HanitaTek
Window Films

Excerpts from Dr. T. C. Hutchinson's (University of California – San Diego) 2009 Study on Seismic Effects

As a member of the AIMCAL Window Film Committee, Hanita Coatings is pleased to present this excerpt from Dr. Hutchinson's recent study of seismic effects, including the effect of window film on a glazing system during seismic events. This study was supported by the members of the AIMCAL Window Film Committee and has been published in 2009.

The full report is considerably longer, and includes chapters that have been deleted from this copy: these are Chapters 2-4 on Experimental Design, Experimental Results and Results Analysis. To facilitate brevity and ease of digital transmission, this version presents the Introduction and the Conclusion, which removes 110 pages from the full document. If you are interested in the entire version, please contact HanitaTek Window Films at lwbrown@hanitatek.com.

STRUCTURAL SYSTEMS RESEARCH PROJECT

Report No.
SSRP 09-02
Final

Experimental evaluation of the in-plane seismic behavior of store-front window systems

By

C. Eva and T. C. Hutchinson

Final Report.

May 22, 2009

Department of Structural Engineering
University of California, San Diego
La Jolla, California 92093-0085

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DISCLAIMER

ABSTRACT

Glass window systems have been shown to suffer significant damage during earthquake loading, resulting in the potential for human injuries and significant economic losses. Film-coated windows are recognized to hold potential for mitigating these adverse affects. However, despite its potential, limited study has been conducted to evaluate the benefits of film-coated window systems under seismic loading. Of those studies undertaken, the focus has been on anchored film, which is less common in practice. Furthermore, no thorough study of the effects of loading histories on window system performance as related to envisioned scenario earthquakes, has been performed to-date. It is unclear if previously used loading protocols are representative of demands induced on window systems used in buildings in the California seismic environment. Finally, previous studies have been limited in terms of their variation of window system geometry, with the largest experimental studies focused on a single 0.83 aspect ratio (height/width) specimen.

In this work, three variables of interest were studied through in-plane seismic racking experiments of store-front window systems: (i) loading protocol, (ii) window film type and attachment, and (iii) aspect ratio. The baseline window system was a 5’x5’ unit, constructed of ¼” annealed single pane glass supported by an aluminum frame, with detailing typical of mid-rise (store-front) window systems. This report presents the overall experimental program, the identified damage modes and associated drift limits, and trends associated with variation of the aforementioned test variables.

ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the financial support and technical guidance extended by the Association of Industrial Metallizers, Coaters and Laminators (AIMCAL) – Window Film Committee, where Mr. Darrell Smith is the program manager and Mr. Andres Vasquez is the technical adviser. Members of the AIMCAL Window Film Committee include Bekaert Specialty Films; CP Films Inc; Hanita Coatings; Johnson Window Films, Madico Inc; and 3M Company. Dr. George Mavroeidis assisted with processing the ground motions and conducted the seismic hazard analysis for the load protocol study. In addition, the writers wish to acknowledge the testing assistance of the Charles Lee Powell Laboratory staff and in particular Dr. Christopher Latham, Mr. Andrew Gunthardt, and Mr. Charley Stearns. This report contributes to the Masters Thesis of the first author, Mr. Charles Eva, where Professor Tara Hutchinson served as the chair. Helpful suggestions of the committee members, Professors José Restrepo and Chia-Ming Uang, are greatly appreciated.

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Chapter 1: Introduction

1.1 Motivation

Previous earthquakes have confirmed that window systems can sustain substantial damage, in spite of observed good performance of other nonstructural elements, within the same structure [1964 Alaska (Lagorio, 1990); 1971 San Fernando (Ayres and Sun, 1973); 1978 Off-Miyaga (Sakamoto et al., 1984); 1985 Mexico City (Evan and Ramirez, 1989); 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 2001 Nisqually (EERI 1990, 1995a, b, 2001; Lingell, 1994)]. Earthquake-induced damage to window systems has the potential to cause human injuries and result in significant economic losses due to business disruptions and loss of functionality (Figures 1.1 and 1.2).

Figure 1.1 Damage to window systems observed during the Palm springs, 1986 earthquake. (Courtesy of the National Information Service for Earthquake Engineering, EERC, University of California, Berkeley)

Figure 1.2 Damage to window systems observed during the Puget Sound, Washington, 1965 earthquake. (Courtesy of the National Information Service for Earthquake Engineering, EERC, University of California, Berkeley)

1.2 Previous work and State-of-Practice

Perhaps the earliest work on this subject in the United States is that reported by Boukamp and Meehen (1960) at the University of California, Berkeley. The authors conducted 33 monotonic, two reversed cyclic, and four impact tests on windows with glass panels ranging in thickness from 1/8" to 1/4". Variables considered included window glass-to-sash clearance, sash type and size, and location of the glass fixity. The authors find that the frame type has a marked impact on the behavior of the units, and that large deformation capacities are achieved by the specimens (up to an interstory drift ratio of 8%). The later finding was attributed to the large glass-to-mullion clearances provided in common practice. The tests of Boukamp and Meehan (1960) were the only such experiments to-date to systematically test specimens of varying (Height:Width) aspect ratios, ranging from 0.5, 1.0, and 2.0 (sizes of 2'x4', 4'x4', 8'x4'). Conclusions from this study indicate that although the overall limit state displacement increases with increasing aspect ratio of the window panel, drift ratios (displacement limit divided by height) may increase or decrease, depending on the hardness of the bedding mastic. Soft mastic resulted in limit state drift ratios that decreased with increasing aspect ratio, whereas hard mastic resulted in limit state drift ratios that increased with increasing aspect ratio. Although these conclusions are valuable, modern window detailing may vary considerably and it is not known how damage modes and associated drift limits are affected by the window system's aspect ratio.

Between the late 1980s and early 1990s, the BRANZ laboratory in New Zealand conducted testing on single window specimens of 4.6' x 4' and 9.2' x 4' (1/4" thick), primarily in an effort to evaluate serviceability drift limits (Thurston and King, 1992). Specimens were loaded with monotonic, static and incremental cyclic loading. Of interest in the tests were displacement rates, boundary conditions, and cycle count per amplitude. The authors find that rotation of the glass, within the window system is the largest contributor to the deformation capacity of the system.

The most extensive testing programs performed on glass panel systems to-date have been those at the University Missouri-Rolla (UMR) and Penn State (Behr and Belarbi, 1995, 1996; Behr, 1998; Memari et al., 2003, 2004). These tests consistently involved 5'x6' sized windows (AR = 0.83), tested in an in-plane loading rig, designed specifically for the window systems (Figure 1.3). Testing performed at both UMR and Penn State involved use of a single loading protocol throughout the investigations. The protocol adopted (termed *crescendo*) is a variation of the Applied Technology Council - 24 (ATC) (1992) protocol for steel moment frames and their components, and it is now recommended by American Architectural Manufactures Association (AAMA) (2001a) for testing of window systems (Figure 1.4). Variables in these tests have been extensive, including, glass type (annealed, tempered, and laminated) and glass thickness (1/4" to 1", with single and multi-pane glazing).

The focus of these experiments was to document the drift limits associated with these two key damage states, which are described in more detail in section 1.2.1. Table 1.1 summarizes the drift ratios in which glass was observed to first crack (serviceability limit state), and then fall-out (ultimate limit state) during the experiments conducted by others. This Table includes only previous work, where the glass thickness matches that considered in the present study; i.e. ¼" annealed monolithic glass, aluminum framing (additional data may be found in Appendix C). From the previous data, monotonic testing resulted in an average serviceability drift ratio of

3.1% with an average standard deviation of 40%. Cyclic testing averages 4.1% with an average standard deviation of 30%. Ultimate drift ratios were not studied in previous monotonic tests however the average cyclic drift ratio was 5.6% with an average standard deviation of 23%. The high standard deviations can be attributed to the variations of glass and mullion types.

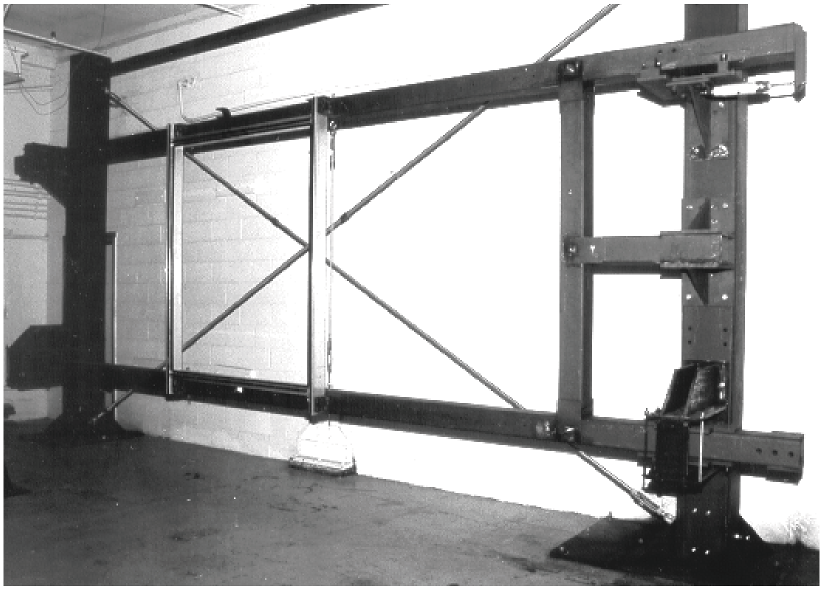
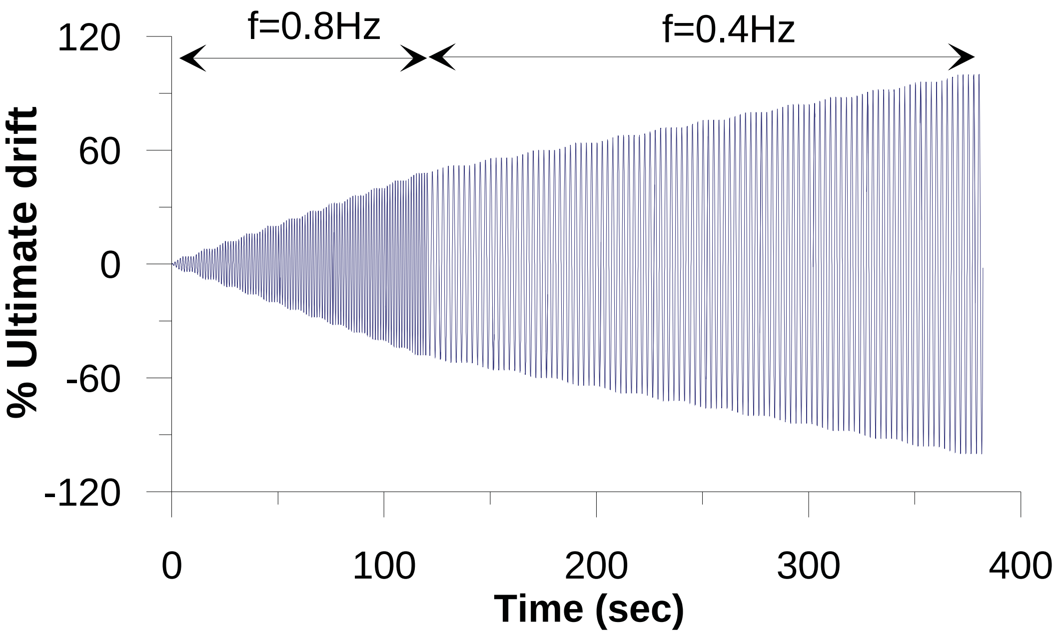
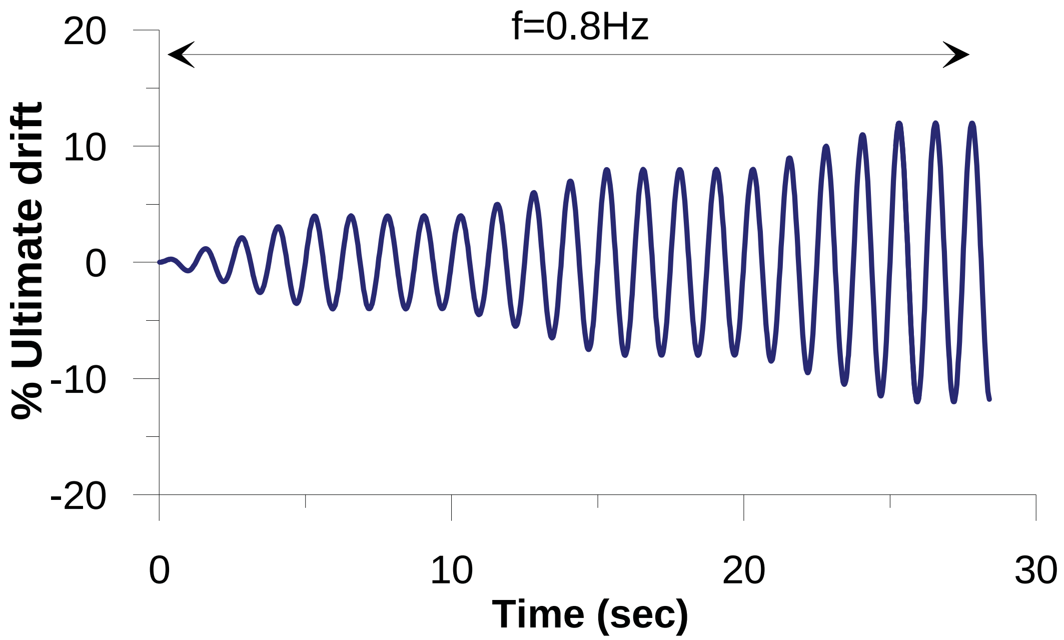


Figure 1.3 Facility at UMR used for dynamic racking tests of full-size curtain wall panels (Courtesy of Behr, 1996).



(a) Full record



(b) First 30 seconds of the protocol

Figure 1.4 Crescendo protocol used at UMR and Penn State for testing of full-size curtain wall panels and adopted by AAMA (2001b) (Behr, 1996)

Experiment condition					Experiment results			
Glass size $H \times L$ (ft)	Glass thick (inch)	Glass type	Load type	Number of specimens	Glass cracking		Glass fallout	
					Drift (inch)	Drift ratio (%)	Drift (inch)	Drift ratio(%)
Bouwkamp (1960)	**Objective: To study the effect of sash material and panel attachment**							
4X8	0.25	plate glass, aluminum sash, all around attachment of the sash to the boards, 1/4 clearance, soft putty	monotonic	1	1.46	1.52	N/O[1]	N/O
4X8	0.25	plate glass, aluminum sash, head-and-sill attachment of the sash to the boards, 1/4 clearance, soft putty	monotonic	1	2.36	2.46	N/O	N/O
4X8	0.25	plate glass, steel sash, all around attachment of the sash to the boards, 3/8 clearance, soft putty	monotonic	1	2.26	2.35	N/O	N/O
4X8	0.25	plate glass, steel sash, head-and-sill attachment of the sash to the boards, 3/8 clearance, soft putty	monotonic	1	1.84	1.92	N/O	N/O
4X8	0.25	plate glass, wood sash, all around attachment of the sash to the boards, 1/4 clearance, soft putty	monotonic	1	3.52	3.67	N/O	N/O
4X8	0.25	plate glass, wood sash, all around attachment of the sash to the boards, 1/4 clearance, soft putty	monotonic	1	3.83	3.99	N/O	N/O
4X8	0.25	plate glass, aluminum sash, all around attachment of the sash to the boards, 1/4 clearance, soft putty	monotonic	1	2.06	2.15	N/O	N/O
4X8	0.25	plate glass, aluminum sash, all around attachment of the sash to the boards, 1/2 clearance, soft putty	monotonic	1	2.8	2.92	N/O	N/O
4X8	0.25	plate glass, aluminum sash, all around attachment of the sash to the boards, 1/4 clearance, hard putty	monotonic	1	1.01	1.05	N/O	N/O
4X8	0.25	plate glass, aluminum sash, all around attachment of the sash to the boards, 1/2 clearance, hard putty	monotonic	1	2.20	2.29	N/O	N/O
4X8	0.25	plate glass, aluminum sash, panel subdivided horizontally, all around attachment of the sash to the boards, 1/4 clearance, soft putty	monotonic	1	4.31	4.49	N/O	N/O
4X8	0.25	aluminum sash, panel subdivided horizontally, all around attachment of the sash to the boards, 1/2 clearance, soft putty	monotonic	1	6.06	6.31	N/O	N/O
4X8	0.25	plate glass, aluminum sash, panel subdivided vertically, all around attachment of the sash to the boards, 1/4 clearance, soft putty	monotonic	1	2.49	2.59	N/O	N/O
4X8	0.25	plate glass, aluminum sash, panel subdivided vertically, all around attachment of the sash to the boards, 1/2 clearance, soft putty	monotonic	1	5.41	5.64	N/O	N/O

[1] N/O – Not Observed

Table 1.1 Summary of related window system tests in literature

Experiment condition					Experiment results			
Glass size $H \times L$ (ft)	Glass thick (inch)	Glass type	Load type	Number of specimens	Glass cracking		Glass fallout	
					Drift (inch)	Drift ratio (%)	Drift (inch)	Drift ratio(%)
Behr et al. (1996) Objective: Evaluate performance of architectural glass								
5X6	0.25	Annealed monolithic (Store front)	crescendo	12	3.02	4.23	4.21	5.90
5X6	0.25	Fully tempered monolithic	crescendo	16	3.98	5.57	3.98	5.57
5X6	0.25	Annealed Laminate	crescendo	12	5.71	8.00	5.71	8.00
Behr et al. (1998) Objective: Evaluate various glass types								
5X6	0.25	Annealed monolithic (Curtain wall)	crescendo	6	1.97	2.80	2.17	3.08
5X6	0.25	Heat-strengthened monolithic	crescendo	5	3.39	4.82	3.39	4.82
5X6	0.25	Fully tempered monolithic	crescendo	5	2.95	4.19	2.95	4.19
5X6	0.25	Annealed laminated	crescendo	6	1.81	2.58	5.59	7.95
5X6	0.25	Annealed monolithic with 0.1mm PET film	crescendo	6	1.97	2.80	3.98	5.66
5X6	0.25	Heat-strengthened monolithic spandrel	crescendo	6	2.40	3.42	2.48	3.53
5X6	0.25	Heat-strengthened laminated	crescendo	6	2.13	3.02	5.12	7.28
Memari et al. (2004) Objective: To study glass fitted with anchored pet film								
5X6	0.25	clear annealed monolithic glass, with film (edge grip)	crescendo	2	2.6	3.30	4.7	5.97

Table 1.1 Continued

1.2.1 Damage States

Previous work has identified two predominant damage states associated with (i) serviceability (Figure 1.5) and (ii) ultimate condition of the window system post-earthquake (Figure 1.6). Serviceability refers to the condition whereby the window system is repairable and does not pose any safety hazards post-event (e.g. minor cracking or gasket damage only). In contrast, the ultimate damage state refers to the condition whereby the window system is not repairable and does pose safety hazards post-event (e.g. large region of glass has cracked or fallen from the unit). The first studies on damage states were conducted by Behr et al. (1995) at the University of Missouri-Rolla. Behr et al. (1995) describe an ultimate limit state as glass damage that poses a threat to life safety because of glass breakage and glass fallout. Behr et al. also describes serviceability damage states or thresholds as system repairs that become necessary due to problems that include visual degradation, risk of future glass breakage due to thermal and wind effects, and loss of building envelope seal integrity.

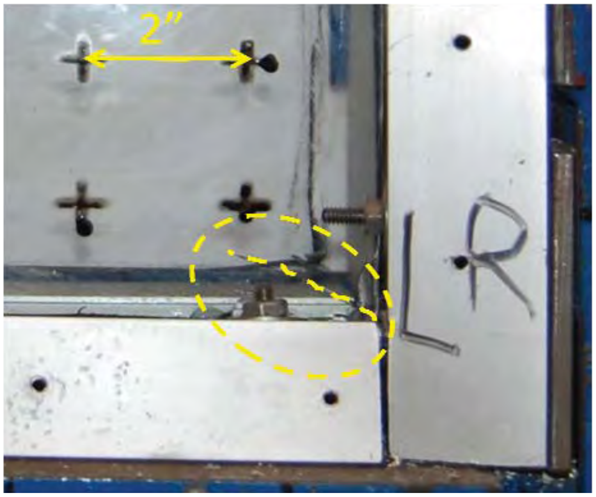


Figure 1.5 Serviceability Damage State: Minor Cracking

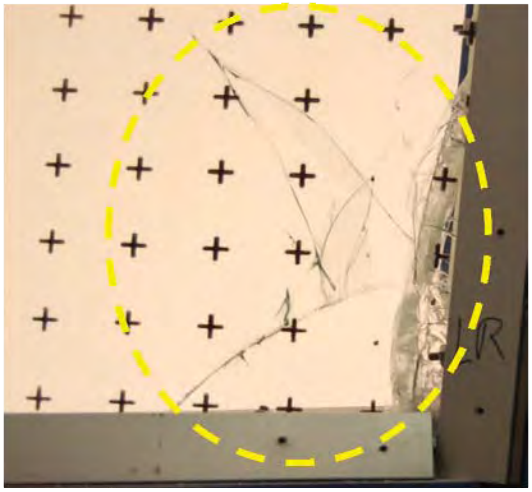


Figure 1.6 Ultimate Damage State: Extensive Cracking

1.2.2 Design Code Prescriptions

The Federal Emergency Management Agency (FEMA) design documents indicate that at a drift ratio of 1%, there is a 50% chance that the glass within a window system will crack (FEMA 461 2006). This recommendation is inconsistent with previous observations, which largely indicate that glass cracking occurs at a minimum drift ratio of 2.5%. A much more conservative value can be found in the Canadian Standards Association (CSA 2005). CSA indicate that the deflection shall not exceed 1/16 inch per foot of height of the glazed opening or 0.5% drift ratio, to minimize window system damage. At the time of this report, the only code which took into account any seismic relation in predicting/preventing glazing damage was the Uniform Building Code (UBC 1994). The UBC states that the allowed maximum drift ratio for buildings with a period of less than 0.7 seconds was 1.5% or $0.0019R_w$, and for buildings with a period greater than 0.7 seconds the maximum allowable drift ratio was 1.1% or $0.0015R_w$. Table 1.2 summarizes this information. All drift ratio values were quite conservative, which exposes the lack of data to accurately predict when glazing damage might occur.

Reference	Drift Criteria
FEMA 461 (2006) (Federal Emergency Management Agency)	At **1% drift ratio**, there is a 50% chance that glazing will crack
CSA (2005) (Canadian Standards Association)	Deflection shall not exceed 1/16 inch per foot of height of the glazed opening. (**0.5% drift ratio**)
UBC (1994) (Uniform building code)	The allowed maximum drift ratio is **1.5%** or 0.0019Rw (T<0.7s), **1.1%** or 0.0015Rw (T>0.7s)

Table 1.2 Summary of design prescriptions for window systems

1.3 Scope of this Work

In this work, three variables of interest are studied through in-plane seismic racking experiments of window systems, namely: (i) loading protocol, (ii) window film type and attachment, and (iii) aspect ratio. In addition, specimen repeatability is evaluated by testing three specimens of select types during the program. The baseline window systems is a 5'x5 unit, constructed of ¼" annealed single pane glass supported by an aluminum frame, with detailing typical of store-front window systems. A total of 53 window systems were tested. The justification for the three variables of interest is as follows:

(i) Loading History – Various loading protocols exist in the literature for simulating seismic demands on structural and nonstructural components [see e.g. for bridge piers – FHWA (2004); for timber components – Krawinkler et al. (2000) or sequential phased displacement (SPD) – e.g.

Shepard (1995, 1996); for steel components – ATC (1992); for cladding systems – AAMA (2001a)]. Such protocols are either displacement or load-controlled, include (or not) reversed cycles of equal or unequal amplitude, and may be at static or dynamic rates. A common characteristic pervasive amongst the types of load protocols representative of seismic loading is the desire to consider reversed cyclic loading conditions due to the reversed cyclic nature of earthquake loading. However, the actual quantity and amplitude of reversed cycles for different components is still under debate. Speculation regarding loading protocol effects has further been increased due to the poor performance of various types of structural components [e.g. Dinehart and Shenton (1998), Ficcadenti et al. (1998), Gatto and Uang (2003)]. Such speculation is no less for nonstructural components [e.g. piping work by Malhotra et al. (2003), Hoehler et al. (2009)]. These and other studies have pointed out the now well recognized fact that to evaluate the performance of a component or system, damage in a component is cumulative and this level of damage depends on the history of deformations or loads that the component undergoes (Krawinkler, 1996).

At present, the accepted protocol for testing window systems is that developed by UMR and Penn State researchers, the aforementioned Crescendo protocol (AAMA, 2001a). The crescendo protocol, shown in Figure 1.4, represents two frequencies of input (0.4 Hz and 0.8 Hz) and incurs ramp up cycles prior to four cycles at each maximum deformation demand. Furthermore, it imposes nearly 200 cycles of displacement to the specimens. It is unclear if such a protocol is representative of demands induced on window systems used in buildings in the California seismic environment. Further, it is unclear what effect other loading protocols will have on seismic drift limits and damage modes of window specimens. Parallel to this study, two new protocols were developed with emphasis on low- and mid-rise building structure drift response. This study indicated that cyclic drift counts on the order of 30-40 were more representative for typical building structures (Hutchinson et al., 2008).

To investigate the effects of load history, it is important to define baseline capacity and damage modes of the window specimens, prior to cyclic degradation. To perform such an assessment, a series of monotonic, displacement-controlled tests are performed first in this study to identify baseline conditions.

(ii) Window Film and Attachment – Film-coated glazing, although not specifically designed to withstand anticipated earthquake events (it's original intent being for safety or thermal purposes), is recognized to hold potential for mitigating the adverse effects in building and other structures under seismic loading conditions. However, to-date, only one study considered film-coated systems (Memari et al., 2004). This study focused on anchored film, which is less common in daily practice.

(iii) Window Aspect Ratio – As noted, the only systematic study of window aspect ratio was that conducted by Boukamp and Meeham (1960). Systematic study of the effects of window aspect ratio on damage modes and associated drift ratios is needed.

1.3.1 Report organization

This report is organized into the following chapters:

- Chapter 2 presents the experimental program, including the test matrix, set-up, instrumentation, and protocol for test execution.
- Chapter 3 presents a summary of experimental results; including identified damage states, physical observations, and a summary of global response characteristics of the window systems.
- Chapter 4 synthesizes results from the experiments, considering the effects of the three variables of interest in this study, namely load protocol, film thickness, and aspect ratio. In addition, comparison with previous work is discussed.
- Chapter 5 presents conclusions and findings of the study.
- Appendices are included to summarize the load rig design, individual test damage reports, and additional experimental data.

Chapter 5: Conclusions

5.1 Motivation

Damage to nonstructural components and systems during earthquakes threaten public safety, and are a major source of economic losses and business disruptions. Previous earthquakes have confirmed that despite good overall structural performance of a building, the nonstructural components and systems within it will very likely have sustained heavy damage. Window systems in particular are very susceptible to damage, due to their brittle nature and integration with the building perimeter.

The window system is a highly complex, and variably constructed system, consisting of glass panels, interface material between the mullion and glass, metal, plastic or wood mullions and an attachment mechanism to the building structure. Moreover, the glass may be filmed for safety of thermal purposes, and this film may be mechanically or chemically attached. Each of these elements poses its own risk of failure under seismic loading. Perhaps the most catastrophic, and dangerous situation is the development of cracks in the glass itself. Risk of human danger is increased upon severe cracking or glass fallout. Unfortunately, window systems are traditionally viewed as an architectural component to the overall building envelope, and therefore no attention is provided to them in design. Indirectly, however, one can consider their drift ratio limits and associated damage states as these relate to demands imposed on the building (windows are attached floor-floor).

Experimental investigations of the seismic performance of window systems in the United States date back to the early 1960's. Review of the literature indicates that limited study on the effects of window aspect ratio, loading protocol, and film coating, have been undertaken in the context of seismic performance evaluation. The largest test program to-date, led by UMR and Penn State, adapted use of a single load protocol, termed the *crescendo* protocol, which subjected the window systems to 180+ cycles of reversed cyclic dynamic loading. This high cycle count is noted as excessive when one compares with the actual drift cycles imposed at the elevation of the window system during earthquakes (Hutchinson et al., 2008).

5.2 Scope of Work

A systematic experimental program is undertaken in this work with a focus on evaluating the effects of: (i) load protocol, (ii) film thickness and attachment and (iii) window aspect ratio, on the window system in-plane seismic performance. In total, 12 small scale, and 53 full-scale specimens were tested. Small scale specimens consisted of 12”x12”x1/4” annealed glass panels subjected to monotonic loading. These experiments were conducted primarily to evaluate the validity of video monitoring of the crack development during the large scale tests.

The baseline large-scale window specimens consisted of 5’x5’ window units, constructed of ¼” annealed single pane glass supported by an aluminum frame, with detailing typical of store-front window systems. These specimens were subjected to in-plane seismic racking in a specially designed racking frame mounted on the UCSD Powell Laboratory shake table. The objectives of these tests were to quantify the damage modes and associated drift limits, considering the aforementioned testing variables.

Full-scale testing began with testing baseline 1:1 aspect ratio windows (5’x5’) under monotonic loading. A slow displacement rate of 0.03 in/sec was used to avoid inertial effects, while allowing observation of the progression of damage and a better understanding of failure modes. Each of the different film thickness and attachment system combinations were tested under the monotonic protocol to establish their baseline behavior. The *loading protocol (LP)* series involved testing of like specimens systematically subjected to the (i) Crescendo Load Protocol, (ii) FEMA 461 Load Protocol, (iii) a newly developed Mid-Rise Load Protocol and (iv) and a newly developed Low-Rise Load Protocol. The latter two protocols are described in a companion report by Hutchinson et al. (2008). The effects of each protocol on the specimens’ drift limit capacity were evaluated, and cross-comparison between the various protocols was conducted. The *window film (WF)* series included 5’x5’ specimens with no film, 2 mil, 4 mil, and 2-ply 8 mil film. Each filmed specimen was built unattached and attached. Attachment involved the wet glazing attachment system, which involves placing a bead of caulking at the top edge of the film, adhering the film to the glass panel. The *aspect ratio (AR)* series included 6’x4’ (AR: 1.5), 5’x5’ (AR: 1.0) and 4’x8’ (AR: 0.5) specimens. Each aspect ratio in the series was composed of 3 specimens. The first specimen had no film, the second had 4 mil film and the third specimen had

4 mil film attached with the wet glazing attachment system. Specimens in both the WF and AR series were subjected to the FEMA 461 load protocol.

5.3 Findings

5.3.1 Identified Damage States

Damage to the window units was categorized into two main groups: (i) Serviceability Damage States (SDS) and (ii) Ultimate Damage States (UDS). SDSs are damage modes, which results in the inability to immediately continue normal (service), while UDSs are damage modes, which are not repairable and pose an immediate safety hazard. Upon achieving an UDS, the window system must be completely replaced. Three SDS and two UDS for store-front style window systems were identified in this study. The SDSs identified were: (i) gasket damage, (ii) minor glass cracking, and (iii) wet glazing attachment system detachment. The UDSs identified were: (i) glass fallout and (ii) major glass cracking. The experimentally determined drift ratios, for all window systems tested in this program, considering the aforementioned damage states were as follows:

- SDS-1 (gasket damage): range from 1.9 to 3.1%, with an average of 2.3%
- SDS-2 (minor glass cracking): range from 1.4 to 11.3 %, with an average of 6.6%
- SDS-3 (Attachment system detachment): range from 4.1 to 6.8 %, with an average of 4.9%
- UDS-1 (extensive glass cracking): range from 1.4 to 11.5 %, with an average of 8.0%
- UDS-2 (glass fallout): range from 3.9 to 11.5 %, with an average of 8.3%

5.3.2 Load Protocol Effects

The effects of load protocol are detailed in a companion report by Hutchinson et al. (2008) and therefore only abbreviated in bullet form herein. Table 5.2 summarizes the minimum, average, and maximum drift ratio associated with the various damage states. Additional findings regarding load protocol include the following:

- Load protocol has an effect on the drift ratio associated with the identified damage states. Specifically, it was observed that the crescendo protocol caused specimens to acquire damage at an earlier drift ratio than any other load protocol. The cause for the low drift ratio is associated with cycle count.

- From the limited study the loading rate has minimal effect on the drift limits associated with both the serviceability and ultimate damage states. The FEMA 461 protocol (20 cycles – static) had slightly smaller drift ratio values compared with the Mid-rise protocol (20 cycles – dynamic).
- To characterize the serviceability damage state, minor cracking was identified as a good metric for loading protocol comparison. Using the FEMA 461 load protocol as a base (20 cycles), the Monotonic load protocol resulted in a 39% increase in drift ratio capacity, the Mid-Rise protocol (20 cycles) showed a 10% increase in drift ratio capacity, the Low-Rise protocol (40 cycles) showed a 1% decrease in drift ratio capacity and the Crescendo load protocol (+180 cycles) showed a 13% decrease in drift ratio. The ultimate damage state extensive cracking showed the same trend when comparing the FEMA 461 load protocol to the others: 39% increase for Monotonic load protocol, 8% increase for Mid-Rise load protocol, 11% decrease for Low-rise load protocol and 22% decrease with Crescendo load protocol.

	(min / average / max) %				
	Monotonic	Crescendo	FEMA 461	Mid-rise	Low-Rise
SDS-1:	N/O	2.2 / 2.2 / 2.2	1.5 / 2.2 / 3.1	2.2 / 2.4 / 3.1	1.6 / 1.8 / 1.9
SDS-2:	2.3 / 7.8 / 11.3	4.6 / 6.0 / 7.3	4.4 / 6.8 / 8.5	6.2 / 7.55 / 8.9	6.8 / 6.8 / 6.8
SDS-3:	4.1 / 5.4 / 6.8	N/A	4.4 / 4.4 / 4.4	N/A	N/A
UDS-1:	5.6 / 8.6 / 11.5	4.6 / 6.0 / 7.3	4.4 / 6.5 / 8.5	7.0 / 8.0 / 8.9	6.8 / 6.8 / 6.8
UDS-2:	5.6 / 8.6 / 11.5	7.3 / 7.3 / 7.3	3.9 / 6.5 / 8.9	7.1 / 8.0 / 8.9	N/A

Table 5.1 Summary of load protocol effects

5.3.3 Film and Attachment System Effects

The most notable observation regarding the window system seismic performance when the unit is filmed is related to the securing capacity of the film, post-damage. Even a moderate amount of film (2 mil) suppresses damage to the window system, and greatly assists with retaining the glass itself, thereby reducing the potential for the safety hazard of glass fallout. Table 5.2 summarizes the minimum, average, and maximum drift ratio associated with the various damage states. Additional findings regarding film include the following:

- When there is no film applied to the glass, the effects of extensive cracking cause on average 74% of the glass to fallout (range of 20%). With only minimal film application (2 mil), less than 1% of glass is observed to fall from the specimen. Increased film thickness (4 and 2-ply 8 mil) increases the level of containment further to less than 0.75% glass fallout.
- For the serviceability damage states there was an average increase of 34% in drift ratio capacity from no film to filmed specimens. For the ultimate damage state the increase in drift ratio capacity from no film to filmed specimens was 12%.
- Increasing the film thickness had no discernable trend in terms of its effects on drift ratio capacity at any damage state when unattached. The minimal amount of film considered in this study (2 mil), would suffice in terms of increasing the drift ratio capacity associated with the identified damage states.
- When the window film is attached using the wet glazing attachment system, the drift ratio values for all damage states was reduced. The attachment system increases the system stiffness, which in-turn creates local stress concentrations along the attached edge of the glass. For like specimens, on average, the serviceability damage state drift ratio was reduced by 32% for specimens attached with the wet glazing attachment system. The ultimate damage state drift ratio was reduced by 37% for like specimens that were attached with the wet glazing attachment system.
- The safety aspects of window film were very evident during the testing. Thicker films (4 and 2-ply 8 mil) reduced replacement time and increased safety by containing the glass in one manageable sheet. The attachment system, when it did not fail, held the shattered panel in place after testing, which provided ample time to setup for safe removal of the specimen.

	(min / average / max) %		
	no film	Filmed	
		Un-attached	Attached
SDS-1 (gasket damage):	2.2 / 2.7 / 3.1	1.5 / 3.1 / 2.2	2.2 / 4.7 / 8.3
SDS-2 (minor glass cracking):	6.8 / 7.8 / 8.9	1.5 / 11.3 / 6.9	1.4 / 4.7 / 8.3
SDS-3 (attach. system detachment)	N/A	N/A	4.1 / 5.0 / 6.8
UDS-1 (extensive glass cracking)	7.6 / 9.2 / 11.5	4.6 / 9.0 / 11.3	1.4 / 6.7 / 10.9
UDS-2 (glass fallout)	7.6 / 9.2 / 11.5	7.3 / 9.1 / 11.3	3.9 / 7.6 / 10.8

Table 5.2 Summary of film and attachment drift ratios

5.3.4 Aspect Ratio effects

The most notable conclusion observed from the experimental program, as related to aspect ratio was that as the aspect ratio increases the obtained drift ratio values for the serviceability damage states increases. For the serviceability damage state minor cracking AR 0.5 had a range of 4.8% to 6.9% and an average 11% drop in drift ratio capacity compared to AR 1.0. SDS-2 (minor cracking) was not attained for AR 1.5 however the drift ratio achieved before system limitations were reached was 7.2%, a 26% increase in drift ratio capacity compared to AR1.0. This observation was consistent only for window systems without film or with film unattached. Stress localization associated with the film attachment increases the variability of the drift ratio capacity. Ultimate damage states showed no discernable trend which could be attributed to limitations of the loading system (the ultimate damage state was not attained for taller specimens), as well as specimen to specimen variability.

5.4 Future Work

This study demonstrated that window film application can beneficially suppress the damage to window systems associated with seismic loading. Most notably, the drift ratios associated with key serviceability and ultimate damage states were increased and glass fallout was largely mitigated. However, the experiments also demonstrated the unfortunate attributes, namely development of local stress concentrations, when the film was attached to the glass unit. These findings were limited to the type of window system considered, namely, store-front type construction. To broaden the application of these findings, future studies should consider the following:

- Additional window system types
- Varying film attachment systems
- Varying glass type and thickness
- Varying sash and mullion details
- Less likely geometries (highly squat or tall slender window systems)

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Appendices

Appendix A: Construction Drawings

Appendix B: Load-Deflection Response Curves

Appendix C: Summary of Previous Experiments

Appendix D: Glass Specifications

Appendix E: Calculations