Drift Limitations Imposed by Glass

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INTRODUCTION

Engineers interested in proper aseismic design have for many years recognized the importance of drift limitations in the analysis of buildings. The reason for this interest is twofold, one to prevent damage, both structural and non-structural, and the other, the disturbing psychological effect on the occupants due to the movements which can cause panic. The California Administrative Code Title 21, which is the building code for the construction of public school buildings in the State of California, has placed in Section 111, the following limitation on drift: "The deflection of vertical-resisting elements due to wind or seismic loads in the plane of the wall shall not exceed one-sixteenth inch per foot of height of the element. Deflection in the plane of the wall from the head to the sill of a glazed opening shall not exceed one-sixteenth inch per foot of height of the opening unless the glass therein is prevented from taking shear or distortion or wire glass is used." This amounts to 0.0052h. Admittedly, this value of one-sixteenth inch per foot of height was not founded on scientific knowledge. It was felt that since Title 21 is directed toward safety and that glass was one of the most hazardous materials in a structure that if any investigation is made it should be directed toward the drift limitation imposed by glass rather than toward the psycological effects.

At the request of several groups, and to obtain this desired information, a research project investigating the behavior of window panels under in-plane forces was performed at the Engineering Materials Laboratory, Division of Structural Engineering and Structural Mechanics, Department of Civil Engineering, University of California at Berkeley.

This paper presents a brief summary of the results of this test program as discussed in detail in the report "Behavior of Window Panels under In-plan Forces", by J. G. Bouwkamp.

The research project was sponsored by the Division of Architecture, Department of Public Works, State of California, and other interested organizations. A complete list of reports resulting from research projects on earthquake engineering subjects as sponsored by the Division of Architecture is given in Appendix I.

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TEST PROGRAM AND PROCEDURE

After giving consideration to the various types of window details used in school construction, the following list of variables were selected:

1. Type of sash (for typical sections see Figure 1)
    - a. Steel
    - b. Aluminum
    - c. Wood
2. Type of Glass
    - a. Double strength: 1/8 inch in thickness
    - b. Crystal: 3/16 inch in thickness
    - c. Plate: 1/4 inch in thickness
3. Bedding mastic
    - a. Soft
    - b. Hard - a gypsum celite plaster was used to simulate hardened aged putty.
4. Clearance of glass in sash
    - a. 1/4-inch clearance all around
    - b. 3/8-inch clearance all around
    - c. 1/2-inch clearance all around
5. Location of wood-screw attachment
    - a. All four sides
    - b. Top and bottom
6. Size of sash
    - a. 2 feet high by 4 feet wide
    - b. 4 feet high by 4 feet wide
        - 1) Single pane
        - 2) Subdivided

c. 8 feet high by 4 feet wide

   1) Single pane

   2) Subdivided

7. Loading

   a. Static

   b. Alternate static

   c. Impact

The sash were mounted on a 2 by 6 inch wood member and attached by means of wood screws. (See Figure 2.) These wood members were attached to a pin-connected or hinged steel frame, thus allowing the window panels to carry the full horizontal in-plane load applied at the top of this hinged frame. (See Figure 3.) As the window panel deforms under the applied load, the dead load of the hinged frame will introduce additional vertical forces on the panel. A spring was installed to keep the hinged frame in equilibrium in any deflected position.

The following measurements were taken by means of 1/1000-inch mechanical dial gages:

1. In-plan movements of glass panel with respect to sash.

2. In-plan movements of the window panel.

3. Out-of-plane movements of the glass panel (only in the Series No. 1).

4. Movement of the hinged frame.

A total of thirty-three specimens, subdivided into Series I, II, and III were tested under a static load to investigate successively, the effect of the variables. Two specimens two by four feet in size were tested under an alternating-reversible load, inducing one-fourth inch deflection increments in each direction. Four panels were tested under impact loads.

TEST RESULTS

The results of the static-load tests and the comparable theoretical in-plan deflections for the Series I, II, and III are given in the Tables I, II, and III.

In general the action of the steel and aluminum-sash window panels with soft mastic is as follows: the sash deflects as a frame until the sash bears upon the glass at the loaded corner and in the region of the diagonally opposite corner. At this point the glass rotates within the sash frame, thereby permitting considerable additional horizontal movement. When the glass is seated in the two diagonally opposite corners there is very slight additional movement as this additional movement is due merely to that which would be permitted by the shortening of the diagonal as a result of the buckling of the glass. (See Figure 4)

For a wood-sash window panel with soft-bedding mastic the edge of the glass penetrates into the wood sash and opens the sash frame corner connections, thereby permitting larger displacements than those of the metal-sash.

When the bedding mastic is hard, the movement of the head of the sill is due primarily to the crushing of the hard mastic and of the wood under the sash frame.

Figure (4) indicates the essential configuration of the sash and glass when soft-bedding mastic is used and no rotation of the window panel occurs due to crushing the wood. Figure (5) indicates the configuration when the sash is allowed to rotate within the building frame. Essentially it was learned that for metal-sash window panels the drift limitations imposed by a single pane of glass bedded in soft mastic is merely a geometrical relationship primarily depending upon the glass clearance (c) and the panel dimensions d (height) and w (width), namely:

$$\Delta - \phi d = 2c\left(1 + \frac{d}{w}\right)$$

In multiple metal-sash window panels a similar expression could be derived in which the total deflection is primarily the summation of the deflections of the individual panes in one vertical line, namely:

$$\Delta - \phi d = \sum 2c\left(1 + \frac{d}{w}\right)$$

Also, an expression determining the drift limitations at failure imposed by a single pane of glass where the bedding mastic is hard, was derived from these test results, namely:

$$\Delta - \phi d = F \quad 2c\left(1 + \frac{d}{w}\right)$$

where $F = 0.36 - 0.115 \frac{w}{d}$

This expression for F represents good agreement with the test results from Series II, but further tests should be performed to evaluate the factor F more accurately.

It can be shown geometrically that in all of the above quantities the portion $(1 + \frac{d}{w})$ should be further decreased by the quantity $\frac{2c}{w}$; however, this has been neglected due to its insignificant effect on the results.

For soft mastic glazed metal-sash window panels the glass failed locally in the loaded corners. The failure occurred by crushing the glass in one and sometimes in both loaded corners. (See Figure 6&7) A similar type of failure combined with the failure of the sash bars occurred in the multiple-pane metal-sash window panels using soft mastic. (See Figure 8.) For wood-sash window panels the glass failure was more complete because of the higher loads or the contained potential energy, under which these panels failed. This large load was a result of the restraining effect of the relatively rigid wood stops at both sides of the glass. For hard-mastic glazed-window panels, a buckling failure of the glass took place generally over the total glazed area. The restraining effect of the hardened mastic on the glass panel allowed a considerably higher failure load than for soft-mastic glazed panels, thus causing a generally complete failure of the pane.

The results from the load-reversal tests indicated that the deflections at failure were practically identical to the deflections at failure for identical panels under a static-unidirectional load.

The results from the impact loading tests, in which the load was obtained by swinging a pendulum weight against the head of the hinged frame, indicated that the deflection of the window panel at failure is essentially the same as that under static loads. (See Table IV.) The energy load required to produce glass failure under these impact-load conditions is higher than under static-load conditions. The failure pattern was similar to the soft mastic specimens although not as pronounced.

This investigation has shown that where care is taken to insure clearance for movement of the glass in the sash, a considerable amount of drift can be tolerated before glass breakage will occur. However, where movement is impaired, such as by a hardened mastic or the sash frame, hazard exists for both the building occupants and the public outside the building. When the glass fails, fragments of glass are thrown outward from both sides of the sash. Upon failure of the two by four-foot panels under static-loading glass fragments were found as far as five feet out from both sides. On the eight-foot high by four-foot wide panels the lateral travel of the glass was as far as 25 feet outward from the sash. Due to testing limitations, this type of complete failure of glass during impact loading was not obtained for the hard mastic specimens; however, it is believed that a similar failure pattern and fragment dispersal would be observed as that of the static load tests.

This investigation also indicates that the drift limitation of .0052h is not conservative where the bedding mastic is hard as indicated by specimen numbers A-1-a-$\frac{1}{2}$-h, A-2-a-$\frac{1}{2}$-h, and A-3-a-$\frac{1}{2}$-h. In each case the tested failure movements, $\Delta - \phi$ d, were 0.02 inch less the permitted design movement. The $\Delta - \phi$ d value would apply to the design of a building where the sash is connected directly to building frame and not to an intermediate wood member.

ACKNOWLEDGEMENTS:

The research project was sponsored by the State Division of Architecture, Department of Public Works, State of California. Additional support in the form of glass was obtained from W. P. Fuller and Company, while the sash was furnished by the Western Architectural Metal Manufacturers, a metal sash manufacturer's association, and the Woodwork Institute of California. The California Council of the American Institute of Architects was consulted for suggestions as to the architectural details of sash which may be used in future buildings.

APPENDIX I

AVAILABLE DIVISION OF ARCHITECTURE

RESEARCH REPORTS

The following list of reports of research projects sponsored by the Division of Architecture are available from Printing Division, Documents Section, Sacramento 14, California:

1. "Behavior of a Continuous Concrete Slab Prestressed in Two Directions", by A. C. Scordelis, T. Y. Lin and R. Itaya, price $1.75, plus tax*.

2. "Behavior of Prestressed Concrete Beams at Transfer" by T. Y. Lin, A. C. Scordelis and R. H. May, price $1.75, plus tax*.

3. "Shearing Strength of Reinforced and Prestressed Concrete Lift Slabs", by T. Y. Lin, A. C. Scordelis and R. Itaya, price $1.50, plus tax*.

4. "Radiographic Inspection of Reinforced Grouted Brick Masonry", by J. R. Benjamin and H. A. Williams, price $1.25, plus tax*.

5. "Lateral Load Tests on Reinforced Grouted Masonry Shear Walls" by R. R. Schneider, price $1.75, plus tax*.

6. "Frictional Effects in Composite Structures Subjected to Earthquake Vibrations", by L. S. Jacobsen, price $1.75, plus tax*.

7. "Action of Timber Structures Subjected to Lateral Loads", by C. E. Troxell and V. Bertero, price $1.75, plus tax*.

8. "Behavior of Window Panels Under In-Plane Forces", by J. G. Bouwkamp, price $1.75, plus tax*.

The following reports are available without charge from the Forest Products Research Center, State of Oregon, Box 571, Corvallis, Oregon:

1. "Lateral Tests on a Full-Scale Roof Diaphragm Sheathed with 2 by 3 inch Lumber", by R. A. Currier, Report No. T-10, October 1954.

2. "Lateral Tests on 12 by 60 foot and 20 by 80 foot Lumber Sheathed Roof Diaphragms", by J. A. Johnson, Report No. T-12, October 1955.

3. "Lateral Test on a 20 by 60 foot Roof Diaphragm with Stapled Plywood Sheathing", by J. W. Johnson, Report T-13, December 1955.

4. "Strength Tests on Full-Scale Plywood Sheathed Wall Section", by R. A. Currier, Report T-15, February 1956.

* If purchaser is California resident, add 4% sales tax.

5. "Racking Tests on Wood Wall Sections with Mullions", by A. D. Hofstrand, Report No. T-17, September 1956.

6. "Lateral Tests on Full Scale Cable Roofs with Lumber Sheathing", by J. W. Johnson and C. H. Burrows, Report No. T-19, October 1956.

The following report is a digest of several papers and is available without charge from the United States Forest Products Laboratory, Madison 5, Wisconsin:

"Diaphragm Action of Diagonally Sheathed Wood Panels", by D. Y. Doyle, Report No. 2082, November 1957.

Nomenclature

A - aluminum sash

S - steel sash

W - wooden sash

1 - panel size 4' x 2'

2 - panel size 4' x 4'

3 - panel size 4' x 8'

p - panel subdivided into 2' x 4' panels with the 4' dimension horizontal

c - panel subdivided into 2' x 4' panels with the 4' dimension vertical

a - panel attachment all around

b - panel attachment to head and sill only

1/2 - 1/4" clearance all around between glass and sash or 1/2" total clearance

3/4 - 3/8" clearance all around between glass and sash or 3/4" total clearance

1 - 1/2" clearance all around between glass and sash or 1" total clearance

s - standard soft bedding mastic (Fuller Steel DAP 1012)

h - hard bedding mastic substitute (gypsum-celite)

d - vertical sash dimension

w - horizontal sash dimension

e - clearance between glass and sash

ϕ - rotation of sash frame

Δ - total displacement of head of sash with respect to sill

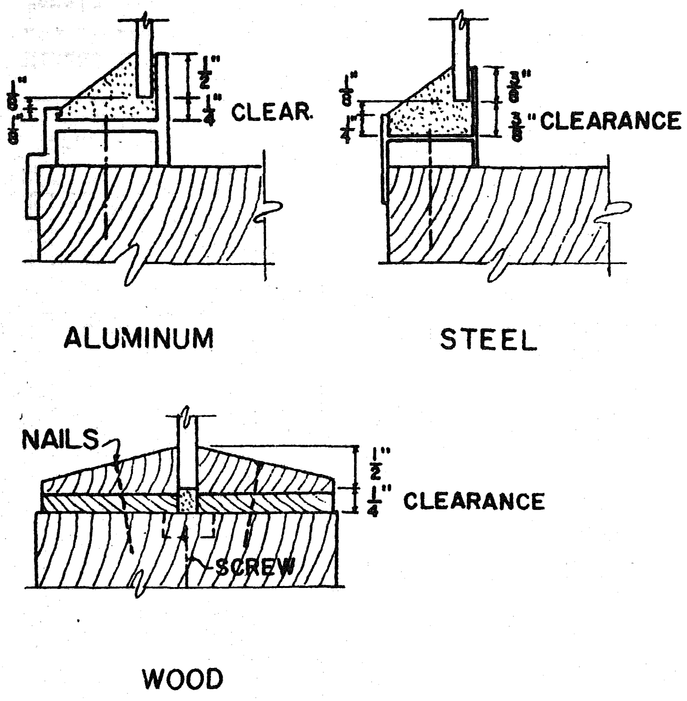


Fig. 1 Sash Details

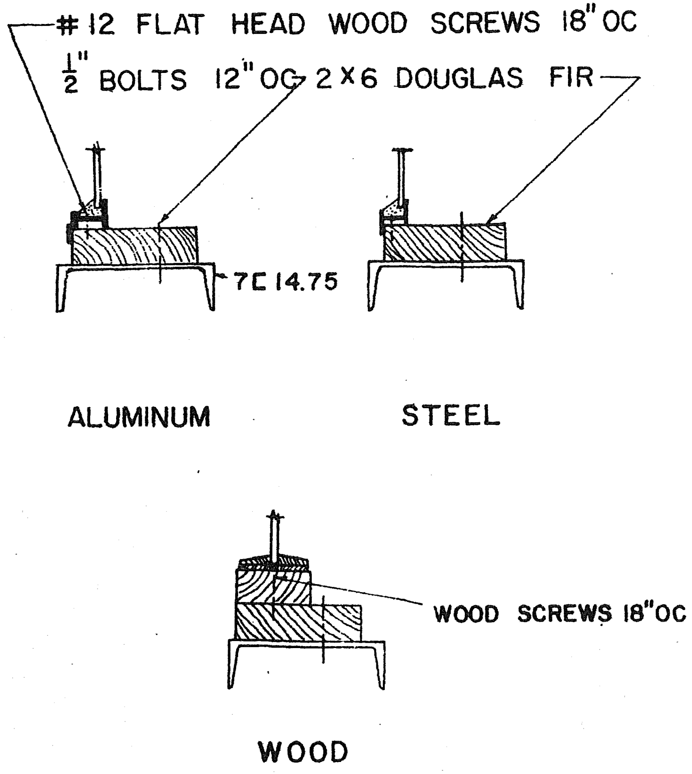


Fig. 2 Mounting of Sash to Testing Frame

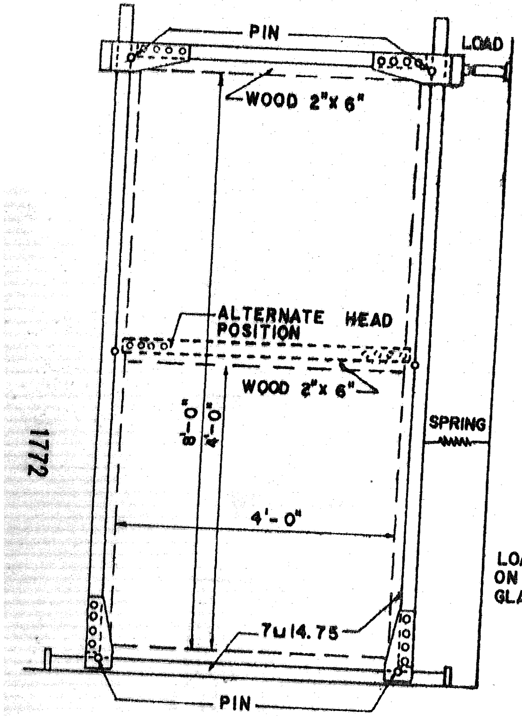
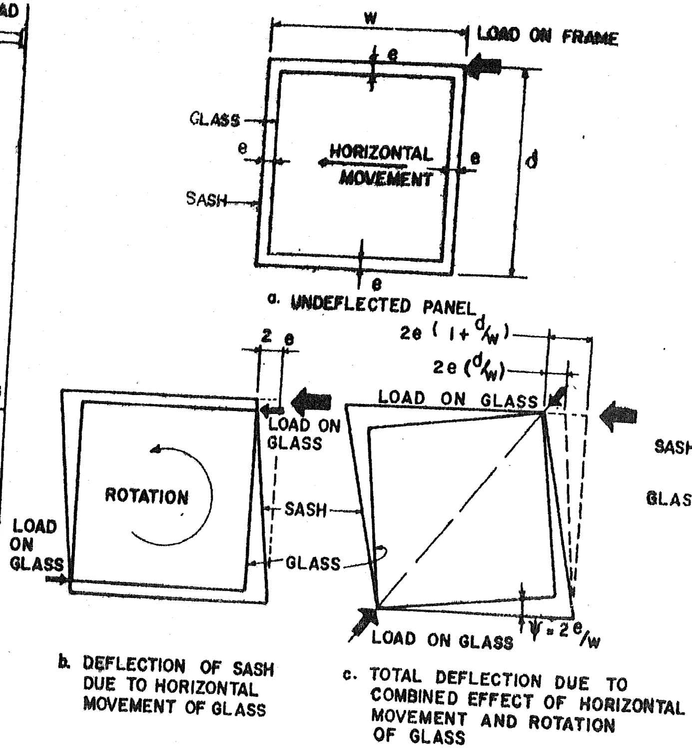


Fig. 3 Hinged Loading Frame for 4'X 4' and 4'X 8' Window Panels



a. UNDEFLECTED PANEL

b. DEFLECTION OF SASH DUE TO HORIZONTAL MOVEMENT OF GLASS

c. TOTAL DEFLECTION DUE TO COMBINED EFFECT OF HORIZONTAL MOVEMENT AND ROTATION OF GLASS

Fig. 4 Displacement of Glass within Sash Soft Mastic Bedding (Zero Rotation Ø of Sash)

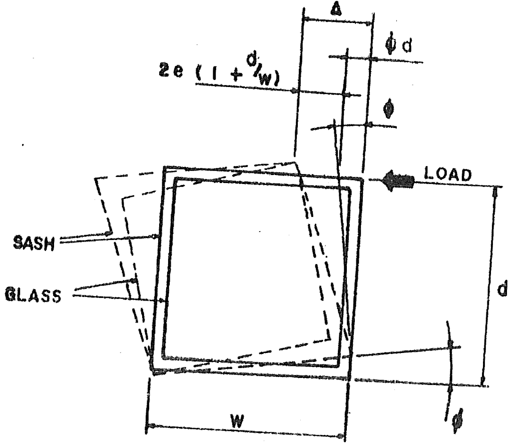


Fig. 5 Displacement of Glass within Sash Soft Mastic Bedding (Rotation Ø included)

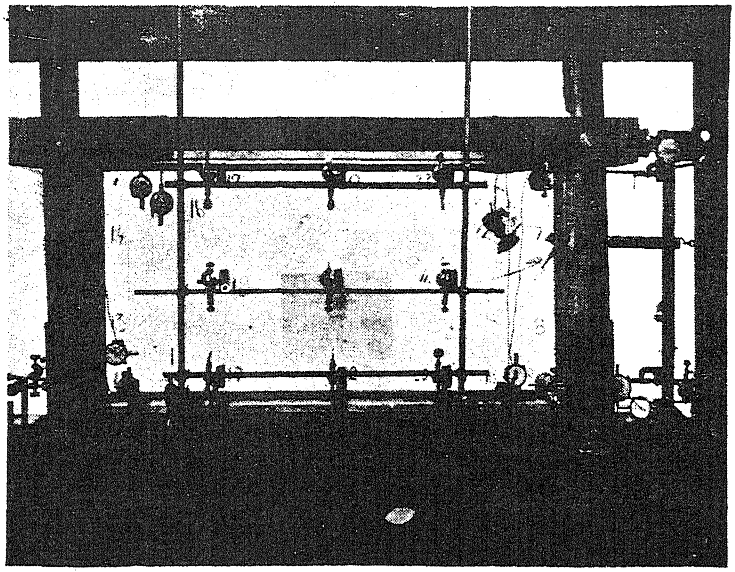


Fig. 6 General Dial Arrangement 4' x 2' Aluminum Sash
Glass Failure Upper Right & Lower Left Corner

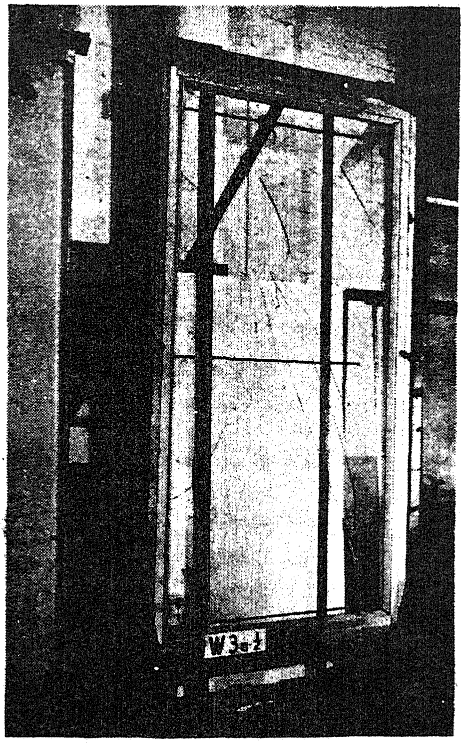


Fig. 7 4' x 8' Wood Sash

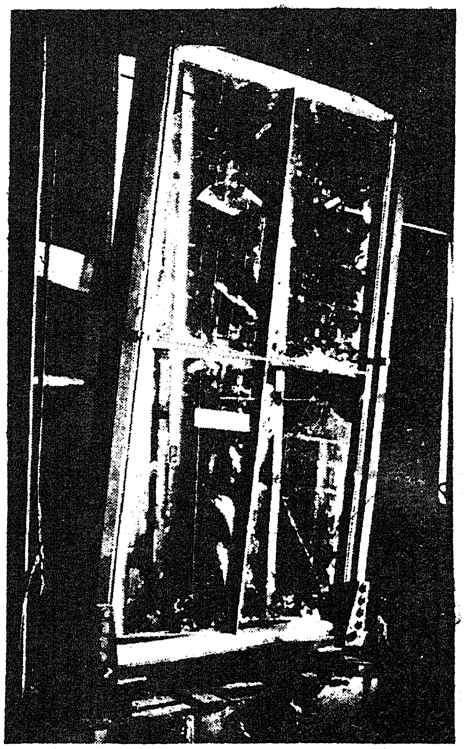


Fig. 8 4' x 8' Vertically Subdivided Aluminum Sash

TABLE I: RESULTS OF SERIES I

OBJECTIVE: Study of the Effect of Sash Material and Panel Attachment

Specimen	Deflections at Failure			Failure Load P lb.	Theory
	Δ in.	ϕd in.	$\Delta - \phi d$ in.		$\Delta - \phi d$
A-1-a-1/2-s	0.85	0.03	0.82	2100	0.82
A-1-b-1/2-s	0.82	0.07	0.75	1940	0.75
A-3-a-1/2-s	1.46	-0.25	1.71	2150	1.50
A-3-b-1/2-s	2.36	0.51	1.85	1620	1.50
S-1-a-3/4-s	1.19	0.00	1.19	2680	1.13
S-1-b-3/4-s	1.19	0.06	1.13	2770	1.13
S-3-a-3/4-s	2.26	0.10	2.16	1720	2.25
S-3-b-3/4-s	1.84	0.28	1.56	1380*	2.25
W-1-a-1/2-s	1.41	0.06	1.35	3440	
W-1-b-1/2-s	2.00	0.05	1.95	3900	
W-3-a-1/2-s	3.52	0.34	3.18	3340	
W-3-b-1/2-s	3.83	0.47	3.36	3430	

* Failure due to vertical compression of glass panel and early buckling before total in-plane movement was reached.

Key

A-1-a-1/2-s = Aluminum sash, 4 ft. horizontal x 2 ft. vertical, attachment all around, 1/2 inch total clearance, soft bedding mastic.

TABLE II: RESULTS OF SERIES II

OBJECTIVE: Study of the Effect of Panel Size, Glass Clearance and Hardness of Mastic

Specimen	Deflections at Failure Δ in.	 ϕd in.	 $\Delta - \phi d$ in.	Failure Load P lb.	Theory $\Delta - \phi d$
A-1-a-1/2-s	0.81	-0.02	0.83	945	0.75
A-1-a-1-s	1.36	0.00	1.36	1720	1.50
A-2-a-1/2-s	1.09	0.28	0.81	4660	1.00
A-2-a-1-s	1.88	0.09	1.79	2400	2.00
A-3-a-1/2-s	2.06	0.37	1.69	2030	1.50
A-3-a-1-s	2.80	0.00	2.80	860	3.00
A-1-a-1/2-h	0.16	0.06	0.10	3850	0.10
A-1-a-1-h	0.27	0.10	0.17	5700	0.18
A-2-a-1/2-h	0.48	0.25	0.23	6420	0.24
A-2-a-1-h	0.67	0.24	0.43	6660	0.49
A-3-a-1/2-h	1.01	0.53	0.48	3550	0.46
A-3-a-1-h	2.20	1.38	0.82	6750	0.93

TABLE III: RESULTS FROM SERIES III

OBJECTIVE: Study of the Effect of Subdivided Panels

Specimen	Deflections at Failure (Δ) in.	(ϕb) in.	$(\Delta - \phi b)$ in.	Failure Load P lb.	Theory $(\Delta - \phi b)$ in.
A-2-p-a-1/2-s	1.82	0.04	1.78	770	1.50
A-2-p-a-1-s	3.02	0.02	3.00	1190	3.00
A-3-p-a-1/2-s	4.31	-0.16	4.47*	1200	3.00
A-3-p-a-1-s	6.06	-0.40	6.46	1300	6.00
A-2-c-a-1/2-s	1.60	0.07	1.53	1570	1.50
A-2-c-a-1-s	2.76	0.06	2.70	1030	3.00
A-3-c-a-1/2-s	2.49	0.00	2.49	860	3.00
A-3-c-a-1-s	5.41	-0.30	5.71	1200	6.00

* Actual failure of first cracking of the glass is not recorded. At failure of 1200 lb. many corners were cracked. This may be the reason for excessive deflection as given in the table.

TABLE IV: IMPACT LOADING

Panel	(Δ) in.	Failure Energy in. lbs.
A-2-a-1/2-s	1.00	1800
A-2-a-1/2-s	1.36	3000
A-2-a-1-s	1.95	6000
A-2-a-1-h	0.75	7800 *

* Actual failure of glass not obtained.

DISCUSSION

H. M. Engle, Consulting Structural Engineer, U. S. A.:

As the speaker has brought out in his paper, control of glass breakage is important in earthquakes, I had one experience in San Francisco, California many years ago. Several panes of glass were broken out of a building 20 stories up. The glass showered down on the street, and it whistled like a bullet as it struck the pavement. Fortunately no one was hit. A large piece landed about 5' from me. If I had been hit it would have been fatal I am sure. From the standpoint of the hazard control of glass breakage in tall buildings in Earthquake is of importance.

J. F. Meehan:

I thoroughly agree with you that precautions must be taken to prevent glass breakage due to drift from seismic forces or wind in the design of not only tall buildings, but of all buildings. This project has indicated that by giving drift proper considerations, glass damage can be essentially eliminated. By simply adding a cushion of wood around the metal sash in a rigid buiding where the bedding mastic is hard increases the deflection at failure of the glass from 160% to 210% (See Table II Specimen Ala½h to A3alh). I feel reasonably certain that if a flexible gasket of some type (around the glass) could be developed, using a metal stop to seal the glass from the weather, and without a wood cushion, the large movements indicated in Table II Specimens Ala½s to A3als could be used as a design basis to prevent glass breakage. Where the sash is anchored directly to the concrete of a rigid building, the 1/16" per foot of height of opening should be reduced.

E. Arze, University of Concepcion, Chile:

1. During the recent earthquakes in Chile it was observed that, in some cases, all the glasses of certain windows will fall to the same side. In your tests, did the glass fall to one or both sides?

2. Did you run any test applying forces as vibrations perpendicular to the plane of the window?

J. F. Meehan:

1. The glass dispersal was to both sides of the sash in these tests. Generally, more glass fragments were found on the side with the soft mastic because this mastic was less rigid than the metal stop of the sash. It is roughly estimated that 60% of the glass went to the mastic side of the sash and 40% to the metal stop side. Where the stops were of equal rigidity, such as the wood sash, the glass dispersal was about equal to each side.

2. We made no tests where the load was applied perpendicular to the plane of the glass. Glass and mullion manufacturers have done a considerable amount of work with static loading in this direction. Glass companies and building codes provide recommendations of permissable glass areas for each thickness and type of glass. There are several recommendations, although not found in building codes, for mullion stiffness in the direction perpendicular to the glass. These are:

   a) $\frac{L}{240}$ for wind pressure of 20 pounds per square foot.

   b) $\frac{L}{175}$ for wind pressure of 10 pounds per square foot.

   c) Glass and frame to resist 35 pounds per square foot, with no permanent set in the framing.