INTRODUCTION

Emergence of curtain walls has produced a distinct change in the approach to achieving performance criteria. Curtain walls have been around for over a century; however, they still present a challenge for building designers, curtain wall manufacturers, and installers. Typical sources of confusion are structural tectonics, façade control functions, and division of responsibility. Curtain walls concentrate all essential protective shield functions of a building envelope in a lightweight, thin, impermeable, and sometimes vulnerable shell, many times thinner than the respective load bearing walls, and include individual components responsible for performing dedicated functions.

MAIN BODY

1. General Description

History: Introduction of the curtain walls was caused by the following needs:

- Smaller wall footprint = resulting in extra floor area available for occupants
- Parallel scheduling = resulting in faster erection
- Lighter structure = resulting in material and transportation savings
- Structural flexibility= resulting in easier seismic engineering
- Improved light access = resulting in a more flexible and economical architectural layout
- Structural independency= resulting in a more flexible architectural layout

Their development was allowed by industrialization and growth of prefabrication concept in the early 19th century and expressed in the first large fully glazed structure (Crystal Palace, London, United Kingdom) in the year 1851 and the first independent frame building (Menier Chocolate Factory near Paris, France) in the year 1871 (Alan J. Brokes, 2003). Half a century later, the best brains fleeing the conflict-engulfed Europe transmitted the new technology into the industrial and financial hubs of the U.S.

Fundamental Classification: Curtain walls, in the structural sense of the expression, come in a wide variety of materials and systems, escaping attempts of rigid classification. The type of a wall is not always obvious to an observer. Nowadays, even building facades built of bulky materials, traditionally associated with the load-bearing function: e.g. stone, brick, and concrete, are commonly built as non-load bearing shells hung on a building structure. A brick veneer is a good example. On the other side of the spectrum lie tensioned cable walls, characterized by a very efficient use of materials, high transparency, high flexibility, and high loads imposed on the main structure.

However, the name “curtain wall” became commercially associated with a light secondary rigid framing system filled or covered with a lightweight cladding. Classification of this narrow group of curtain walls may follow many different characteristics:

- By place of assembly: stick systems, unitized, semi, etc.
- By function: fire rated, acoustic, blast resistant, etc.
- By mullion materials: wood, steel, aluminum, composite, glass, etc.
- By mullion type: tubular, truss, cable, structural glass, etc.
- By glass type: reflective, low-iron, anti-reflective, etc.
- By glass attachment: captured, structural, semi, planar, etc.
- By glazing access (for replacement): internal, external.
- By configuration: single, double skin, freeform.
- By heat transfer: warm, cold, thermally improved, thermally broken (or the material group per DIN 4108 standard).

As many specification writers are well aware, even classification of this, relatively narrow group of curtain walls may present a challenge. An example of possible ambiguity is the adjective “structural” used in the expression „structural curtain wall.” It’s traditionally interpreted as a description of the characteristic of the adhesive used for bonding glass to its framing substrate. More recently it became used to describe the desired characteristics of glass used to build the frame itself (as opposed to the infill material) sometimes without use of any adhesive material. (See Figure 1). Some countries developed early code-referenced standards and glossaries, e.g. UK, Germany, China, and Australia. (e.g. EN 13119: Curtain walling – Terminology. 2007)

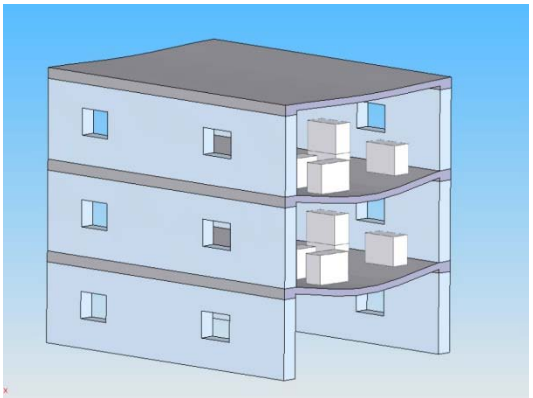
Figure 1. Example of the vocabulary challenge. The structural glass wall, with horizontal structural glass mullions suspended on stainless steel cables. The glass fins play structural role by resisting lateral load, as opposed to the traditional load-collecting role of glass. No structural sealant used here.

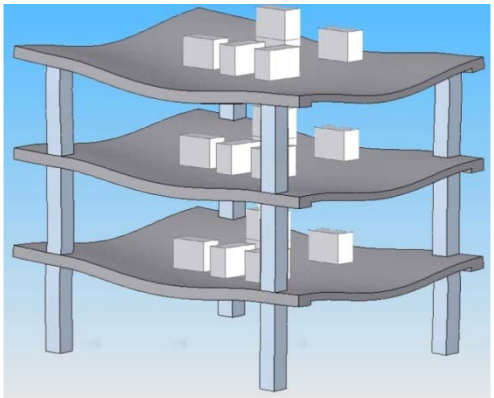
2. Differential Movements

In this author’s experience, interactions between building facades and structure are notoriously disregarded in the design phase. Analysis of loads, their transfer, differential movements, and coordination between structure movements and the architectural shell are required in early stages of design, and the structural considerations may greatly influence the architecture. Their oblivion is unfortunately manifested in field failures, ranging from persistent leaks of inadequately designed seals to rare but spectacular collapses caused by inadequate joinery. (See Figure 12). Emergence of the façade engineering as a separate specialized discipline owes much to this sad state of affairs, as designers and contractors found themselves overwhelmed by the complexities of high performance facades (Ledbetter, 2001).

Load capacity: Load resistance is the most distinguishable characteristic of curtain walls. They are incapable of carrying any vertical load from the building. On the opposite side of the spectrum lies a load bearing wall that can be compared to a stack of compression-resistive building blocks supporting a gravity load of building structure placed atop.

Movements: The introduction of a ductile frame to replace rigid load-bearing walls increased a building’s freedom of movement. While loads generally remain the same, the biggest difference between having a window punched in a load-bearing wall and having a curtain wall lies in the exposure to movements of the building. There are three movements to be considered: vertical, lateral in plane of a wall, and lateral normal to a wall plane. The movements are typically defined by the span ratio; therefore the extension of structural spans recently seen in modern structures significantly increased the deflection building components must accomodate. The typical live load movement limits of the main frame are often expressed by building codes in terms relative to the length (or height) of a deflecting component: as in L/360 for the simple span , L/240 for cantilever, H/300 for story differential movement (International Building Code, 2006). (See Figures 2 and 3). Similarly, the typical live load movement limits of a curtain wall would be expressed by ratio relative to the length of a deflecting component, as in L/180 for the lateral mullion deflection normal to a wall plane, or L/50 glass deflection with respect to the shorter edge of a pane. Upper thresholds often apply to longer spans, e.g. 1 inch [25.4mm] often limits the glass deflection.





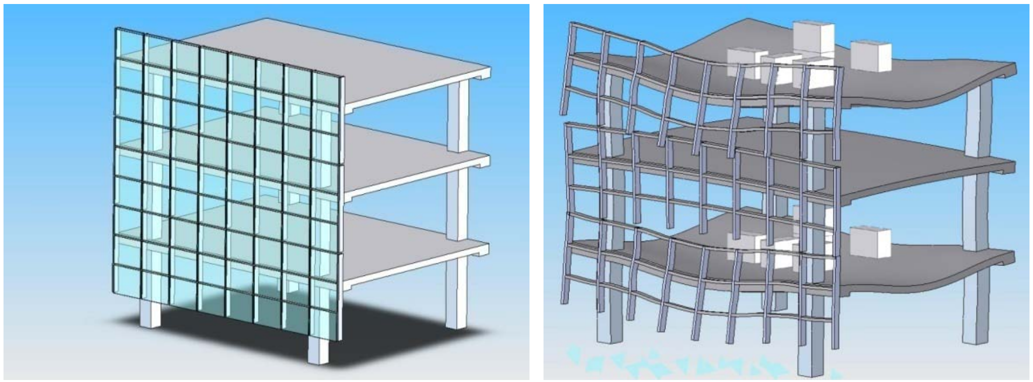


Figure 2. Vertical movement of building structure. Note the difference between a rigid load bearing wall (upper left picture) and the flexible frame support.

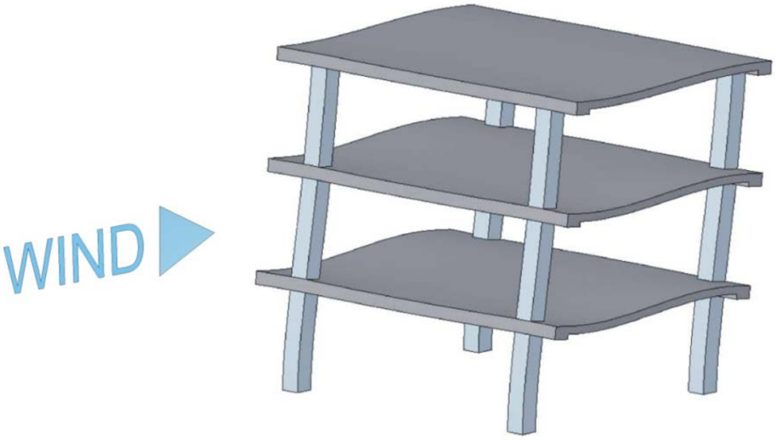


Figure 3. Horizontal movement of building structure. Frame is generally more flexible than walls.

A simple calculation reveals that an L/360 live load sag in a middle of a 30ft [9.144m] simple span reaches 1 inch [25.4mm]. This differential vertical movement would need to be accommodated by a curtain wall hung on the spanning structure. It would also need to be accommodated by all functional façade control layers spanning this movement joint. E.g. such a vertical differential deflection (which is often one of the most violent differential movements experienced in buildings located outside seismic zones) could destroy a roofing flashing between a parapet wall and adjacent roofing. A proper solution would be to design a parallel curb and locate the roofing movement joint atop. This author has commonly identified this problem in architectural details he has reviewed.

An architect, upon discovery of the magnitude of movement may turn around and direct the structural engineer to design a sturdier, more expensive structure. However, in this author's experience, this communication seldom takes place – the interested reader is directed to the discussion about communication in the paragraph #4 below. A non-coordinated structure moving in excess of the curtain wall capabilities would cause it to share the structural loads. The curtain walls are not intended to share structural loads from a building frame. Curtain wall manufacturers typically provide a maximum 1/2in. [12.7mm] differential vertical movement allowance in their off-the-shelf systems, and disclaim warrantability of structure movement. The above examples identified typical issues associated with the vertical movement of the main frame only. Similar analysis is required for live loads with respect to the two lateral movement degrees of freedom. This author observed a tendency to detail and dimension corner cladding joints (e.g. mitered) in a way that restricts the design movement. This may lead to spalling, fracture, and collapse of stone cladding at building corners.

The same joinery needs to allow for tolerances of adjacent assemblies, which in case of some field-fabricated components may be very poor (Ballast, 2007). For example, ±1 inch [25.4mm] tolerance of field cast concrete is often assumed in fabrication of curtain wall anchorage. This author has observed many failures stemming from lack of consideration for differential movements (Kazmierczak, 2008).

Once the main frame movement is analyzed, the next step should be analysis of movements of the curtain wall, including thermal movements. The decoupling of the outer shell layers from the relatively stable building interior by thermal isolative layers caused more volatile thermal movements. (See Figure 4). This effect is compounded in mullions, as they are of greater dimension (Hinks and Cook. 1998). These movements are particularly challenging in systems where the wind-resisting framing is placed outboard or split by a thermally isolative layer.

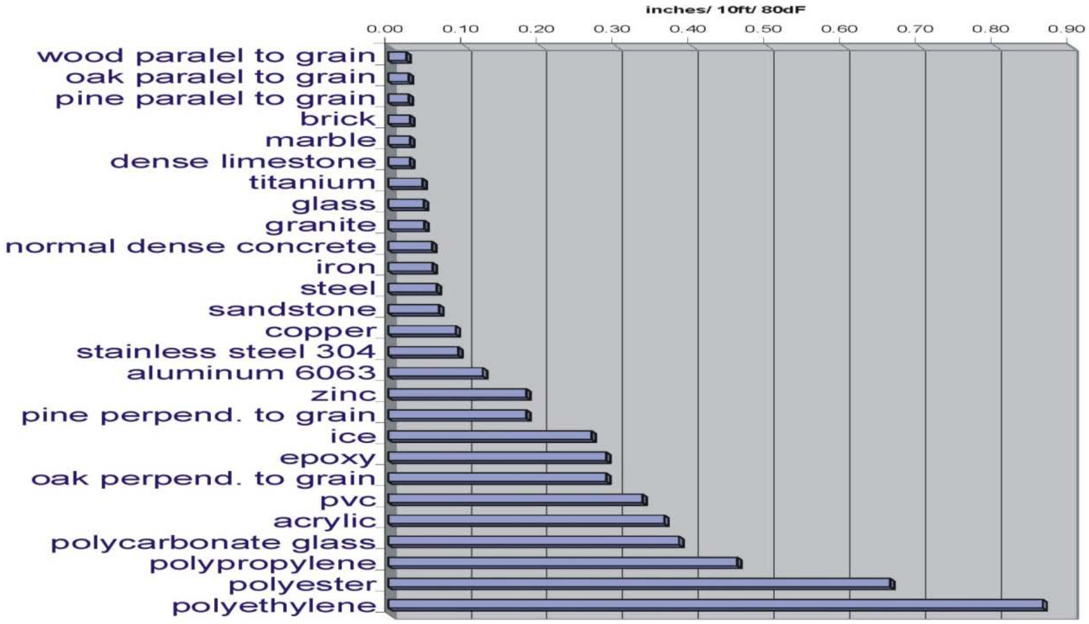


Figure 4. Thermal movement of a 10ft long piece of a material subjected to an 80°F temperature differential.

A capable joinery employed to accommodate the movements is the key to wall's integrity. A wall is only as good as its weakest component, which almost invariably happens to be joinery. Seals of the systemic joinery and intra-system transitions should perform all the required façade protective functions and allow for free movement. (See Figure 6). The recognition of this principle led to development of many well-performing detail solutions seen in the off-the-shelf foreign systems and sophisticated domestic custom curtain walling, (ranging from use of a dedicated inserts and collars of elastomeric membrane coupled with generous overlaps). These solutions are contrasted with the poorly performing details characterized by a single sealant joint performing all façade control functions, subjected to differential movements in excess of its elasticity, and interrupted at every anchor and corner, with another sealant joint placed in the back, attaching to a non-continuous substrates (horizontal mullion) and interrupted at every anchor and corner. This solution was publicly identified as incorrect in America almost 30 years ago (R.L. Quirouette, 1982). Unfortunately, this solution is still seen prevalent in domestic manufacturers' catalogs and stems from misunderstanding of functions performed by curtain wall components and the exact location of the boundary between wet and dry environments. (See Figure 5).

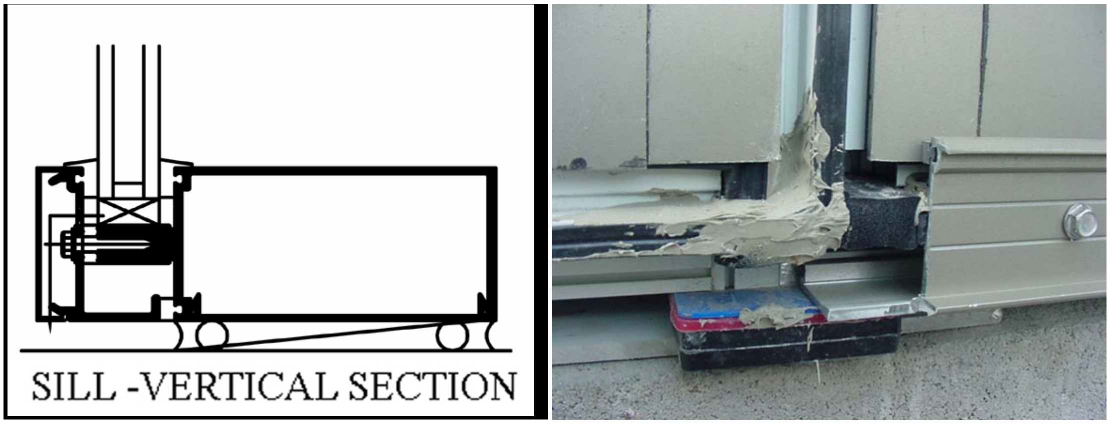


Figure 5. A typical vertical section detail of exterior wall's sill and a photo of the same condition in the field. The front sealant joint is discontinued at every anchor and corner. The back sealant attaches to horizontal mullion which is discontinued at corners and forms gaps at every end. Both sealant beads have insufficient substrate width. The sealant joints, traced 360° around the fenestration perimeter, would typically not withstand the differential movement. The horizontal aluminum leg bridges the mullion thermally. Field-applied systemic sealant separates wet and dry zones of the curtain wall.

3. Façade Functions

Occupants and users of a building expect walls to protect their interiors from external adversary forces. It would be logical to design building enclosures (not just curtain walls) to address their expectations.

The external skin, freed from load- bearing function, acts purely as a building envelope, protecting the interiors from forces, such as:

- Rain – controlled by e.g. waterproofing, seals, and screens
- Sun - controlled by e.g. shading and coating
- Heat Flow -- controlled by e.g. thermal insulation, low emissivity and absorbtivity surfacing
- Light- controlled by e.g. shading and coating
- Wind - controlled by continuous path of a structural resistance
- Windborne Debris- controlled by opening protections
- Blast - controlled by a continuous path of a structural resistance
- Water Vapor - controlled by configuration of vapor retarding and permeable layers
- Air flow - controlled by air barriers
- Aggressive Airborne and Waterborne Chemicals - controlled e.g. by adequate coatings
- Wildlife – controlled by e.g. bird nets, termite barriers, baffles, etc
- Dirt Accumulation – controlled e.g. by sloping configuration, hydrophilic surfaces.
- Snow - controlled e.g. by sloping, parapet, and ledge configuration, heat traces, etc.
- Flood - controlled by e.g. openings
- Hail - controlled by resistive layers
- Earthquakes – controlled by e.g. ductility and movement joints
- Noise and vibrations- controlled by e.g. addition of mass, damping, skewing and distancing layers
- Maintenance Loads - controlled by means of access and continuous path of a structural resistance
- Fire – controlled by e.g. thermal resistive layers
- Smoke– controlled by e.g. smoke and air resistive layers
- Theft – controlled by e.g. organic glazing layers , shutters, steel plating, and openings hardware
- Normal Wear and Tear – requiring e.g. maintenance and inspection access

The list of priorities will vary depending on project requirements. The façade functions should be considered in conjunction with each other because they overlap. A detail solution would be only as good as a research preceding its development. A solution overlooking a force would most likely fail once exposed to it. Plastic foams are the recent example (Bomberg and Lstiburek. 1998) These functions should not only be addressed by dedicated components of a building enclosure but also remain continuous throughout the entire section of the shell. Each function may be represented by a line and traced on façade drawings for continuity. (See Figure 6). A discontinuity would result in a failure because a façade is only as good as its weakest link. The components responsible for performing these functions should be properly interfaced at all systemic and perimeter transitions to assure continuity of façade layers. Joinery between each two adjacent systems should be analyzed in their respective 360° perimeters to assure that no offsets are created at corners and the inter-systemic interactions allow for their proper solution. These functions may be differently addressed by separate components of proprietary curtain wall systems available on the market, requiring a specialized knowledge to recognize and connect them adequately.

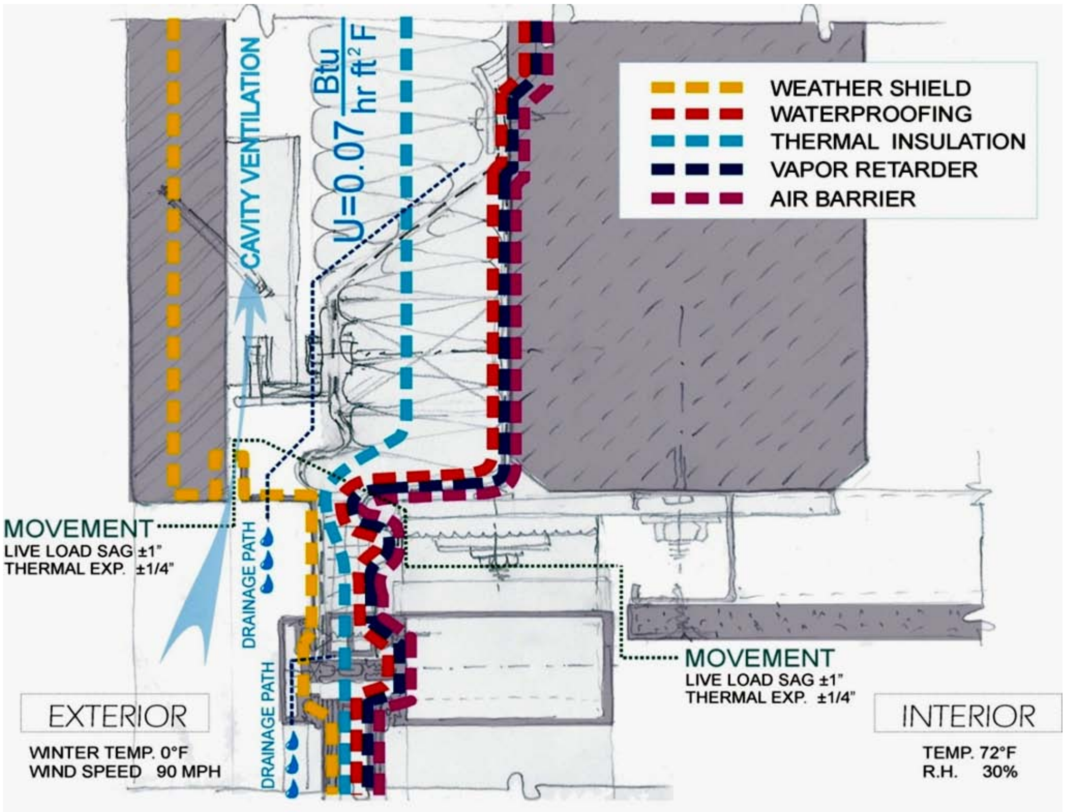


Figure 6. Example of functional analysis of a vertical section detail of exterior wall. Façade control layers, represented by thick dashed lines, should be able to resist the adversary forces through the inter-systemic joinery subjected to differential movement.

This in turn requires oversight of the engineering process by a façade engineer familiar with the fundamental principles of façade engineering and the systemic solutions used in the commercially available curtain wall systems and adjacent systems: e.g. roofing, below-grade waterproofing, terraces, and other façade appurtenances.

Some functions may be economically impractical to satisfy by glazing, the component most frequently associated with curtain walls: A good example is two almost mutually exclusive needs: improving the interior day lighting conditions and lowering heat transfer through a building envelope. The technological development of glazing, as impressive as it has been, has not improved the glazing yet to be comparable with opaque materials in many respects, such as heat transfer (Straube, 2008), sound transfer (Heusler et all, 2009), and blast resistance (Hinman, 2009).

The functions also represent users' expectations; therefore this author frequently contrasts them with the typical performance failures:

- Condensation and Frosting (typ. inadequate heat flow performance)
- Glare (typ. inadequate light control)
- Noise (typ. inadequate sound mitigation or generation of the inborn noise by the wall itself)
- Leakage (typ. inadequate rain water resistance)
- Glass breakage (typ. inadequate impact resistance, differential movement, or material failure)
- Free fall of wall fragments (typ. inadequate structural attachment)
- Aesthetic imperfections of glass and coatings (typ. miscellaneous reasons)
- Corrosion (typ. inadequate corrosion protection, galvanic action of dissimilar metals, etc.)

Generally, how resistant are curtain walls to failures? The data is not easily available. Owners and managers, who would be the best source of the data, are incidentally the party least eager to speak up for public relations purposes. The data is available from construction testing instead. Mockup testing is crucial in assessing unproven systems and for the purposes of contributing to subsequently finalized designs. Generally, only the most prominent projects have sufficient funding to individually test their walls. The mockups built for the laboratory tests generally represent the highest and best contractors' efforts on the largest and best projects. Therefore, the results are hardly random. The owner of one of the largest wall mockup testing laboratories in the world, where many of the most prominent building walls were tested, ranging from Sears Towers in Chicago to Petronas Towers in Kuala Lumpur, estimated in 2007 that 95% of walls tested in his laboratory failed their first tests. The typical testing includes a dynamic water testing and structural test at 100% and 150% of the design wind pressure. (See Figure 7).

Figure 7. Dynamic water testing of a curtain wall in a laboratory. Only 5% of walls generally pass their first test.

If only 5% of the best walls passed their first mockup test, how well would the average wall perform? Mother Nature conducted an informative, accidentally random test up to the wind requirements set by previous building codes but no curtain wall specific statistical data is available. The Hurricane Wilma became a true test fir hurricane resistance of building inventory in South Florida. According to the weather data collected by NOAA, generally no wind speed was recorded that significantly exceeded the wind resistance requirements set by previous Florida building codes (110 and 120mph). The highest recorded gusts were in the 100-120 mph range. Wilma's eye passed over five counties in South Florida: occupied by population of 5.3 million, living on 8303 square miles according to the 2000 census (U.S. Census Bureau). Property damages reported in Florida, (not limited to the wind peril and not limited to walls), exceeded $10 billion of 2005 USD (Pasch et all, 2006) – which makes approximately $2000 per capita. There is no specific curtain wall damage actuarial data available. The analysis is complicated by several factors, e.g. two different methodologies in calculating wind gusts (fastest mile and 3 second gust) and by the following hurricane Katrina, much gentler than Hurricane Wilma in South Florida, but causing damage difficult to distinguish from Wilma. The general conclusion is that significant percentage of construction doesn't meet basic building code requirements. Based on this author's observations, curtain walls frequently failed by water infiltration and detachment and fall of wall components (characterized by e.g. missing aluminum trim - snap caps) in addition to sustaining widespread impact damage by windborne debris. Some assemblies failed catastrophically, revealing a defective assembly. (See Figure 12).

Cause of failures: Curtain walls are complex systems comprised of many separate components; however, their failures as whole units may be generally divided into the following categories:

- Design Errors and Omissions, e.g. improper choice of materials and systems.
- Materials without proven performance, e.g. insufficiently tested glass coating technologies.
- Deficient Shop Fabrication, e.g. failure to detect early and prevent by QA and QC.
- Deficient Field Installation,
- Improper or Deterred Maintenance, e.g. underfunded maintenance budget, improper of missing staff training, omission of commissioning design -"instruction manual,"
- Ordinary wear and tear, e.g. failure of "bottleneck" materials and solutions.

4. Design Responsibility And Communication

Majority of failures seen by this author in the field could be easily prevented by an adequate design or a subsequent quality control. In some cases there is an implied, misplaced expectation a contractor would conduct quality control of the design. Observing the design and construction process this author identified gaps in communication and misunderstood delegation of responsibilities as major culprits of failures of building enclosures. It's also observation of this author, that in case of building envelope failures, the cost is typically paid by insurance companies, owners, and contractors, while control is mainly in hands of designers and manufacturers. Whenever the spread of risk is inverse to the division of responsibility, interesting things are bound to happen: the ultimate result is the encouragement of waste. To quote the NIST report (Gallaher et al. 2004): "Many parties, each with expert knowledge in different disciplines, often operate in isolation and do not effectively communicate knowledge and information with teaming partners both internally and externally." The façade design may be compared to a no-man's land subjected to "triple witching." (See Figures 8 and 9). The problem affects building enclosures in general, but curtain walls get a large share, exacerbated by a fundamental, widespread misunderstanding of their structure and function, described in the paragraphs above.

In the most typical scenario a curtain wall is delivered as one of a number of Design-Build systems on a Design-Bid-Build façade. The process can be briefly characterized by two main stages:

First design stage: In the traditional design-bid-build mode, a curtain wall is first defined by an architect of record, who should provide oversight of work of the structural and mechanical engineers and other (acoustical, blast, lighting, fire, code) consultants. This duty is non-delegable (Kelleher et all, 2009). The oversight becomes a challenge, as the two groups often don't speak the same language. This author found himself serving frequently as a translator and facilitator of the communication between the two groups. The secondary structure and structural connections between each façade system lie in a grey area between scopes of the architect and the structural engineer. The connections should be engineered by a structural engineer (responsive to both types and magnitude of loads and locations at which the proprietary façade systems would need support) and coordinated with functional façade control layers, to allow for proper transitions of thermal, waterproofing, air, vapor, and other control layers. This inter-systemic anchorage and transitions should be engineered with input from someone with a sufficient knowledge of the adjacent systems to allow for proper transitions of all façade control layers, in order to provide their continuity. This input is often solicited, with varying results, from sales staff of systems' manufacturers and on basis of their printed catalogs and brochures. (See Figure 5). As a result of the processes described above, the transition details, secondary structure design, specifications of design data and performance requirements should make their way to the construction documents. It's this author's observation that the transition details are correctly detailed, secondary and primary structures coordinated, and specifications sufficiently describe the façade, only when a specialized façade engineering professional, covering all facets of façade engineering, prepares both of them (as is the practice elsewhere e.g. in Europe) becoming a proxy of design-build teams and narrowing the gap between architectural documentation and submittals.

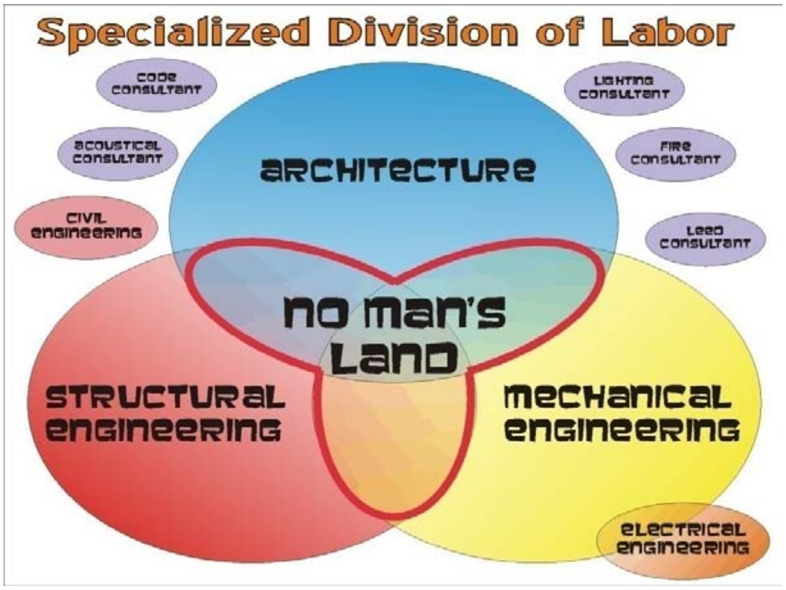


Figure 8. Caricature of the "no-man's land" in the architectural design phase. Curtain walls are often located in this area.

Delegated design stage: In the construction phase, the systems are delegated to respective Design-Build teams for engineering of their respective systems. In the ideal world, the engineering teams would receive both design data and performance requirements mentioned earlier to allow for proper engineering. This author has seldom seen the design data (e.g. structural deflections of a supporting structure) being expressly specified in the construction documents. A gap in the information flow to the delegated design teams is created as a result. Some curtain wall manufacturers responded to this situation by simply disclaiming any liability for structural movements in the standard limited warranty language.

Interfaces of systems changed in the substitution process would need to be redesigned based on general architectural design intent inferred from the architectural details. The secondary structural data should be coordinated by the General Contractor between each two adjacent subcontractors' work to assure that all loads are safely resisted and transferred onto the main building structure. General Contractors' failure to coordinate work of subcontractors (Kelleher et al, 2009) would affect the interfaces among adjacent systems. These gaps, often marked as "by others" or "not in contract" on submittals, create essentially a "no-man's land." (See Figure 9).

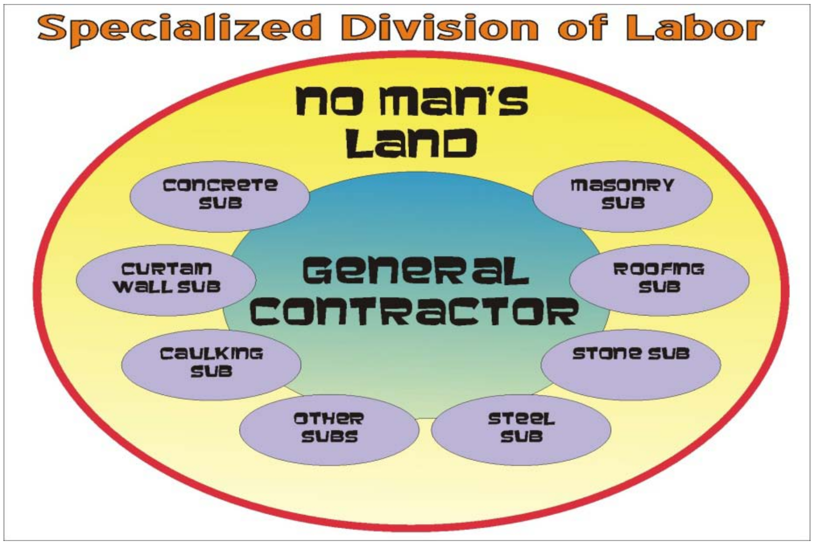


Figure 9. Caricature of the "no-man's land" in the construction phase marked with yellow color. As was the case in the design phase, curtain walls are often located in this area.

Results: The ultimate result of the "triple witching" described above is failures observed in the field. One spectacular failure stems from the attempts of detailing a curtain wall like a window: with perimeter attachments, as opposed to a simple span frame. A curtain wall is seen with jamb mullions attached to an adjacent structure, as opposed to the remaining mullions which are attached directly the structure. The adjacent structure would need to have sufficient load resistance to take the reactions from the jambs. (See Figure 10 exemplifying this challenge). This may be correct if the adjacent system is capable of safely transferring the curtain wall reactions onto the main frame and the differential movements are verified. However, more often than not, the adjacent system is not fully coordinated. (See Figure 11). An example of a resulting failure is shown in Figure 12. The wall was designed to 110mph fastest mile wind load and failed during Hurricane Wilma. Initial breakage of glass caused unanticipated service condition: pressurization of the building interior. Aluminum jamb mullions were exclusively supported onto adjacent CMU piers, which were not designed to collect reactions from the curtain wall.

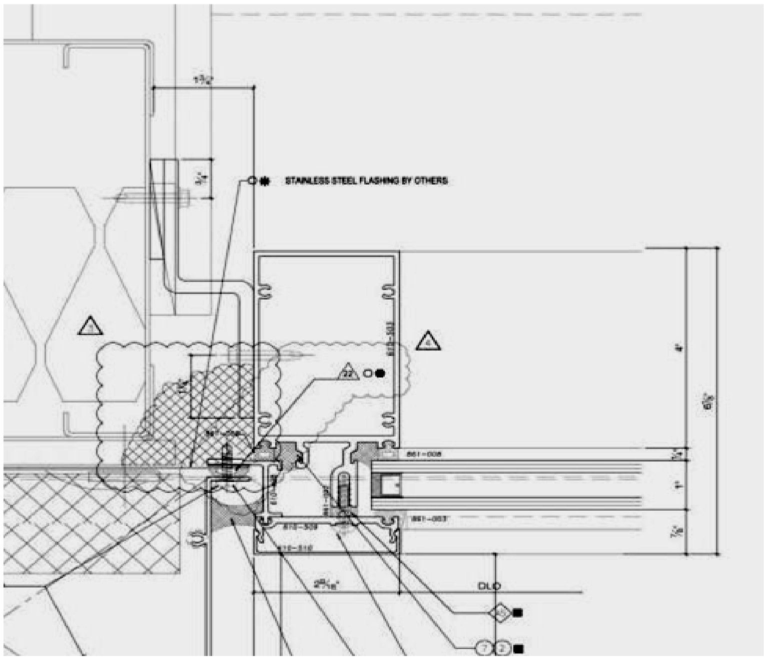


Figure 10. Plan detail of a jamb of an exterior curtain wall. Note the fixed side attachment of the glazed curtain wall jamb mullion to the adjacent light gage metal framing. See also Figure 11 and 12.

Figure 11. Interior photograph of the head of exterior wall. Indirect support of a glazed curtain wall jamb mullion through an adjacent light gage metal framing. (Note the stub of the single deflection track on the left side.)

Figure 12. Exterior photograph of exterior wall. A spectacular, catastrophic collapse resulting from uncoordinated support of a curtain wall.. Jamb aluminum mullions were exclusively supported onto adjacent CMU piers, which had insufficient load resistance to collect design reactions from the curtain wall. Photo credit – Mr. Alessandro Abate.

CONCLUSION

This author has observed a significant gap between the users' expectations and actual performance of curtain walls, ranging from a simple glare discomfort to a major structural collapse. In the course of his design, forensic investigation, and consulting activities he identified the reasons for poor performance is often a misunderstanding of fundamental principles of façade design and structural concept of curtain walls by construction parties, and gaps of oversight and coordination in the established project delivery routines. Therefore, this author's goal is to provide education on subject of façade engineering, and this paper is one of the steps bringing this goal closer.

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