Performance of Glass Panels Under Seismic Loading

by

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B.S., Civil Engineering (2000)

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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil and Environmental Engineering

at the

Massachusetts Institute of Technology

June 2001

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Abstract

The primary goal of this thesis is to analyze current trends in the improvement of the performance and safety of glass during an earthquake. The four sections consist of an overview of glass as a building material, glass installation methods, rehabilitation methods for existing structures, and building code related issues. The thesis is based on an analysis of sources including books, journal articles, industry publications, and industry websites. Important discussion points include the shortcomings found in past designs to the current state-of-the-art design approaches. Finally, conclusions are made regarding the direction of the current practices and areas that should be targeted for further improvement.

Thesis Supervisor:	Jerome J. Connor
Title:	Professor of Civil and Environmental Engineering

Acknowledgements

My wife, Tiffany, for all her love and support during the last five years. I never would have made it without you. You are the most amazing woman I have every met!

My parents, for giving me my ambition and stubborn determination to make it this far.

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My friends, who have made it fun during all these long years of school.

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1 Introduction

As designers continue to advance the technology of structural engineering, we are seeing a change in the damage patterns associated with structures subjected to seismic loadings. In recent earthquakes, many newer building experienced little or no damage to the primary structural support system, but had substantial damage to secondary building systems such as cladding, interior partitions, and glass. WFAA radio news in Seattle, Washington recently stated, "While brick and *shattered glass* littered the streets, there appeared to be little serious structural damage," following the 6.8 magnitude earthquake in early 2001, yet damage estimates for that quake topped $2 billion. In the 1994 Northridge earthquake, "many commercial buildings lost 40-60% of their shopfront glazing" (Pantelides, 1996). Even in the Mexico City Earthquake of 1985, many of the mid-rise office buildings that experienced no primary structural damage still experienced severe glass damage.

When an earthquake occurs, and damages a building's glass, it can pose a severe danger regarding life safety issues, produce an extreme financial loss, and affect the immediate serviceability of structures. During an earthquake, breaking glass can create a hazard to people both passing in front or below glass storefronts and facades. Falling debris is one of the most common causes of injury and death during an earthquake. Falling glass also creates a dangerous impediment to people attempting to exit buildings during the panic that usually accompanies a major quake. Besides the enormous risk to human life, broken glass can account for a significant portion of the damage costs incurred from a seismic event. To make matters worse, failed storefronts, windows, and facades leave buildings temporarily unusable and exposed to vandalism and looting following an earthquake, compounding the initial financial losses (Figure 1).

Figure 1 - Glass Storefront Damage following Loma Prieta Earthqauke (Solutia, Inc., 2001)

This paper will be broken down into four major sections: glass as a material, glass installation methods, rehabilitation methods, and code issues relating to glass. The first section will discuss glass as a building material, how it is made, why it is so prone to breakage during earthquakes, and the different types of glass currently used in construction. The second section of the report will address original techniques that have been developed during the past few decades to support glass on structures and to minimize the damage causing stresses associated with earthquakes. In the third section of the report is an overview of some current methods employed to rehabilitate glass in existing structures. Finally, a brief discussion is provided regarding the way in which building codes address the issues of glass design.

2 Glass as a Material

Glass is possibly the oldest material made by man. Historians estimate that the first glass was discovered around 7000 B.C. and used only for ornamental purposes until approximately 1500 B.C. (Amstock, 1997). Around 1500 B.C., man first began forming glass into useful items by making glass vessels in Egypt. Once its usefulness was discovered, glass has found its way into many areas of human life over the last 3500 years. However, lacking the ability to make transparent sheets of significant size, glass was not used to cover windows until the 17th and 18th century. Until the early nineteenth century, window panes were very small and lacked quality transparency. Finally, glass polishing and plate glass were developed in the early 1800's, allowing widespread window glass to become a reality. As with most areas of science and technology, a true understanding of glass has only started to develop over the past 150 years, culminating with tremendous advances in manufacturing, possible sizes, clarity, and performance of architectural glass applications (Figure 2).

Figure 2 - Improvement in Size and Transparency from 17th Century to Modern Glass (Schittich, 1999)

Considering the current trends in glass, understanding of this historic material is only just beginning. New architectural aspects of glass are currently being developed that include the use of glass as a primary load bearing system (Figure 3), improvement of glass properties to control solar and heat effects (Figure 4), the design of dynamic facades (Figure 6), and the constantly improving understanding of traditional architectural glass applications.

Figure 3 - Structural Glass Pedestrian Walkway
(Schittich, 1999)

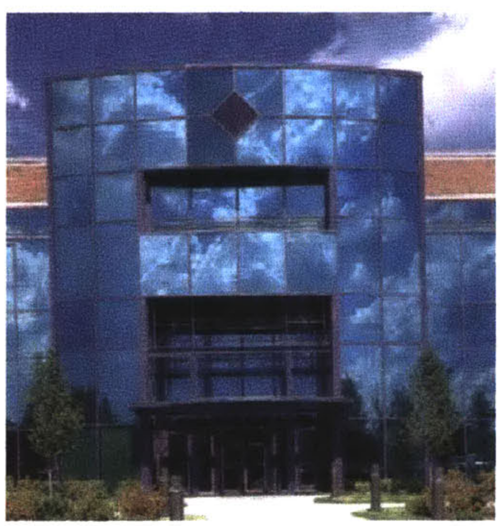

Figure 4 - Energy Efficient Solar Glazing
(www.solarseal.com, 2000)

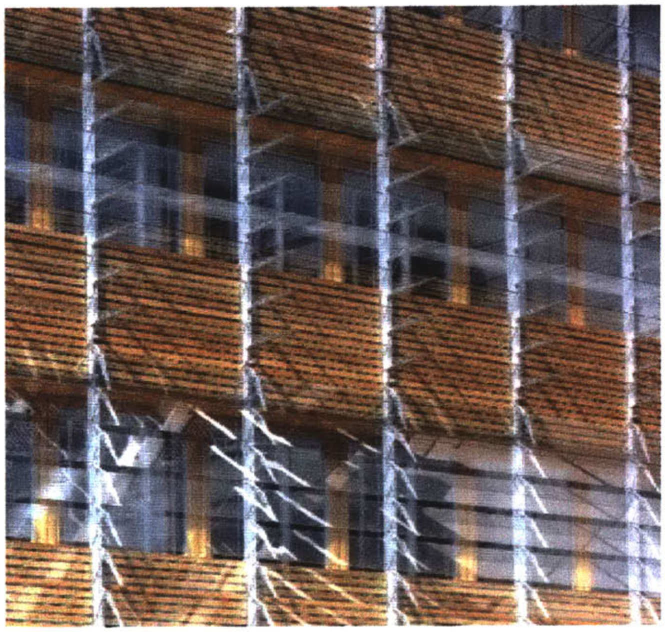

Figure 5 - Dynamic Glass Façade
(Schittich, 1999)

2.1 General Properties

While many types of glass have been developed, soda-lime-silica glass is the primary type used in building construction. Soda-lime-silica glass is typically composed of a chemical composition as seen in Table 1 (Nilsson, 1993). In addition to soda, lime, and silica, many of the additives to glass contribute to its non-structural characteristics such as color, heat reflectivity, and light transmissibility.

Silica (SiO_2)	71 – 73%
Alumina (Al_2O_3)	0.5 – 1.5%
Iron oxide (Fe_2O_3)	0.05 - 0.15%
Calcium oxide (Na_2O)	5 - 10%
Magnesium oxide (CaO)	2 – 5%
Sodium oxide (Na_2O)	13 – 16%
Potassium oxide (K_2O)	0 – 1%
Sulphur trioxide (SO_3)	0 – 0.5%

Table 1 – Chemical Composition of Soda-Lime-Silica Glass

The primary method of manufacture of glass for building construction is known as "float glass" (Figure 6). In the float glass process, glass ingredients are first heated to their molten temperature in a furnace. Second, the molten glass is rolled in a continuous ribbon onto a bed of molten tin to the desired depth. As the glass moves across the molten tin, it is heat polished, removing most of the imperfections from the surface. Heat polishing is the most important improvement associated with float glass; previous methods of glass manufacture used hand or machine polishing, and contributed to flaws and imperfections that weakened glass and promoted failures. Finally, the glass is annealed, or cooled under controlled conditions to establish desired permanent stresses. After the glass is cooled, the flat panels are then cut to the desired size and prepared for installation. Pilkington Brothers developed the float glass process in the 1950's and today it is by far the most widely used method of glass manufacturing. Other older methods of manufacturing flat glass include cast glass, sheet glass, and plate glass, all of which are steadily being replaced by the float glass method due to its ability to minimize the flaws frequently resulting from traditional glass manufacturing processes.

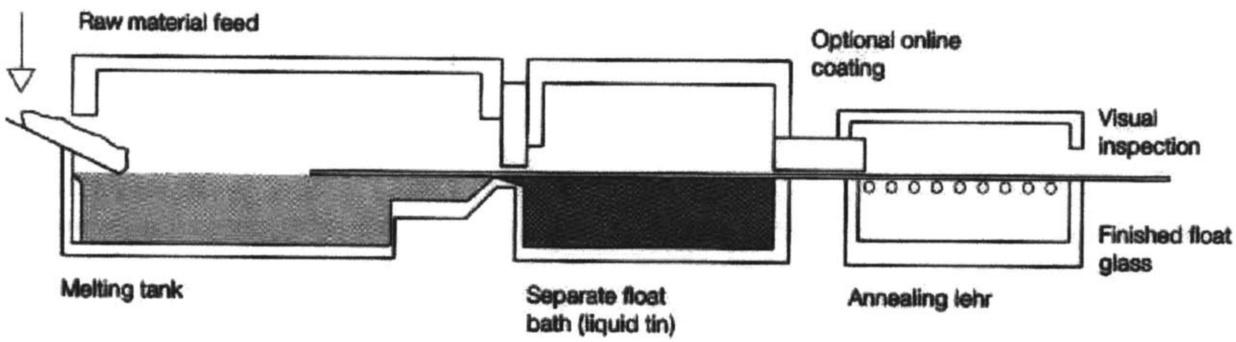

Figure 6 - Float Glass Manufacturing Process
(Schittich, 1999)

To understand glass as a structural material, it is important to realize the fact that glass is not actually a solid in the same sense as materials like concrete or steel. Rather, glass is actually a super-cooled liquid, which makes it subject to additional design considerations. One of these considerations is the fact that glass is very sensitive to creep. As a result, glass can carry up to 3 times more load in 1 second than constantly over a 24-hour period.

For example, creep characteristics of glass are important when considering the amount of load that a pane within a glass roof can resist during an earthquake, versus the amount of load that glass could support during a sustained snowstorm. In addition, if a glass panel or wall system is not designed with creep resistant attachments, the strength expected in design calculations to resist a seismic load may have already been partially used by residual loading due to self-weight induced creep.

Another important aspect in the design of glass is the presence of flaws. A flaw is a very small surface defect or imperfection, often undetectable to the unaided human eye. Glass is a naturally strong material, with theoretical strengths well in excess of even the best steels. However, due to flaws resulting from the manufacturing process, design strengths for glass, which are derived primarily from experimental tests on glass panels, are much lower than theoretical strengths. The problem results from the fact that although strong in theory, a glass panel needs only to have one flaw to fail under reduced load. When a flaw is present in a loaded panel of glass, the flaw attracts localized stresses that quickly lead to local failure and initial cracking, once cracking begins, the load path within the glass is interrupted. With a cracked panel (interrupted load path), a sustained load will quickly cause further cracking, leading to a complete loss of strength and total collapse. In some cases, only an initial small crack is needed, and the glass panel will eventually completely fail due only to its own self-weight and the effects of creep.

As result of the improvements in the manufacturing process, specifically the float glass technique, the amount of flaws inherent in glass panels have been greatly reduced compared to the past. Previous methods of manufacture such as sheet glass and plate glass required a considerable amount of hand or machine polishing. In the float glass manufacturing process, the use of heat polishing removes a major source of glass flaws. In addition, improved inspection and quality control procedures have made the occurrence of flaws in final construction materials much less common.

Finally, brittleness plays a role in the behavior of glass. Unlike steel, or even concrete to a lesser extent, glass is a brittle material. When subject to loading, glass can deform within its elastic limits, but upon exceeding those limits, failure is immediate and it most cases catastrophic. The brittle behavior of glass makes it an especially challenging material to design for seismic loading, since unlike many other building materials, it has no ability to absorb energy through plastic deformations.

2.2 Glass Types

Of the many types of glass currently available, there are multiple types that have improved designs to resist or control breakage due to both the in-plane and out-of-plane loading that occurs during an earthquake. Common types of improved glass include fully tempered, heat strengthened, and laminated. All of the improved glass types discussed in this section are based on standard float glass. The improvements are then made through processes that include thermal, chemical, physical, or a combination of these processes.

2.2.1 Float Glass (Annealed Glass)

Float glass, as describe in section 2.1. refers to the manufacturing process used in making the glass sheets. Although float glass is a silica sand based material, many other materials are usually added during the float process. The materials added during the float process are used to achieve both structural and non-structural properties. Since all of the common types of improvements to window glass are made using float glass, the term "annealed glass" (referring to the standard cooling process) has become the popular term to define standard float glass that has not had any improvements. It is of importance to note that all of the improvements to annealed glass result in changes in the strength of the glass, but do not change the fundamental stiffness of the material. Typical engineering design values for soda-lime-silica float glass ("annealed glass") are listed in Table 2 (Pilkington, 2000).

Modulus of Rupture (M.O.R.) in Flexure for 60-Second Load Duration:

Mean M.O.R. (Probability of breakage 50%)	6,000 psi	(41 MPa)	Annealed
	12,000 psi	(82 MPa)	Heat Strengthened
	24,000 psi	(165 MPa)	Fully Tempered
Typical Design M.O.R. (Probability of breakage 0.8%)	2,800 psi	(19 MPa)	Annealed
	5,600 psi	(39 MPa)	Heat Strengthened
	11,200 psi	(77 MPa)	Fully Tempered
Modulus of Elasticity (Young's)	10.4×10^6 psi	$(7.2 \times 10^{10}$ Pa)	
Modulus of Rigidity (Shear)	4.3×10^6 psi	$(3.0 \times 10^{10}$ Pa)	
Poisson's ratio	0.23		
Density	158 lb/ft^3	(2.53 g/cm^3)	
Coefficient of Thermal Stress	50 psi / °F	(0.62 MPa/ °C)	
Coefficient of Linear Expansion	4.6×10^{-6} in/in*°F	$(8.3 \times 10^{-6}$ mm/mm*°C)	

Table 2 – Engineering Design Values for Annealed Glass

Although slipping in popularity, annealed glass (or standard float glass) is still the primary type of glass used in manufactured windows, such as Anderson Windows (Figure 7). Annealed glass is also still used in large size applications such as storefronts and curtain walls, but is slowly being replaced by improved glass, which increases both safety and security of the applications. When annealed glass breaks, it is the most dangerous type of glass, often breaking into large, sharp, jagged shards of glass, which can become dangerous or deadly projectiles in the event of fallout during an earthquake. As a result, standard annealed glass is no longer allowed for glass doors, roofs, or any sloped overhead applications by most building codes. In addition, annealed glass provides no security against vandalism associated with looting in the aftermath of a major earthquake.

Figure 7 - Anderson Windows
(www.andersonwindows.com, April 23, 2001)

2.2.2 Heat Strengthened Glass

The first type of improved float glass is heat strengthened glass. To create heat strengthened glass, standard float glass is reheated similar to fully tempered glass, but cooled more slowly. ASTM requires that heat strengthened glass has a surface compressive strength between 3500psi and 10,000psi, and a minimum edge compressive strength of 5000psi (Amstock, 1997).

Unlike fully tempered glass, heat strengthened glass has a much larger range of properties. Depending on the strength of the particular piece, the earthquake performance will vary considerably. At low strength, near 3500psi, the glass breaks much like unimproved float glass, but does not have as sharp and jagged edges. At higher strengths, heat strengthened glass will break into small pieces similar to fully tempered glass. Finally, compared to annealed glass, heat strengthened glass is more likely to remain in place during an earthquake and reduce injury when complete failure does occur, but typically will not perform as well as fully tempered glass. Heat strengthened glass is not approved by most codes as a "safety glass" and therefore cannot be used for sloped glazing or glass roofs. The most common use of heat-strengthened glass is for upper levels of high-rise office buildings, in which there are not pedestrians walking on both the outer and inner sides. In this unique case, due to the danger of any size particles falling from excessive height, heat strengthened glass may provide an advantage due to its increased likelihood of remaining in the frame when cracked

2.2.3 Fully Tempered Glass

The second type of improved float glass is fully tempered glass. To create fully tempered glass, standard float glass is reheated to approximately 685 degrees C and then rapidly cooled by a stream of cold air. ASTM states that fully tempered glass has a minimum surface compressive strength of 10,000psi and a minimum edge compressive strength of 9700psi (Amstock, 1997).

Fully tempered glass is one of the most common types used to incorporate earthquake resistant design characteristics. As a result of the tempering process, when fully tempered glass breaks, it does not create large, sharp, jagged, and dangerous shards like annealed glass, rather it breaks into very small, much safer pieces called "dice"

(Figure 8). These dice are small enough to reduce or eliminate injury in the case of complete glass breakage, and lacking significant size or sharpness, do not even pose a severe danger to people when used in overhead applications. As a result of the behavior of fully tempered glass, it is often referred to as "safety glass". Due to its safety characteristics, fully tempered glass is one of the types of glass that may be used for sloped glazing systems or glass roofs in accordance with most building codes. Fully tempered glass also provides increased security against vandalism and looting after a major earthquake due to its higher strength and lower chance of breakage. However, once breakage does occur, fully tempered glass provides no additional protection regarding building security then standard annealed glass.

Figure 8 - Broken Fully Tempered Glass

2.2.4 Laminated Glass

Laminated glass is composed of two or more layers of glass with a PVB (polyvinyl butyral) plastic interlayer (Figure 9). The layers of laminated glass may not all be composed of the same material, thereby taking full advantage of the varying structural properties of each glass type. For example, two outer layers consisting of fully tempered glass may be laminated over a middle layer of standard float glass, improving safety, while still maintaining costs in an application where thicker glass is needed to resist out-of-plane deflections from loads such as wind. Another benefit of laminated glass is its ability to resist glass fallout when partial to complete breakage does occur. In earthquake applications, laminated glass increases the safety of passersby who may be subject to falling glass. However, it is important to note that some tests have shown that in extreme cases of out-of-plane loading, the entire laminated panel of glass has fallen out and created a much heavier piece of falling debris. Despite the risk of complete fallout, most designers consider laminated glass to be equal or better than fully tempered glass in earthquake prone applications. The preference is primarily due to the ability of laminated glass to resist both breakage during and earthquake, and to continue to provide some level of safety and security when breakage does occur. Most building codes accept the performance level of laminated glass for use in “safety glass” applications.

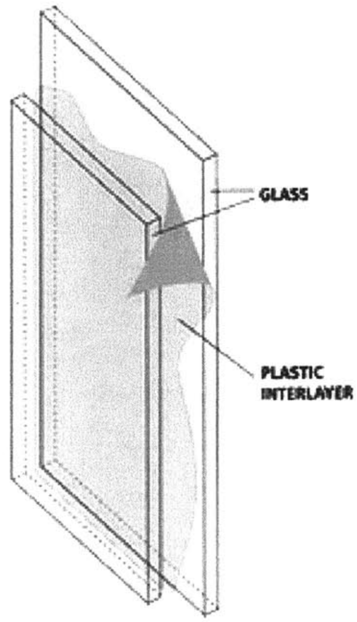

Figure 9 - Laminated Glass

(North American Laminated Glass Information Center, 1999)

3 Glass Installation Methods

There are many different methods available for installing glass in structures. In this section, an overview is given of the most common methods used in building design; glazing systems, curtain walls, and point fixing systems. While glazing systems are the most traditional, and therefore most widely seen, curtain walls and point fixing are finding their way into more projects every year. In the recent glass designs of high profile projects throughout the world, especially in Europe, point fixing is now being used as the method of choice to exploit the properties and performance of glass. Point fixing is quickly gaining in popularity due to its ability to design around significant structural movements, making it an ideal method for high seismic regions. While at the same time, advances in glazing methods and curtain wall technology have allowed these methods to keep their majority market share. Overall, the significant advances in all areas relating to glass and structures over the past twenty years have made glass not only a safer material, but also a more versatile and dynamic material in which the full range of possibilities are only beginning to emerge.

In addition, this section discusses two installation methods used to strengthen glass. First, the use of a perpendicular glass panels or fins attached at specific intervals along the glass to increase the out-of-plane strength. Secondly, the use of either passive or active guyed structures consisting of rods and wires that also increases the load capacity of glass through the installation method. While both of these methods are just additions to glazing, curtain wall, and point fixing designs, they produce significant variations in performance, therefore having important implications in earthquake design.

3.1 Glazing Systems

Glazing is the most traditional method of installing glass. In a glazing system, glass is supported within a frame system, which may be fabricated from aluminum, vinyl, wood, or other materials. The frame system may consist of just a single rectangular window in a residential structure, all the way up to a complex arrangement of windows of various shapes covering a high-rise building. While there are obvious differences in performance across these various systems, they are all still referred to as glazing systems. In a glazing system, the glass panels or "lites" are installed somewhat freely into the frame and held in place by the action of an inner frame pressing against an outer frame using a glazing bead (Figure 10). The glazing bead allows for moderate racking of the glass without imposing significant stresses, so long as the corners of the glass panes do not come in contact with the outer frame.

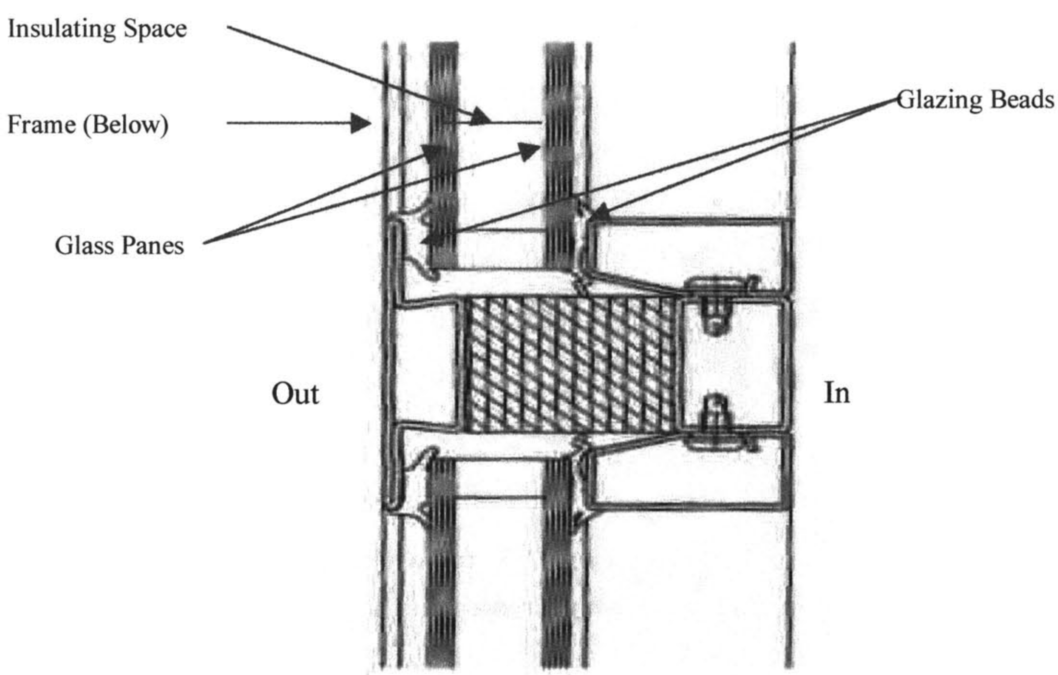

Figure 10 - Typical Glazing System
(Compagno, 1999)

It is also possible, using a pressure glazing system, to support the glass against the inner frame, minimizing the visible frame surface on the exterior of the structure (Figure 11).

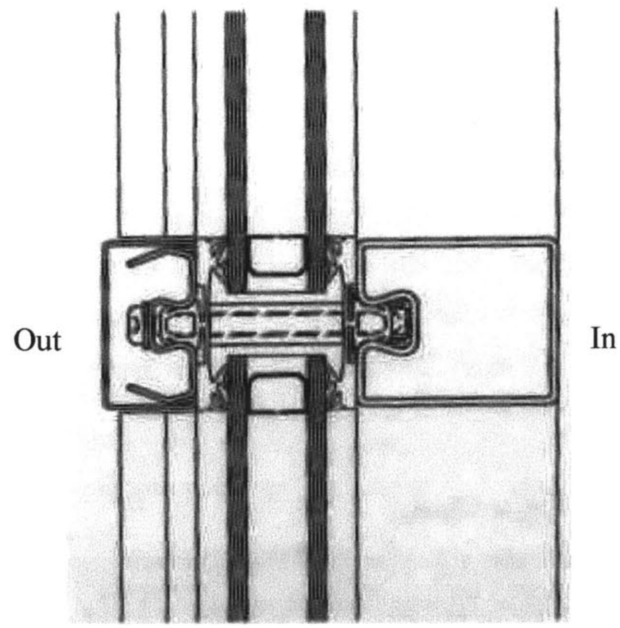

Figure 11 - Pressure Glazing System
(Compagno, 1999)

Finally, a structural glazing system has been developed in which no frame is visible on the exterior of the structure. Rather, the glass panels are supported by the structural properties of a bead of high stress silicone adhesive (Figure 12). Using the structural system, rather then allowing racking through a glazing bead, the motion is accommodated through the flexibility of the silicone adhesive. Obviously, the structural glazing system cannot accommodate as large of movements as the more traditional glazing systems.

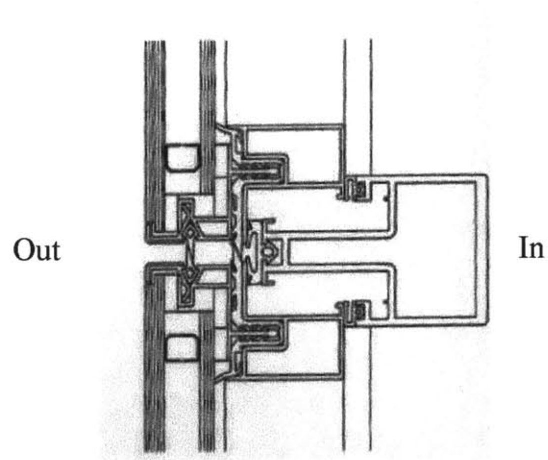

Figure 12 - Structural Glazing System
(Compagno, 1999)

The complete glazing systems are then fairly rigidly attached to the structure. Therefore, in almost every glazing system, the seismic design is based on the interstory drift of the total structure. In order to accommodate in-plane earthquake related movement, a glazing system must be able to deflect the required amount without the glass edges making contact with the frame (Figure 13). When glass corners or edges do come in contact with the frame, the resultant concentrated stresses are the primary cause for glass breakage. Due to this design constraint, some glazing systems with large size glass panes have been designed to allow in-plane movement of a single glass lite of up to 2 inches.

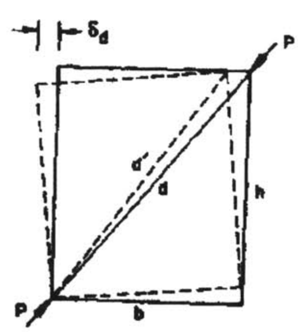

Figure 13 - Interstory Drift Loading on Glass in Standard Window Frame
(Sucuoglu, 1997)

3.2 Curtain Walls

Curtain wall systems, also known as suspended glazing systems use the actual structural properties of glass to create high performance, long span glass wall panels (Figure 14). Curtain wall systems support glass using a combination of bolts and clamps in which the entire vertical load is carried from the top of the wall section. Each curtain wall section extends the entire height of the building floor, and in some cases spans multiple floors. Curtain walls typically perform better than glazing systems under earthquake loading. As a result of the ability of bolted connections to easily rotate (at levels below the upper rigid connection), curtain walls experience reduced localized stresses, allowing them to accommodate much larger interstory drifts. Some newer curtain wall systems completely isolate the glass from the buildings structural system causing an uncoupling of its relative movement, further minimizing stresses.

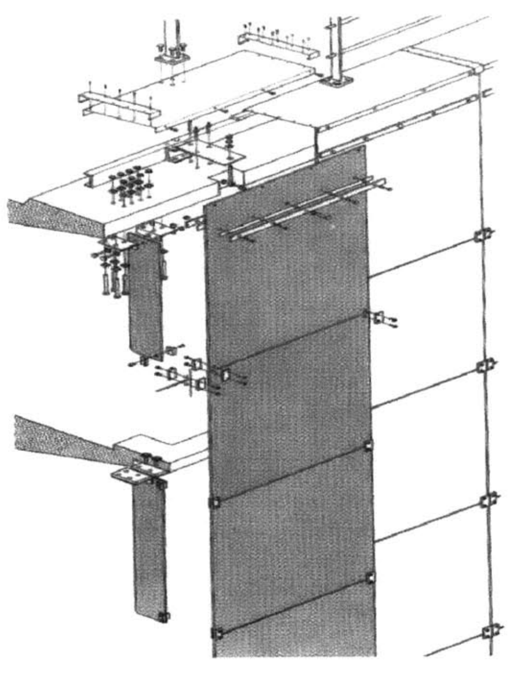

Figure 14 - Typical Curtain Wall System
(Behling, 1999)

3.3 Point Fixing Systems

Recent development of point fixing wall systems has contributed to ability of glass wall systems to withstand extreme seismic loadings. In a point system, the glass is hung at points, just as the name suggests. The points are usually located at the corners and/or joints between panes. There are many variations in the method of attachment of point fixing systems. A point fixing system may use a bolt through the glass panel. Some point systems have been developed using a clamping system, which places fittings both on the exterior and interior of the glass, but does not penetrate through the point. The characteristics that all point fixing systems have in common is the ability to rotate in conjunction with the in-plane and out-of-plane movements associated with seismic loadings. More descriptively, the actual point fixing fittings are designed to either move with the glass, or to be articulated such that the glass may rotate about the point fixing fitting in similar way to a ball bearing. An excellent example of the use of point fixing technology can be seen in the Glass Hall recently constructed in Neue Messe Leipzig, Germany (Figure 15). In the Glass Hall, point fixing was used for both wall and roof attachments to create an impressive structural system.

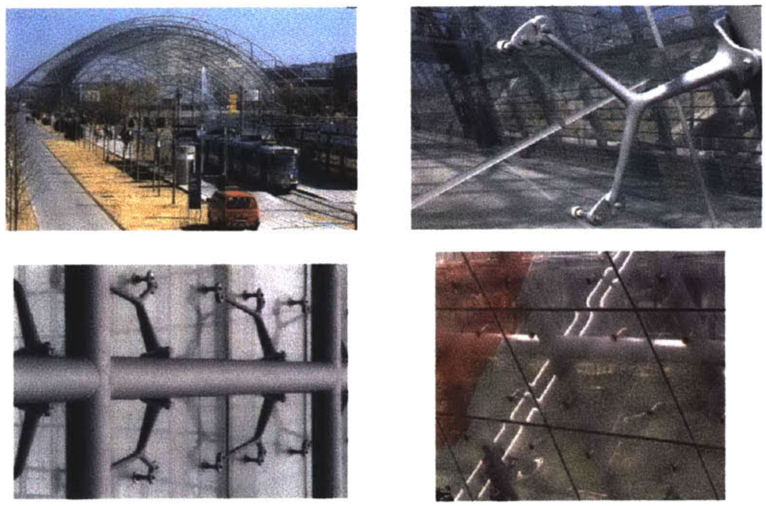

Figure 15 - Point Fixing System, Glass Hall, Neue Messe Leipzig, Germany (Ritchie, 1997)

The Pilkington Planar Corporation has developed most of the advances in point fixing. Pilkington has been a leader in the glass manufacturing industry for over 150 years. Many of the fittings developed by Pilkington Planar have been designed to allow for substantial in-plane movement to withstand Zone 4 seismic forces (Figure 16). The newest point fixing designs are now incorporating articulated bolts that all for glass to rotate more freely in all directions.

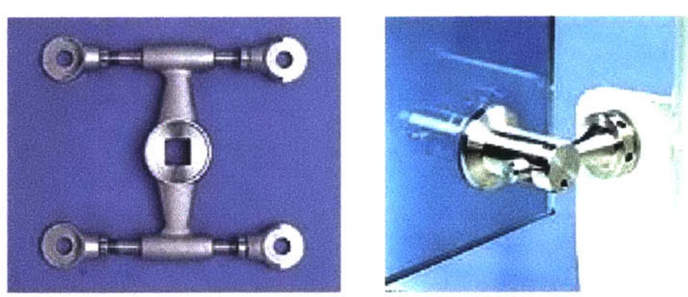

Figure 16 – Pilkington Planar Point Fixing Fittings (W&W Glass Systems, Inc., 2000)

3.4 Anti-Buckling Glass Fins

In order accommodate large vertical spans, without buckling of the glass panes, a system of vertical fins has been developed. The fins, made entirely of glass, use the structural properties of glass itself to improve the out-of-plane stiffness of the entire wall system. These fins are usually clamped at the bottom and top, and use a point fixing system to attach to the glass wall panels at intermediate locations. Two examples of the use of glass fins to increase lateral stability can be seen at the Park View Restaurant in Hong Kong and the Museum of Fine Arts in Boston (Figures 17 and 18).

Figure 17 - Glass Fins, Park View Restaurant, Hong Kong (W&W Glass Systems, Inc., 2000)

Figure 18 - Glass Fins, Museum of Fine Arts, Boston, Massachusetts (W&W Glass Systems, Inc., 2000)

3.5 Guyed Glass Structures

In a guyed glass structure, the main objective is to minimize the stresses within the glass by introducing an external stress that counteracts the loading. The source of the external stresses may be either due to passive or active prestressing. The prestressing is applied through a system of metal rods and wires, usually made of either aluminum or steel. The glass in guyed structures may be hung using any of the traditional methods: glazing, curtain walls, or point-fixing systems. Examples of various guyed glass structural design ideas are shown in Figure 19.

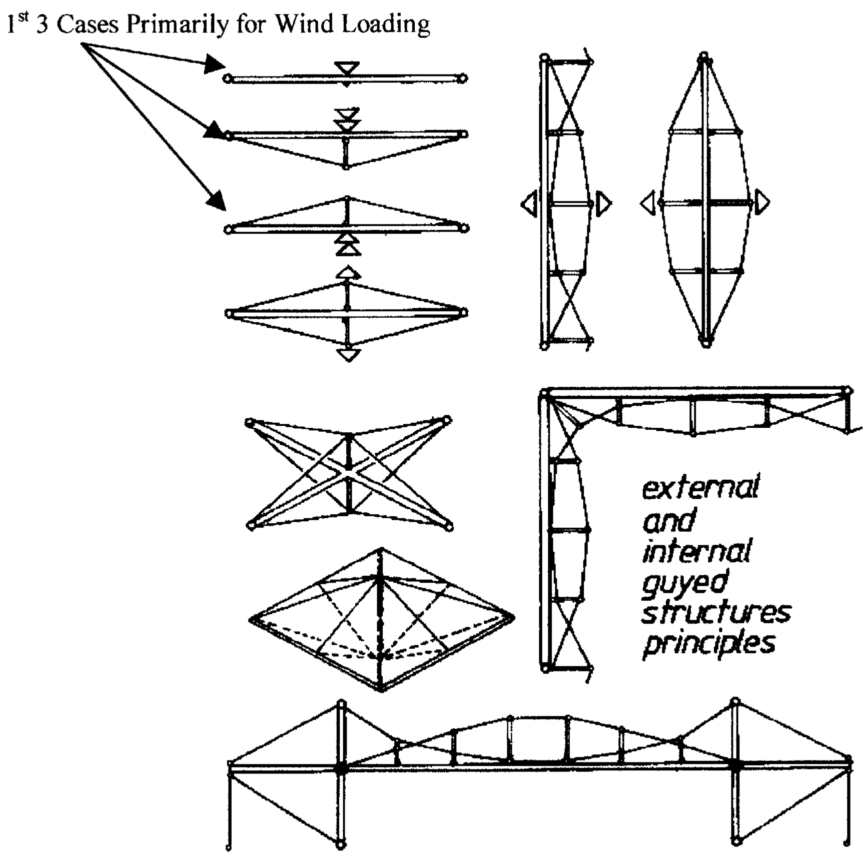

Figure 19 - Guyed Glass Structures

(Eekhout, 1990)

In a passive guyed system, the load capacity of a pane of glass may be doubled in the out-of-plane direction. The doubling of capacity is achieved by prestressing the glass with forces in the opposite direction of the anticipated loading. In the case of wind loading, this is very effective, however in the case of seismic loading, the loading is applied alternately in opposite directions. Therefore, the first three cases in Figure 19 show guyed systems that would not be as effective against earthquakes, but the remaining systems could be more readily adapted due to their ability in resist forces in both directions. Examples of how guyed glass systems are architecturally placed in structures may be seen in the guyed walls of the Glass Music Hall in Berlage Exchange and the guyed glass roof for the Flower Gate in Hulst (Figures 20 and 21).

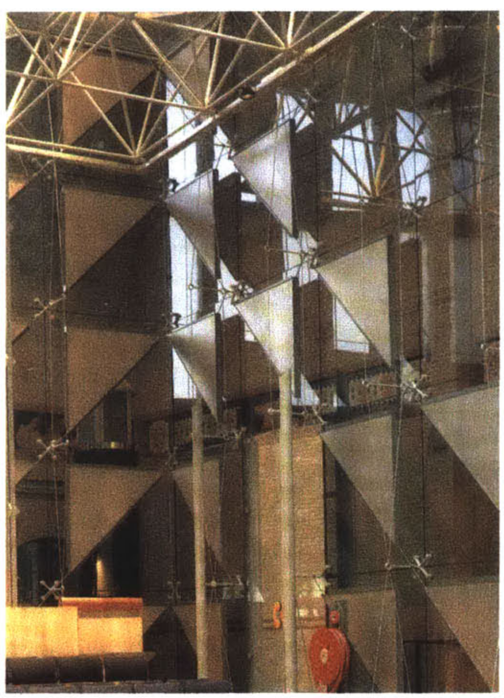

Figure 20 – Guyed Walls of Glass Music Hall in the Berlage Exchange (Eekhout, 1990)

Figure 21 - Guyed Glass Roof for the Flower Gate in Hulst (Eekhout, 1990)

In order to make maximum use of the guyed system, an active control of the prestressing force could be used. In the case of active control, the forces applied to a structure due to external loadings are carefully processed and analyzed in order to adjust the controlling prestress force applied by the guyed structural system (Figure 22). The active method could actually increase the capacity beyond the 2x of a passive system, and would only be limited by the compressive strength of the glass. Although, there are no known applications of actively guyed glass systems, development of active control systems for other materials is underway and could easily be applied to glass.

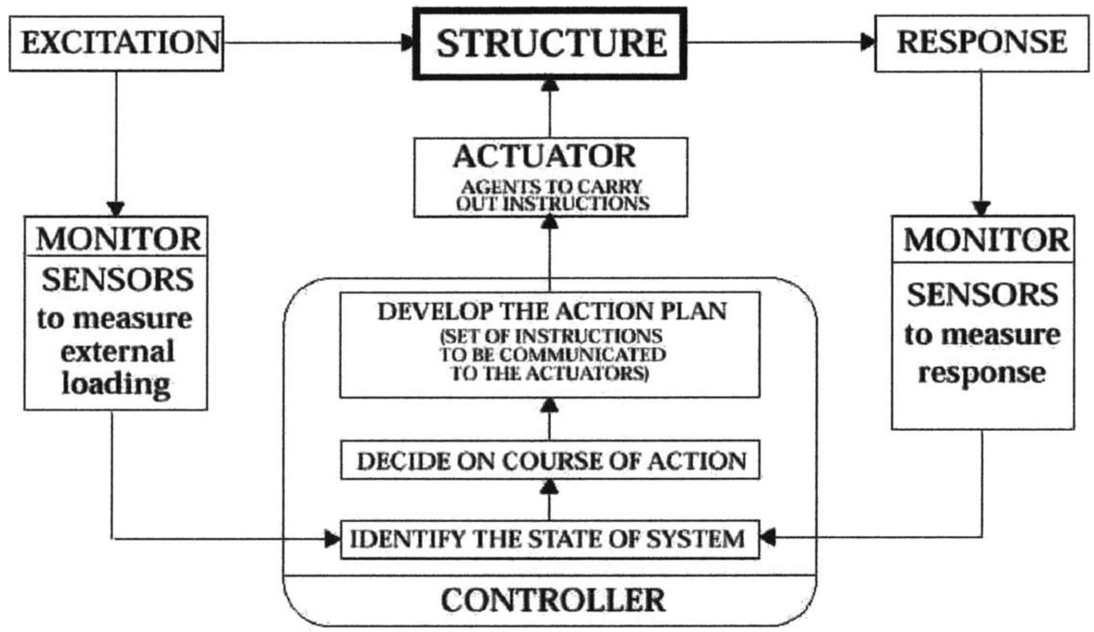

Figure 22 - Components of an Active Control System

(Connor, 2001)

4 Rehabilitation Options

Although many improvements have been seen the design of glass in new construction, few methods of rehabilitating existing buildings to reduce the risk of injury and damage are available. One of the main methods of rehabilitation currently available is PET (Polyester) film application method, which has come under criticism lately for its effectiveness. Another possibility is complete replacement of existing glass and/or frames with improved glass and/or frames that allow more movement, however this option has seen only minimal acceptance due to the high cost. Finally, the use of acrylic substitutes to replace glass, especially in first level storefronts has seen mixed results, and is not expected to see widespread use. Considering the amount of damage related to broken glass in major earthquakes, it is easily seen that something must be done. However, insufficient resources are being invested in the search for new alternatives to retrofit glass in existing structures for a reasonable cost. In the meantime, this section gives an overview of the few methods currently being used, and a brief discussion of their effectiveness.

4.1 PET Film Applications

One of the methods of retrofit currently available, aftermarket PET (Polyester) film, has seen mixed results and is now being questioned as to its effectiveness. PET film retrofitting consists of applying a laminating PET film to the glass to increase resistance to breaking. First, it is very important to distinguish between aftermarket PET film laminating and actual "laminated glass" in which there is a PVB (polyvinyl butyral) plastic interlayer placed between two factory heat-sealed layers of glass. Aftermarket PET film is only a thin layer of adhesive backed PET plastic film, which comes in both clear and tinted colors. Aftermarket PET film application is not performed under any building codes, but only by the responsibility of the contractor, therefore significant variations in the quality and related performance have been found. Also, PET film is usually only applied to one side of the glass, and experience has shown that in earthquake loading the broken shards of glass may not remain attached to the PET film, therefore causing a dangerous flying glass hazard similar to untreated annealed glass.

Finally, a critical aspect of PET film installation regards the amount of coverage of the glass panes. Sometimes, the PET film is only applied to the exposed glass surface within a window frame, this is a simplifying method that may save time and money for installers, but may have a dangerous side effect in terms of performance. When PET film is only applied to the exposed glass surface, the remaining portion of the glass, the outer section covered by the frame has a resultant strength lower than the laminated main section. When incomplete application occurs, the glass at the edges, which is covered by the frame and is coincidentally the glass under the highest stress, has a tendency to fail first. When the unlaminated glass within the frame fails, the entire pane of laminated glass may then fly out of the frame as a larger, and more dangerous projectile than if the glass had remained unlaminated and had failed by breaking into much smaller pieces.

4.2 Glass and/or Frame Replacement

An effective, but expensive alternative to retrofit older storefronts and high hazard structures is the complete replacement of the existing glass system. Older storefront designs often do not incorporate the newer, more effective, improved glass types such as fully tempered and laminated glass. In addition, older glazing systems often do not accommodate the necessary interstory drifts that are required by the present building codes. Therefore, a logical solution is the complete replacement of these obsolete and dangerous glass applications. Unfortunately, complete replacement is not an easy or inexpensive task. Most of the complete replacements that do occur are associated with a major renovation of the entire structure. These replacements often occur as a result of building code requirements that force the renovated building to meet glass systems requirements not in effect when the structure was first built. Without the mandate of the building codes, and without the expenditure associated with a full renovation it is unlikely that building owners will pay for the replacement of the glass and associated systems in most structures. It is often more cost effective to wait and risk a catastrophic earthquake, rather than to perform a glass replacement that still is not 100% guaranteed to survive a quake. In some rare situations, glass has been replaced to facilitate improvements such as lowering energy costs, or increasing safety in very high hazard areas such as glass doors or roofs. Finally, while desirable, a full replacement of all the glass and glass systems to meet current building codes is unlikely, and probably unreasonable in some cases due to the costs involved, therefore a more economical solution is desperately needed.

4.3 Acrylic Substitution

One method of rehabilitation that has seen mixed results is the use of an acrylic substitute, as a replacement for glass. While an entire overview of clear acrylic panels is well beyond the scope of this paper, it is important to briefly mention its strengths and weaknesses relating to earthquake performance. Acrylic as a material is an opposite of glass; it has a higher flexibility and a lower strength. As a result, clear acrylic panels used for storefront glazing on buildings were post earthquake security is a concern provides a possible alternative. While lower strength than most glass glazing, acrylic panels are typically able to withstand the deflections due to the loading of a moderate earthquake. However, in order to achieve the necessary sizes common on storefront applications, the acrylic panels must often be of a greater thickness than the equivalent glass panels, negatively affecting transparency. In addition, long-term performance of acrylic is much lower than glass. For example, acrylic panels are easily scratched, and even things like gentle washing and windblown dust can cause deterioration in the transparent properties of the panels. To summarize, clear acrylic panels have seen limited use in storefront designs, but the increase in security often comes with a decrease in the quality of the appearance, making them appropriate only for low-end applications.

5 Code Issues

Most building codes from around the globe address glass design in the same manner. Seldom is glass itself even mentioned in the structural sections of the code, but typically, glass design is addressed by limits on in-plane building movement and by minimum out-of-plane stresses for building components. Basically, most codes address the issue of glass design by focusing on the rest of the structure, and not on the actual glass itself.

5.1 In-Plane Loading

Design for in-plane loading of glass focuses on avoiding the introduction of localized stresses into the individual glass panes. As a building moves laterally, a typical rectangular opening rotates and no longer holds the same rectangular shape. As a result of this rotation, the glass panels often come into contact with their supporting frames only at point locations, which maximize the likelihood of a failure due to the intrinsic structural behavior of glass (Figure 23). In order to avoid these failures, building codes have established a set of limits on in-plane lateral movements of a structure, also known as "interstory drift". A comparison of the different limits on interstory drift used by many of the largest building code authorities can be found in Table 3.

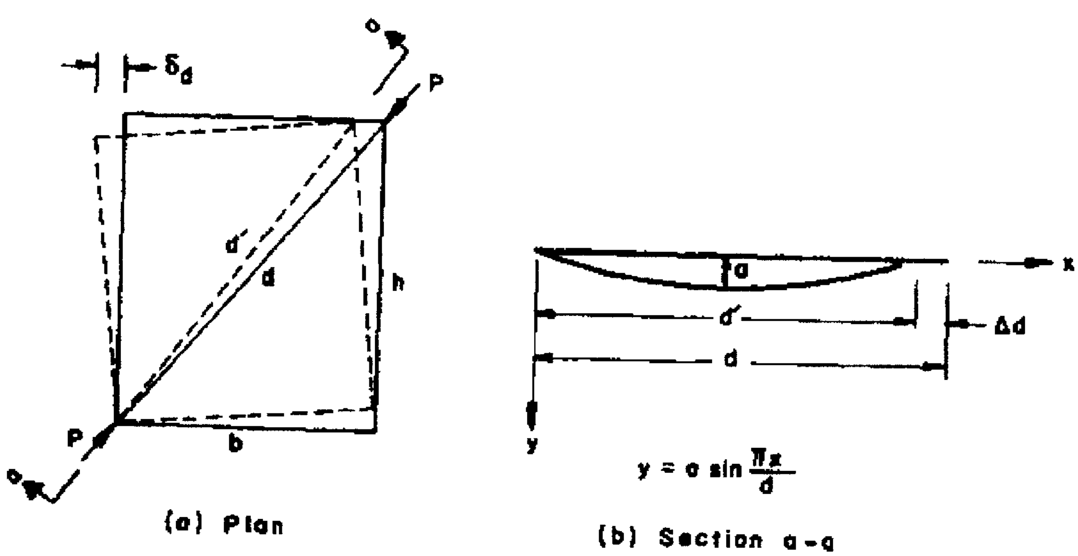

Figure 23 - Interstory Drift Loading on Glass in Standard Window Frame (Sucuoglu, 1997)

Code	Design Limit State	Maximum Drift Ratio
NEHRP	Ultimate	0.015
UBC	Ultimate	0.015 or 0.0019 Rw $T < 0.7$ s 0.011 or 0.0015 Rw $T > 0.7$ s
New Zealand	Ultimate	0.02 $h_n < 15$ m 0.015 $h_n > 30$ m
Canada	Ultimate	0.02
Japan	Service	0.005-0.0083
CEB	Service	0.002-0.0025
ECCS	Service	0.003-0.006

Table 3 – Maximum Drift Ratios of Major Building Codes (Sucuoglu, 1997)

Although designing for interstory drift has been fairly effective in reducing glass damage during earthquakes, new understanding of the behavior of glass under loading has made it possible to actually account for some of the load resisting characteristics that are usually ignored. In a structure composed of a primarily non-glass exterior, interstory drift design may be necessary due to the non-compatibility of the materials. However, in newer, lighter, glass-based facades, the need to look beyond traditional design methods is necessary. In a primarily glass façade, the strength of the glass under lateral in-plane loading becomes critical in the overall design requirements, an aspect overlooked in almost every major building code. Glass product manufacturers currently dictate the design of glass intensive facades, and withhold the glass property data needed by outside designers to create their own design. Therefore, designers are required to specify the use of pre-manufactured glass systems, and have little room for flexibility or creativity.

5.2 Out-of-Plane Loading

Out-of-plane loading is typically addressed in building codes by requiring components of a building to withstand specific forces. While occasion earthquake related failures are the result of out-of-plane loading, they are much more rare than failures due to in-plane loading. In newer structures, there is a requirement associated with the force capacity per square area that must be met. Occasionally, earthquake loading will control this factor, but more often in the case of glass, it is a product of wind loading.

6 Conclusion

In conclusion, glass is a constantly improving building material. Historically, a lack of understanding has led to designs that were inadequate to withstand seismic loadings. However, the improvements in methods of attaching glass to a structure and methods of improving glass properties should soon make these glass design problems of the past. In addition, an important, but mainly overlooked issue, will be how to retrofit the millions of existing structures that have inadequate designs. In order to achieve the needed state of practice, additional research and accompanying changes to building codes will be required.

It would appear that the there are two trends regarding the direction of the glass industry. One direction being taken is to design glass systems that are isolated from the structures motion, and therefore the uncoupled glass systems only have to resist minimal forces. Examples of isolated systems would include some curtain wall designs and some point fixing applications. The other direction that is being seen is to design the glass systems so that there is an allowance for glass movement, without inducing excess stresses into the glass panels themselves. Examples of systems that allow glass movement would primarily be glazing systems, but many curtain wall systems and point fixing applications have also been designed to allow glass movement. In addition, the improvements in manufacturing, laminated glass techniques, and glass strengthening methods are contributing to safer, higher-performance glass designs. Also, European designers, following a rich history of glass related developments, are constantly leading in glass related design with even newer and more innovative ideas such as guyed structures for the incorporation of glass within a building. Finally, the ability to both to avoid inducing excessive forces in seismically loading glass systems (through either method: allowing glass movement or uncoupling glass from the structure) and to increase the strength of the panels against failure is combining to achieve the state-of-the-art in earthquake resistant designs.

Despite the positive advances seen in new designs, existing structures and building codes continue to be the areas needing the most improvement. Little research is being done to develop efficient and effective methods to retrofit the millions of existing structures with inadequate or even dangerous glass designs. It will be important to develop new methods for glass retrofit that provide vital safety improvements to building owners, while still maintaining a reasonable cost. In addition, many building codes continue to ignore the issue of glass performance, and often allow only glass manufacturers to establish standard designs, thus limiting creativity within the industry. Around the world, building codes should address glass related issues in methods that will continue to ensure public safety, while encouraging a much higher level of innovation than has been seen to date.

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