structural practices

Curtainwalls in Modern Buildings

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Curtainwalls are an essential element of modern building design, primarily as an aesthetic feature to define the architecture and maximize the amount of light that enters the workspace. Naturally, like other facades, they also represent the first line of defense against most natural elements including wind, rain, temperature, and light. The curtainwall also plays a significant role in building protection including earthquakes, explosive events and forced entry. As a key design feature, curtainwalls draw additional attention which requires superior quality through the design, analysis, fabrication, and installation for architects, engineers, vendors and contractors.

In recognition of immense importance of all of those performance factors, the Curtainwall Committee of the ASCE's Architectural Engineering Institute's (AEI), in cooperation with the Ornamental Metal Institute of New York, organized a two-day symposium in New York City that addressed many important aspects of modern curtainwall design. The subjects that were discussed in the symposium covered manufacturing, architectural, engineering and performance issues.

This article discusses three important aspects of curtainwall behavior that were presented in the symposium. Mitigating fire from spreading to adjacent floors in the design of curtainwalls is the first topic discussed. The article continues with a discussion on the mitigation of modern hazards that affect curtainwalls. Recent earthquake design conceptual improvements for curtainwalls will be presented, followed by the balanced curtainwall design approach for mitigating the blast loading effects.

In all, it is clear that curtainwalls is an extremely complex component in the overall construct of buildings; it needs and deserves the utmost attention of owners, architects and engineers.

Fire Considerations

Protecting Fire Spread to Adjacent Floors

Considerable attention has recently been given to the building code requirements regarding the protection of fire spread to adjacent floors when curtain walls are used. The purpose of this article is to identify a reasonable fire-safety objective with respect to fire spread to adjacent floors, and then to evaluate existing and potential future code requirements. While both interior and exterior fire spread need to be considered, the focus of this article will be on the interior spread of fire.

Interior Fire Spread

One of the primary fire safety concerns related to curtain walls is the potential for fire spread to occur in the void space that exists between the edge of the floor slab and the curtain wall (*see Figure 1*). The *ICC Performance Code for Buildings and Facilities*™ objective related to this issue states that wall, floor, roof, and ceiling assemblies forming compartments shall limit the spread of fire. Therefore, if the floor slab has a fire resistance rating, fire spread to an adjacent floor should be limited. The *International Building Code*® (IBC) contains prescriptive requirements as to when a floor is required to have a fire resistance rating and how to protect the void space between the floor slab and the curtain wall. Current code provisions require that the fire resistance rating of the floor slab be continued to the exterior wall.

Recent code change activity has raised several issues related to the current prescriptive requirements. The *Code* text refers to "an approved material or system" without reference to a nationally recognized test procedure. At the time the *Code* was developed, a nationally recognized test standard did not exist and therefore the *Code* provided some details regarding the test. However, in the absence of a nationally recognized standard, different test laboratories in the U.S. have been conducting the test differently. ASTM has now released a test standard to evaluate systems designed to protect the void space.

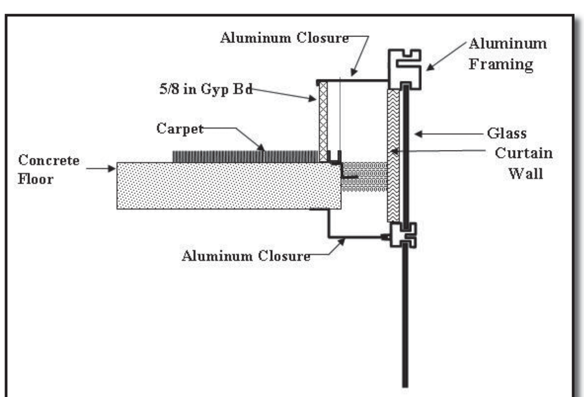


Figure 1: Vertical Section: Junction of Exterior Wall and Floor

The second issue that has been debated is the appropriate rating for the means used to protect the void space. Current prescriptive code requirements state that the material or system shall provide the same fire resistance rating as required for the floor slab. This requirement has led to some application problems, in that current systems used to protect the void space are supported from the curtain wall which may not have any fire resistance rating.

From a fire protection standpoint, the actual desired performance is for the void space to be protected. If the fire resistance rating of the curtain wall is referenced, the desired performance may not be achieved. Since many curtain walls are not required to have any fire resistance rating if the required fire resistance rating is used as the basis for the requirement to protect the void space, there would be no required fire resistance rating. Attempts to address this issue have included establishing a minimum of 30 minutes. However, there still is no basis to assure that the curtain wall, and therefore the system protecting the void space, will truly provide 30 minutes of protection. Using the required fire resistance rating also would not address the scenario where the performance of the curtain wall exceeds the minimum prescriptive code requirements.

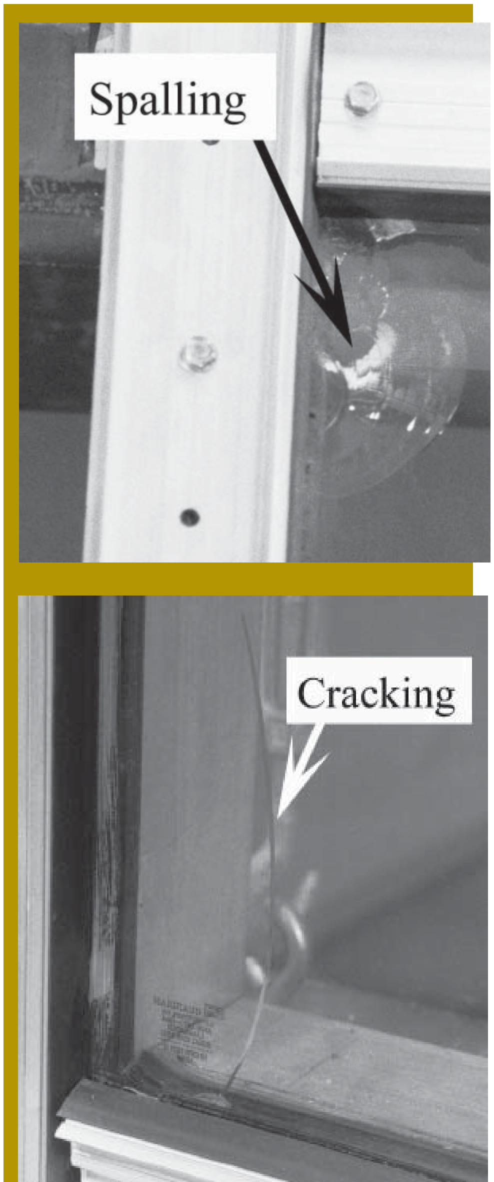
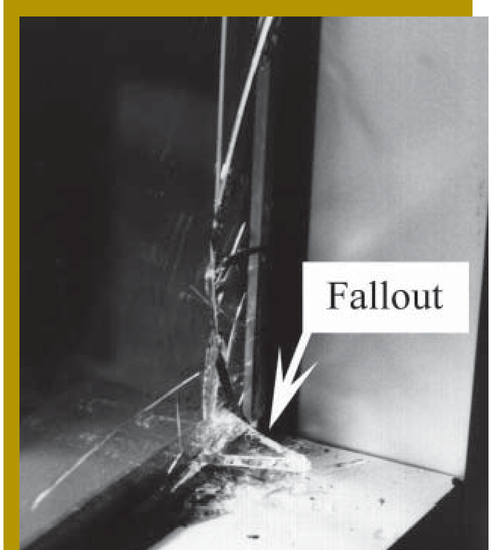


Figure 2: Examples of Spalling and Cracking (Serviceability Issue) and Fallout (Safety Issue) Failure in Annealed Architectural Glass Panels



To address the problem associated with referencing the required fire resistance rating of the curtain wall, proposals have been submitted to use the actual fire resistance of the curtain wall assembly. While this may be the more technically valid approach, it does result in considerable application problems. First and foremost, each curtain wall assembly would need to be tested to determine the actual fire resistance rating of the assembly. To truly evaluate this performance one would have to conduct a large scale multistory test or possibly use a modified, existing intermediate-scale fire test.

Therefore, current prescriptive codes have retained the reference to the required fire resistance rating of the floor assembly. The intent of the provision, however, is to only address the spread of fire thru the void space. Therefore, if the curtain wall assembly does not have the same integrity from fire as the floor slab, the system protecting the void space need not perform after the integrity of the curtain wall fails. This intent statement is clearly stated in the code change proposals resulting in the current text in the IBC. Since the NFPA format allows for annex material, the intent is also clearly stated in an Annex note in NFPA 5000™.

Seismic Damage Mitigation Concepts for Architectural Glass

Recent west coast earthquakes in the U.S., and moderate to strong earthquakes affecting cities elsewhere in the world, have further revealed the vulnerability of architectural glass. In an earthquake, the architectural glass damage could pose a "safety" hazard because of the falling shards. If the glass panel simply cracks but stays within the frame, it can be considered a "serviceability" failure, which would require replacement. Damage to a glass panel held within the glazing frame is caused because of its interaction with glazing frame as the latter deforms under building structural frame in-plane lateral displacement (drift).

Current building codes (e.g., IBC 2003) have a specific requirement on the drift capacity of the glass panel (glass fallout) in glazing systems (e.g., curtain walls, storefronts). The rationale behind such a requirement is that the glazing system should accommodate the building story drift without posing a life safety hazard (e.g., a glass piece at least 1 sq-inch in size falling out).

The simplest way glazing designers have used to avoid damage to glass due to its interaction with the glazing frame, as the frame is being deformed in a racking type movement during earthquakes, has been to provide sufficient clearance between the glass panel edge and the glazing frame pocket. However, providing excessively large glass-to-frame clearance is not feasible for all glazing frame types because it would require wide mullions, which may not be aesthetically desirable.

Some of the other approaches that have been used in the past to improve the seismic performance of architectural glass include (recommended by FEMA 74 (1994)) use of tempered glass, use of laminated glass, and use of PET film. The first two solutions are applicable to new designs, while the use of PET film is primarily for retrofit situations of existing glass. The use of anchored adhesive films has been recognized as an effective way to mitigate life-safety hazards due to earthquakes. Based on research at Penn State, the use of tempered glass can improve the serviceability drift (i.e., drift level that causes cracking) as compared to annealed glass. On the other hand, the use of laminated glass (made with annealed glass) does not substantially improve the serviceability drift compared to annealed monolithic glass, but it can improve the ultimate drift (i.e., drift that causes glass fallout). *Figure 2* shows examples of glass spalling, glass cracking and glass fallout, while *Figure 3* shows an example of PET Film application and how glass shards are retained because of the film after a racking test under large drifts.

Recently, there have been some significant developments in methods for seismic damage mitigation of glazing systems. Seismically isolated curtain walls and unitized systems have been suggested to accommodate earthquake-induced inter-story drifts. The basic concept behind such approaches is to isolate the curtain wall frame from the damaging structural frame displacements by modifying the method of attachment of the curtain wall system to the building structure.

Another approach that was also recently developed at Penn State is to employ modified geometry at glass corners (Rounded Corner Glass (RCG)) instead of the conventional rectangular corners. Laboratory studies of RCG architectural glass panels have shown that such geometry modification can increase the serviceability drift without the need to change the glazing frame details and its connection to the structural frame. The advantage of the RCG glass panel over the conventional rectangular corner as it interacts with the glazing frame is conceptually shown in *Figure 4*.

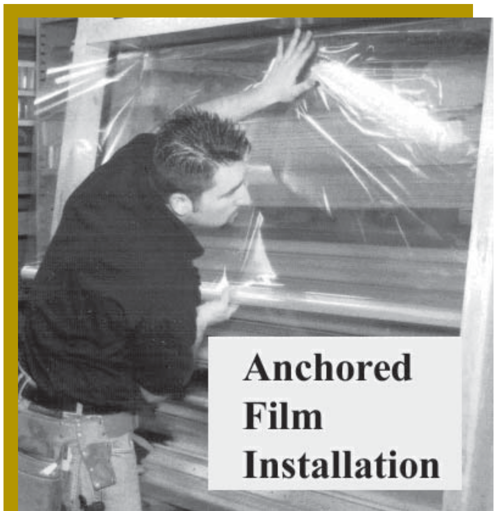


Figure 3: Application of PET Film and How Glass Shards Are Retained by PET Film

Today, in some cases glazing systems are expected to perform satisfactorily under multi-hazard loading conditions for safety and security concerns besides the normal serviceability design criteria. The same glazing system that must resist wind storms may also be expected to accommodate seismic induced building story drifts, and in some cases provide protection against flying glass shards in blast situations. Therefore, there is a need for more engineering work on these "nonstructural" systems than ever before. This requires the involvement of structural engineers in the design process and the understanding of various performance objectives expected of these systems.

Balanced Design for Blast Loading

Most blast curtainwall performance specifications contain the criterion that the curtainwall must be a balanced design; however, the criteria usually does not discuss what balanced design means. Depending on the type of building, whether it is new construction or the renovation of an existing building, this criterion will have different implications. The objective of this paper is to illustrate that curtainwalls can be improved to resist the blast environment, and also to explain the implications of "balanced design" criterion, which is also know as "glass fail first".

The objective of the balanced design criterion is to maximize the potential energy dissipation from a blast event by assuring that the system deforms in a predictable fashion, that no part of the curtainwall fails prematurely or in a brittle manner and that ultimately the occupants of the building are protected. Note that this criterion will typically not govern the performance of the glass and mullions when subjected to the design blast pressure and corresponding impulse; however, it will have a significant impact on the design of the connections between the mullions and the anchorages to the structure.

Balanced design prescribes a hierarchy of yielding. Starting with the glass, each support element is slightly stronger than that which it is supporting until the system reaches the base building. In other words, the silicone that attaches the glass to the mullion is able to carry the maximum load that the specified glass can accumulate and transfer. Similarly, the respective mullions and anchor clips can transfer the maximum load of the system that it is supporting. As all designs start with the glass and the support elements build on the strength of the glass, a cost efficient protective curtainwall utilizes the 'weakest' glass that can be specified for the project. Note that several other design criteria must be considered including architectural finishes, wind loading, manufacturing, transportation and installation. You will find that handling during manufacturing and installation usually governs the minimum thickness design. Therefore, the critical factor in the designing of protective curtainwall systems is the analysis and design of the framing and attachment elements. Understanding how and when to apply the proper load consideration and understanding the analytical results will lead to a cost effective design for a protected curtainwall.

Typically, most new blast resistant glazing make-ups will have a laminated inner lite of glass. If the glazing does not exit the frame when responding to an explosive event (a "no-break" or "break-safe" condition), then the glass make-up may potentially have some reserve capacity. The balanced design procedure dictates that the loading should be artificially increased to the maximum glass capacity, the point at which it would exit the frame. This dynamic load or the resulting glazing reaction is then used to load the supporting mullions. As a result, the mullions will have to be redesigned to meet the larger dynamic loads. The larger mullion sections will in turn produce larger reaction forces, which will be used to design the mullion to mullion connections and the connections to the supporting structure. These larger forces are typically the resulting reactions from the ultimate bending or flexural capacity of the mullion members.

As a result of applying the "balanced design" criteria the curtainwall has been significantly improved. The construction costs associated with the curtainwall has been reduced as a more efficient system has been utilized and money was not wasted developing large section and over-robust connections. *Figure 5* shows an example of a modern curtainwalls that was designed using a balanced design approach.

For new construction, this will have little effect of the base structure as the design team can account for the enhancements prior to construction. However, for renovation projects, the existing structural slabs may not be able to develop these forces without structural upgrades. These upgrades may not be feasible depending of the project scope of work.

As an alternative, the curtainwall designer may want to consider using a larger response criterion for the curtainwall framing members in lieu of the prescribed performance criteria or the traditional two degrees of support rotation. Assuming that the glazing has

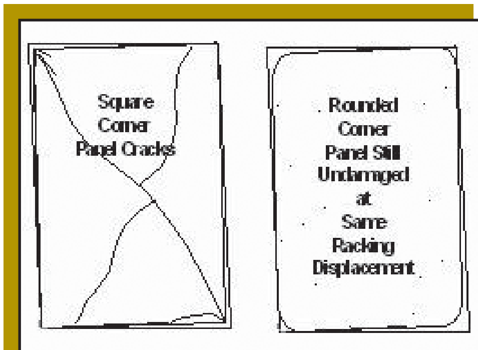
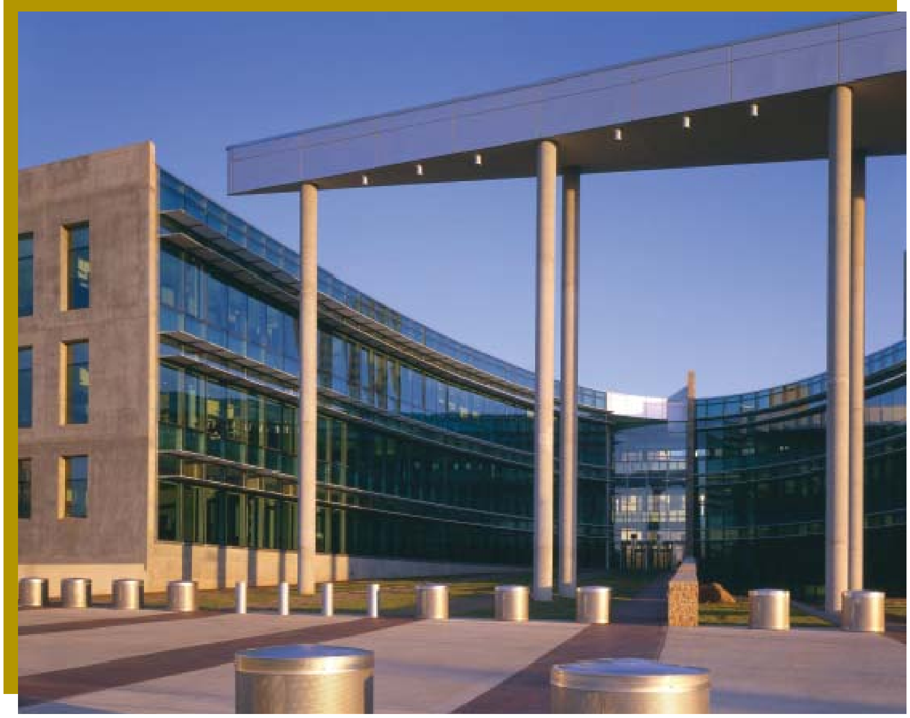


Figure 4: Rounded Corner Glass Panel Can Provide Greater Cracking Drift Capacity

Figure 5: Balanced blast design can yield a light, but blast-worthy curtainwalls



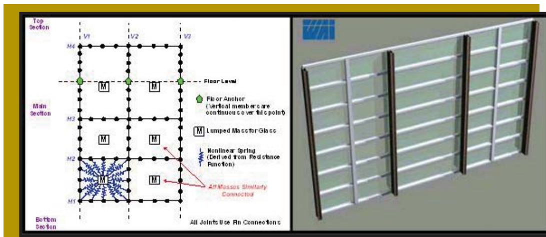


Figure 6: Modeling Representation and Computer Rendering of the Curtainwall Design

reached its ultimate capacity, the supporting framing members should also be designed with a response criteria that would define the mullions failure. This criterion is not easily determined due to the lack of test data and understanding of closed and open mullion sections. However, it may be reasonable to assume a failure criterion for the supporting framing members of four to six degrees of support rotation. This in turn will produce another problem, as rotation limits larger than two degrees of support rotation will exceed the bending capacity and will now result in catenary or tension forces being developed in the members. The typical analysis tools, such as the single-degree-of-freedom models, utilized by blast engineers can not calculate the tension forces. Non-linear finite element programs are the only tools available to calculate true catenary forces.

When utilized by a qualified blast consultant, non-linear finite element programs can be used to model slip connections, where the slip is calculated thus reducing or eliminating the catenary forces. The result is a design that can sustain much high levels of damage prior to dismembering. This design will then fully utilize all the material and geometrical non-linear behavior within the curtainwall. A balanced design curtainwall system will thus be the most efficient and cost effective design to resist blast loads. *Figure 6* shows an example of blast-designed curtainwall utilizing several of the aforementioned principles. It is clear that an elegant curtainwall can be constructed, even with the utmost blast demands, if efficient engineering principles are observed.▪

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