load deflection and to take shear and moment. (Fig. 7- Slab Edge Detail Sketch).

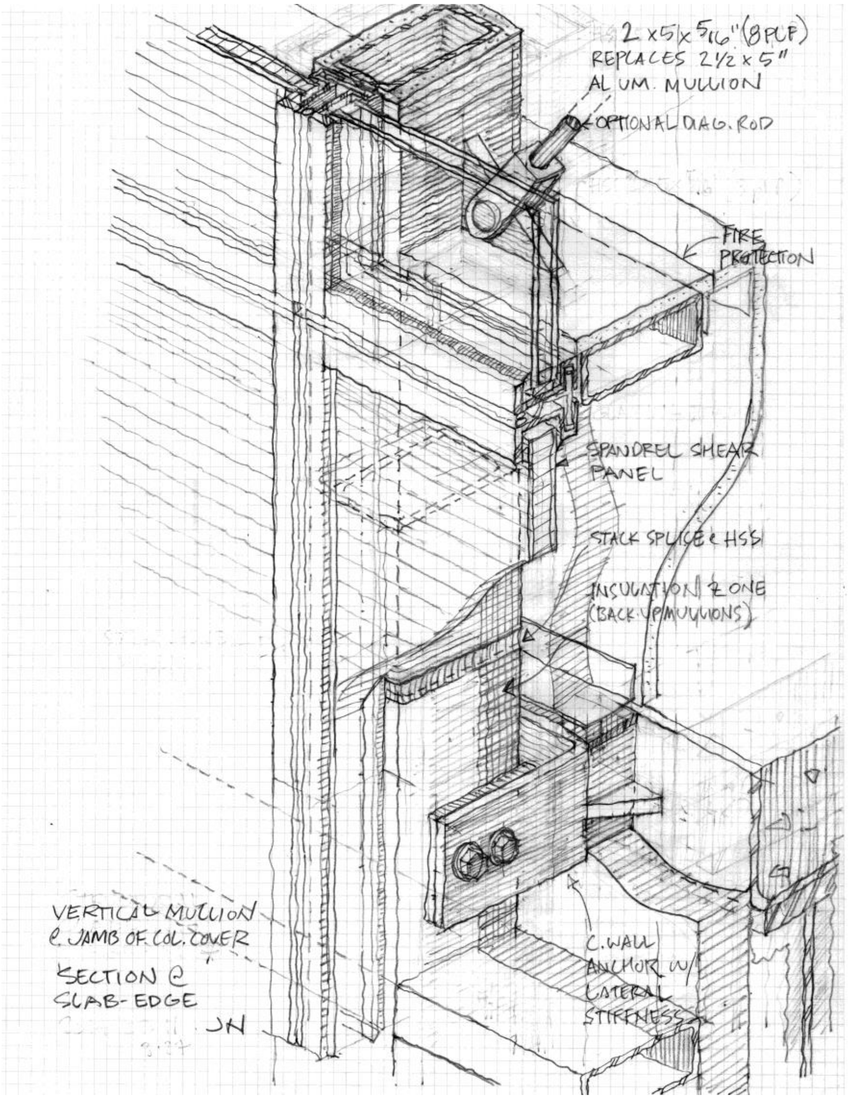

Figure 7: Cutaway sketch of wall at slab-edge.

CASES

The schemes analyzed here were devised in a collaboration between architect and engineer. The variations on the infill panel follow the architectural outlines of common spandrel or column cover areas, relating to the energy code limits on vision glass. The engineering balanced capacity of members and connections and attraction of load, suggesting schemes mixing panels and rods.

To assess the structural potential of the skin, we take a simplified 24-story braced frame with a 90’x90’ footprint. In the variants on the structural enclosure framing, we look at capacity to reduce drift, excluding the ground floor enclosure to leave access unimpeded. Wind load is based on 115 mph 3-second gust.

With a floor plate based on a 3-bay 30’ structural grid, the face of the exterior wall offset from center of structure making the footprint 95’ face-to-face, and a floor-floor height of 12’, with a 4’ parapet, the area of the exterior wall is 106,400sf. (380 lf of perimeter x 12’ fl-fl= 4,560 sf of wall/ fl x 23 flrs = 104,880sf of wall plus 4-0”” parapet x 380’= 1,520 sf).

The study comprises four structural scenarios which were modeled in the structural analysis program ETABS. Comparisons of tonnage of steel (in kips), tower deflection and total embodied CO2 in the primary structure and the cladding framing are shown in Figures 13, 14 and 15.

DATA

CASE 1

Braced frame designed to take all wind load in conventional fashion, as a baseline for comparison (**Fig. 8,** 3-D model view from ETABS, drift by story and elevation diagram with deflection). Total steel in kips = 3183. Maximum deflection approximately 7.5” or H/460. The total aluminum in the base-case curtain wall enclosure can be estimated at 2.25 psf x 106,400 sf= 240 kips. (27 lf of mullion per 5’ x 12’ panel at 5 plf = 135 lbs/60= 2.25 psf. This does not include the aluminum in the glazing or cassette zone common to all of the cases). Total tons of embodied CO2= 1,162 for steel, plus 264 for aluminum = 1,426, per industry metrics.

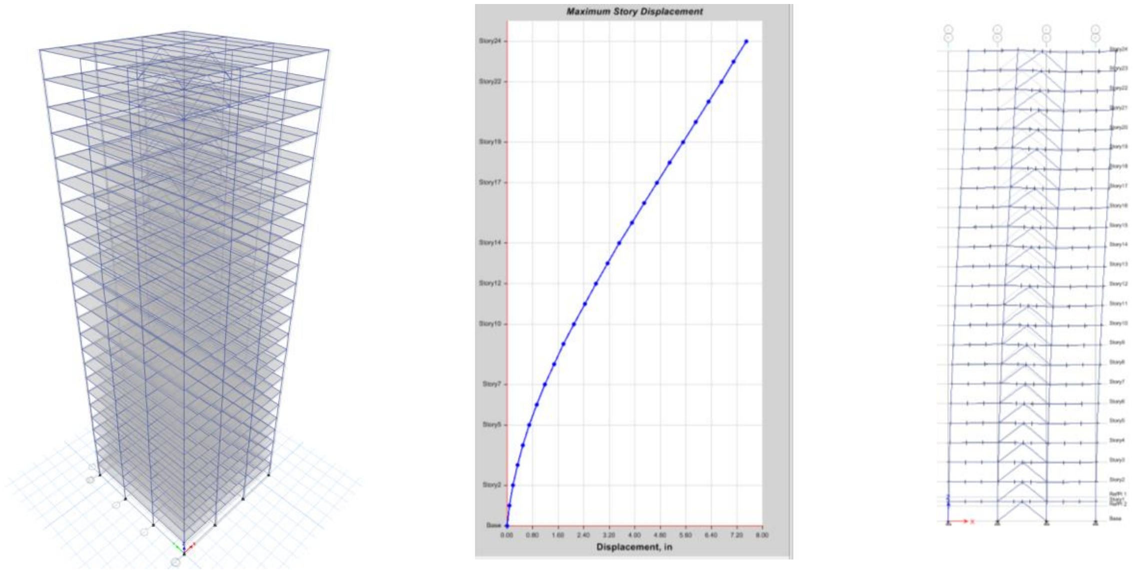

Figure 8: Case 1, 24-story Braced Frame. 3-D view of ETABS model, wind drift graph and elevation diagram showing deflection under wind load. (HOK).

CASE 2

Braced frame with structural cladding, 67% opaque surface moment-frame structural mullion network with plate infill on spandrels and columns. (**Fig. 9,** 3-D model view from ETABS, drift by story and elevation diagram with deflection). The primary frame is reduced in strength and weight from Case 1. Total steel in kips= 2,909 in the frame, and 1,349 in the structural cladding. Maximum deflection of approximately 3” or H/1,152. This is extremely stiff. The degree of fixity of the connection of skin to frame is reduced along with extent of shear plate in the next case. Total tons of embodied CO2= 1,554 for steel, per industry metrics.

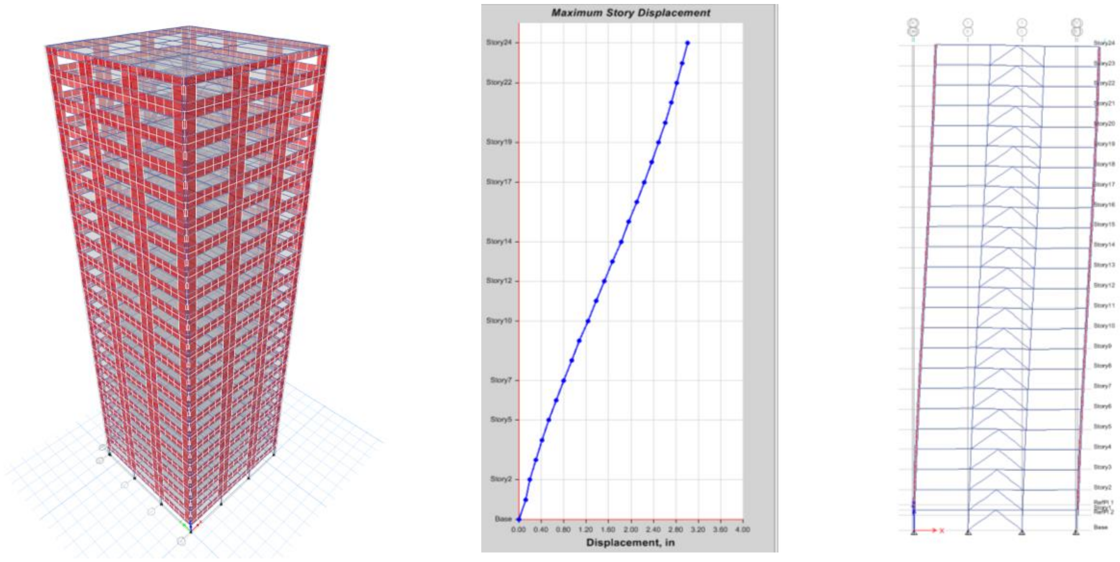

Figure 9: Case 2, 24-story braced frame with steel plate structural cladding. 3-D view of ETABS model, wind drift graph and elevation diagram showing deflection under wind load. (HOK).

CASE 2 BRACED FRAME ONLY

The Case 2 reduced-weight frame without any cladding illustrated the magnitude of the cladding's contribution to stiffness. Total steel in kips = 2909 in the frame. Maximum deflection was approximately 11" or H/300. This is significantly more than the normal range of H/400-600 for wind drift of structures clad with curtain wall.

CASE 3

Braced frame with structural cladding, 67% opaque surface moment-frame structural mullion network with plate infill on columns, x-rod bracing on spandrels. (**Fig. 10,** 3-D model view from ETABS, drift by story and elevation diagram with deflection). Total steel in kips = 2,944 in the frame, and 988 in the structural cladding. Maximum deflection of approximately 6" or H/575. This is at the high end of the normal stiffness for wind design. Total tons of embodied CO2= 1,435 for steel, per industry metrics.

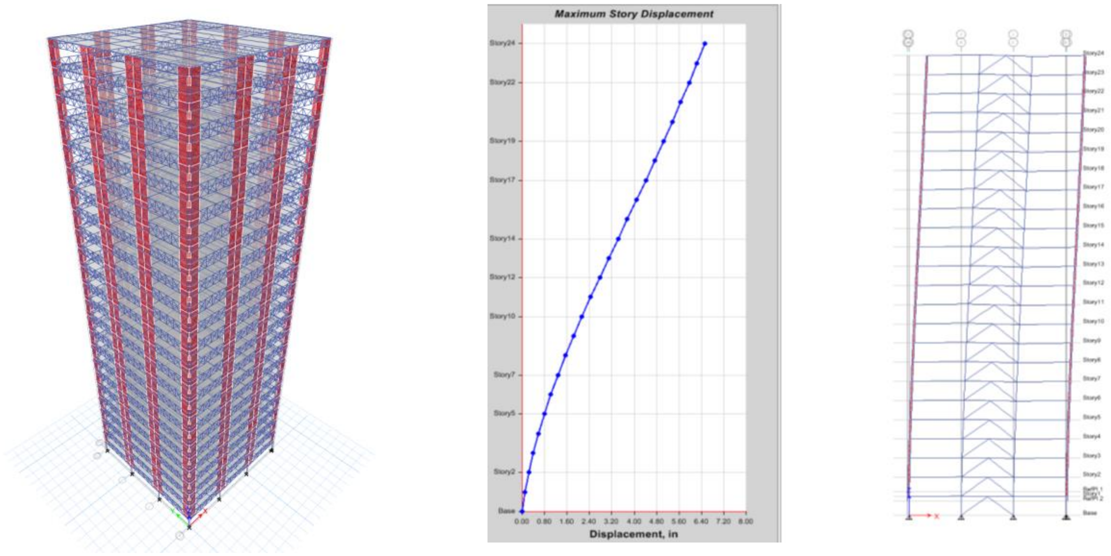

Figure 10: Case 3, 24-story braced frame with steel plate at columns and x-rod braced structural cladding. 3-D view of ETABS model, wind drift graph and elevation diagram showing deflection under wind load. (HOK).

CASE 4

Braced frame with structural cladding, 67% opaque surface moment-frame structural mullion network with x-rod bracing. (**Fig. 11**, 3-D model view from ETABS, drift by story and elevation diagram with deflection). Total steel in kips = 2,921 in the frame, and 601 in the structural cladding. Maximum deflection of approximately 7.5” or H/460. This is at the low mid-range of the normal stiffness for wind design. Total tons of embodied CO2= 1,285 for steel, per industry metrics.

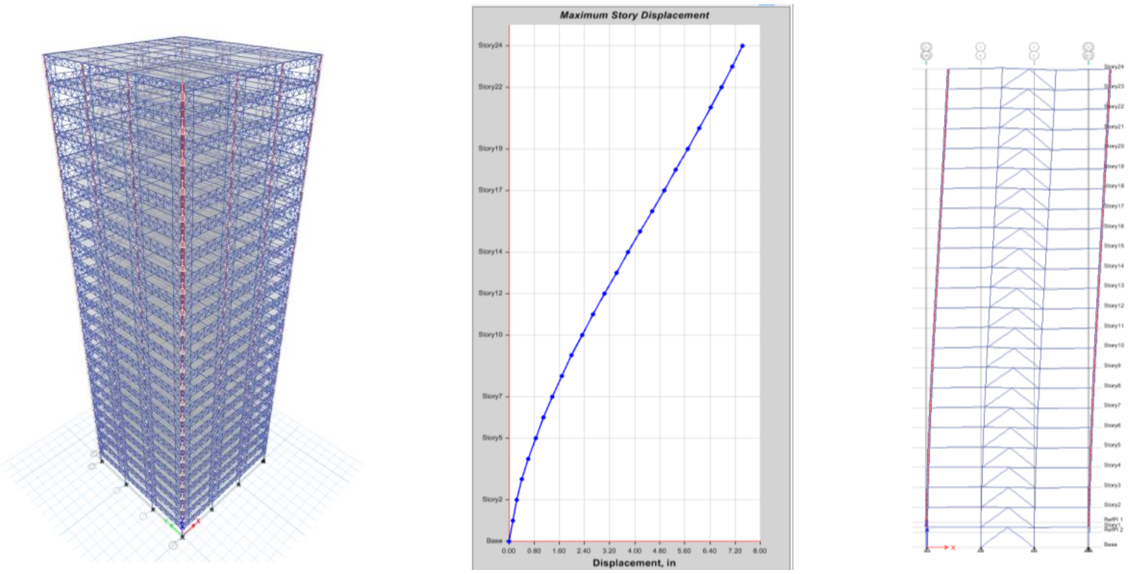

Figure 11: Case 4, 24-story braced frame with x-rod braced structural cladding. 3-D view of ETABS model, wind drift graph and elevation diagram showing deflection under wind load. (HOK).

All of the structural cladding schemes function as a thin moment-resisting framework. The force diagram from the structural model of Case 4 shows how the members react to wind acting from the left (**Fig. 12**, Typical floor of cladding framing showing stresses).

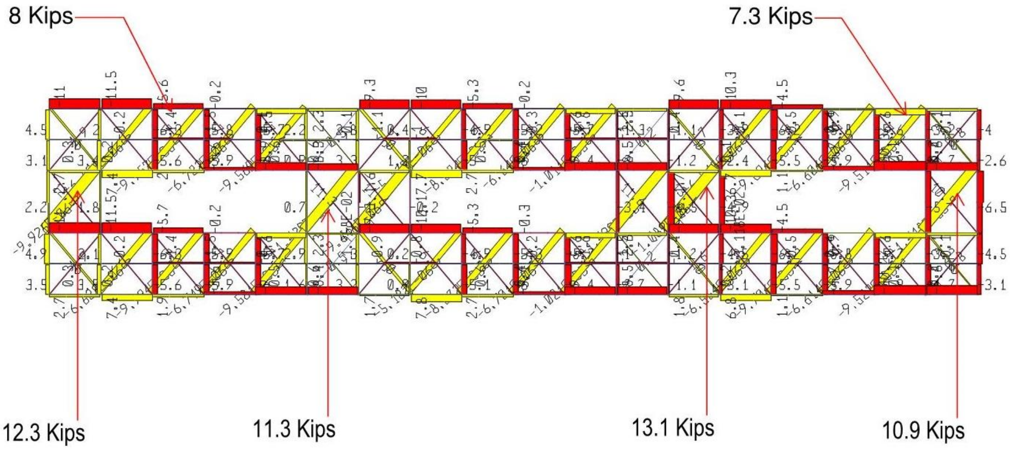

Figure 12: Case 4, 24-story braced frame with x-rod braced structural cladding. Elevation diagram of typical floor (Level 16) showing stresses under wind load. (HOK).

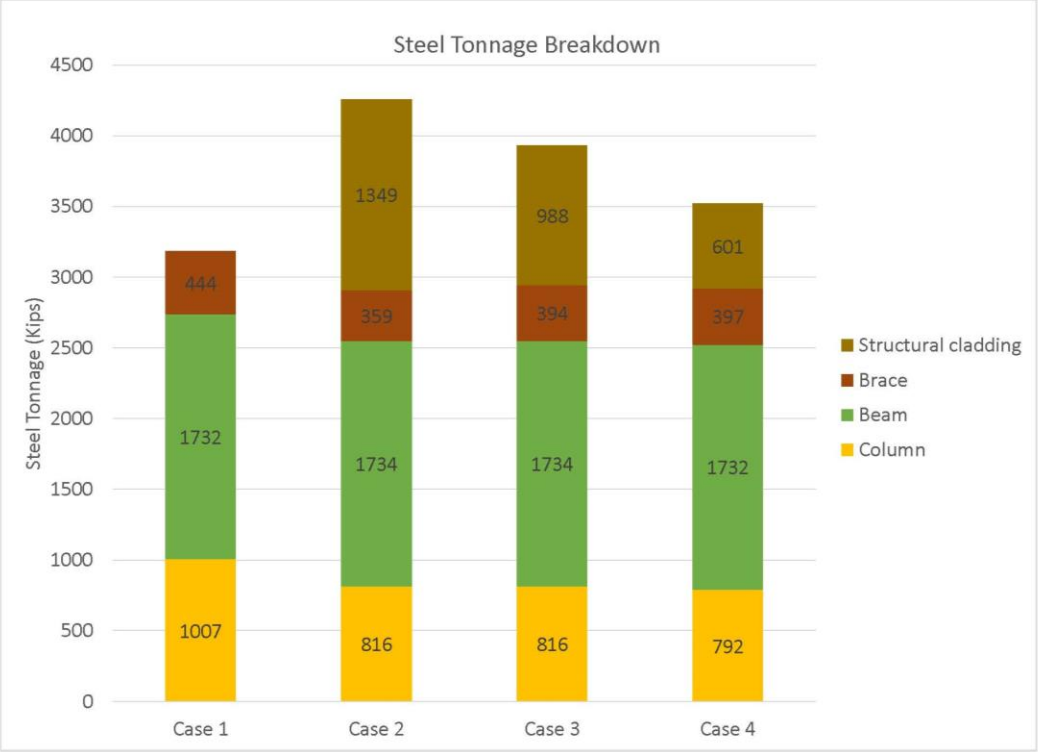

Figure 13: Steel tonnage comparison. (HOK).

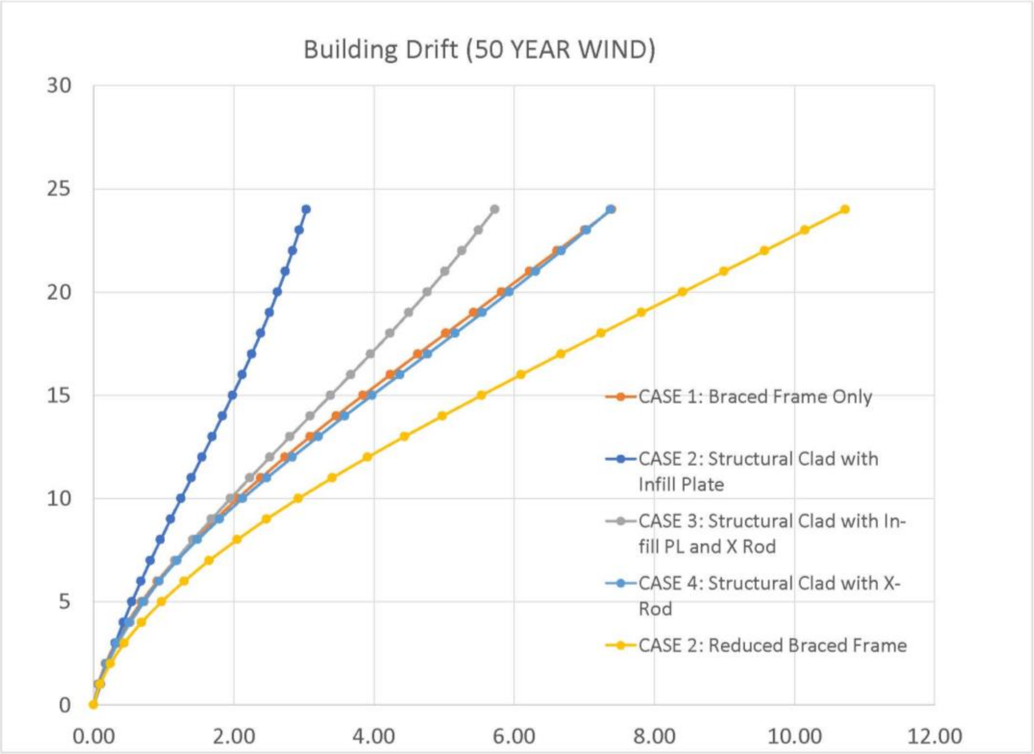

Figure 14: Deflection comparison. (HOK).

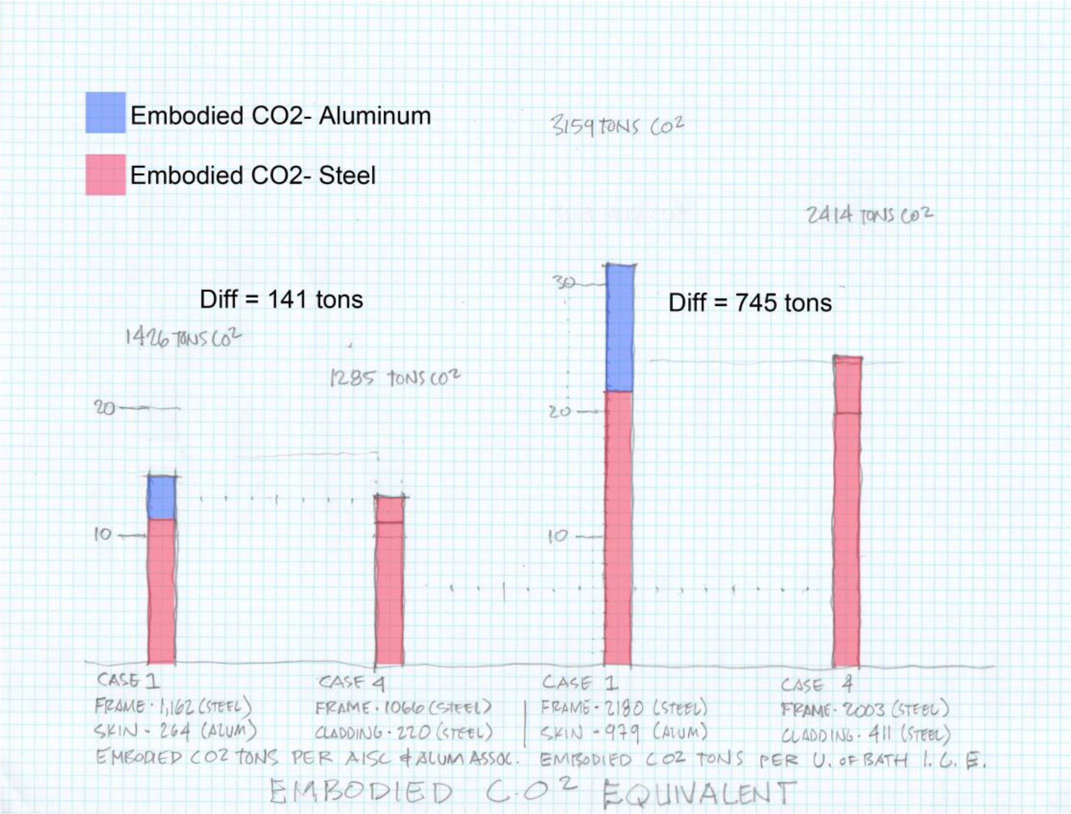

Figure 15: Embodied CO2 comparison, Case 1 normal Braced Frame and Case 4 reduced stiffness Braced Frame with structural cladding, embodied CO2 per AISC and Aluminum Association and according to Inventory of Carbon and Energy, Bath University.

EXPLANATION

Case 4 with x-rod bracing in the cladding framing saves about 140 tons of embodied CO2 relative to the base case, using the industry-published metrics for steel and aluminum, or roughly 10% of the total, which is not a great deal but is still measurable. Using the University of Bath Inventory of Carbon and Energy metrics, the structural cladding produces a savings of 745 tons of embodied CO2, or almost 25%. With refinement of the structural cladding concept, this result will improve.

FUTURE WORK AND CONCLUSION

FURTHER STUDY

Despite the extreme thinness of the conventional building enclosure, structural cladding of that nominal thickness works to provide lateral bracing and reduce the weight of the primary structural frame, and the concept has potential for development. Next steps for research would include (Fig. 15, Notes on further study):

- Detailing of connections that could control stiffness of the skin to avoid attracting too much force, also potentially damping drift with flexible or soft connections.
- Thermal analysis of connections.
- Shaping of the building surface to create intrinsic stiffness of curved or folded forms that could enhance the capacity of the surface membrane.
- Study of larger bracing configurations to improve efficiency.
- Capitalizing on the compressive strength of glass itself.

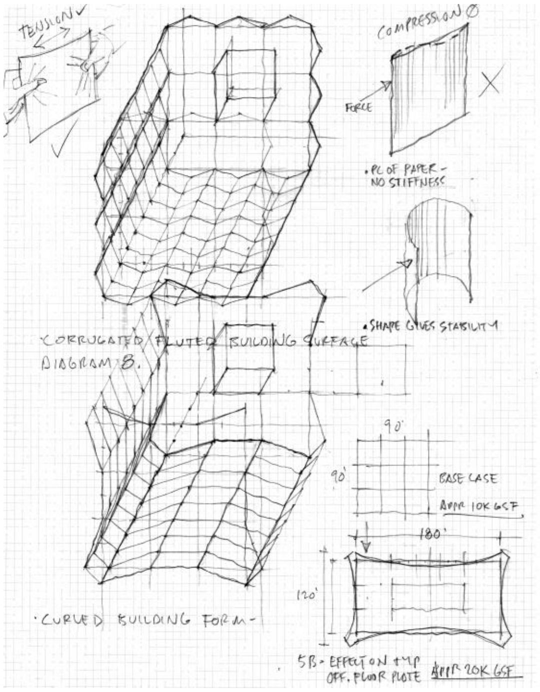

Figure 15: Future study will examine the potential for structural contribution of curved and corrugated surfaces.

CONCLUSION

Since Greenough, Ruskin and Sullivan connected form and function in the 19th century, modern architectural theorists, including engineers like Nervi and Arup, have argued for honest expression of structure as an ethical and aesthetic imperative (Greenough; Ruskin; Sullivan; Nervi; Arup). Meanwhile critics, such as Ford in his Details of Modern Architecture arguing that modern building is by nature layered not monolithic, and G. Scott in The Architecture of Humanism at the start of the 20th century, who critiqued the ideal of expression of structure as a “mechanical fallacy,” have treated this as a naive idea (Ford; Scott). It seems clear that the potential advantages, in terms of sustainability, of making surface into visible structure suggests that aesthetics—the appeal of seeing structure-- should be heeded as a promise of functional benefit in architecture.

The re-integration of structure and cladding seems to resonate with the words of Eiffel when he wrote:

> *Because we are engineers, is one to believe we give no thought to beauty in our designs or that we do not seek to create elegance as well as solidity and durability? Is it not true that the very conditions that give strength also conform to the hidden rules of harmony?* The Eiffel Tower. (Eiffel)

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