ADVANCEMENTS IN THE DESIGN OF WINDOW GLASS AGAINST WIND ACTION

Joseph E. Minor, P.E.[1]

Introduction

Procedures for designing window glass in engineered buildings are being influenced by two current developments in North America. The advancement of theory-based design methods may result in the replacement of empirically-based design charts which have served for more than 20 years. Breakage of window glass by windborne debris, most notably during Hurricane Alicia in August 1983, may affect design practices and building codes. This paper outlines new theoretical developments and summarizes recent window glass performance in windstorms which may influence design practice.

Theoretical Developments

In the late 1950s, experiments by LOF Company, reported by Hershey and Higgins [1], led to LOF design charts [2]. Similar, but less extensive, tests by Orr [3] led to glass thickness recommendations by PPG Industries [4]. Tests by Bowles and Sugarman [5] contributed to design charts advanced by Pilkington Flat Glass, Ltd. [6]. These three empirically based charts are similar in appearance, but contain differences. Charts in Australian Standard 1288 were developed by using the most conservative components of these three empirical charts.

In 1979, PPG Industries advanced glass thickness recommendations based upon a theoretical stress analysis of thin, rectangular glass plates [7]. The PPG stress analysis employed relatively early (1969) finite element formulations by Melliere [8], and is reported to use considerable amounts of computer time [9]. No model building code or standard has adopted the PPG glass thickness recommendations.

In 1979, Vallabhan and Wang published a stress analysis for thin glass plates which employs a method of finite differences [10]. The numerical analysis is very efficient with computer time, has been verified experimentally (Ref. Fig. 1), and is available as an annotated computer program [11]. Refinements of this program [12] provide for the analysis of thin glass plates on elastic supports representing gaskets or sealants. Design charts based upon these stress analyses have not appeared, although such charts could be generated.

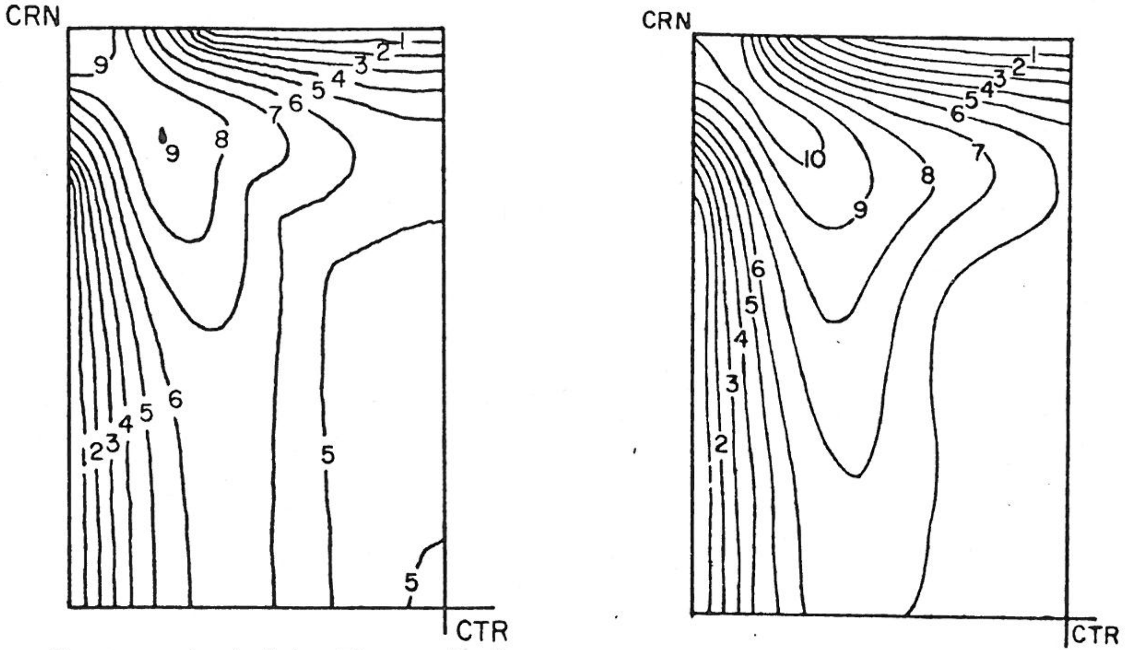
Brown in 1972 [13] and Beason in 1980 [14,15] advanced theoretical methods for predicting glass plate failure under uniform lateral pressure. These methods utilize a theory of fracture in their formulation. Committees of the Canadian General Standards Board and the American Society for Testing and Materials are considering these methods as a basis for design.

Performance of Window Glass in Windstorms

A pattern of window glass failure in windstorms beginning in 1970 and culminating with a dramatic event in Houston, Texas in August 1983 establishes windborne debris as a factor in glass breakage. Glass in the Guaranty Bank Building in Corpus Christi, Texas was damaged by windborne debris in 1970 and again in 1980 (Ref. Fig. 2). Windborne debris was reported to be a factor in window glass and cladding damage in Cyclone Tracy (1974), Hurricane Frederic

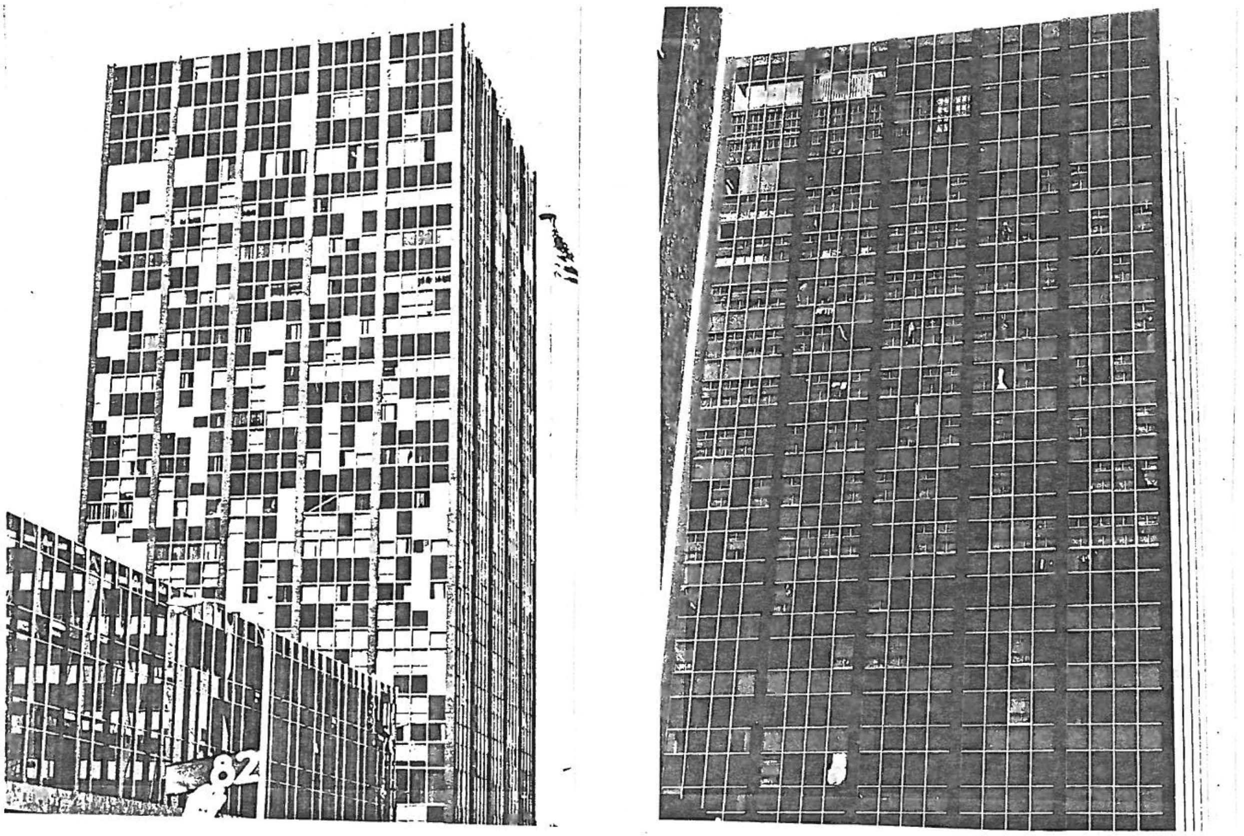
---

[1] Director, Glass Research and Testing Laboratory, Texas Tech University, Lubbock, Texas, U.S.A. 79409



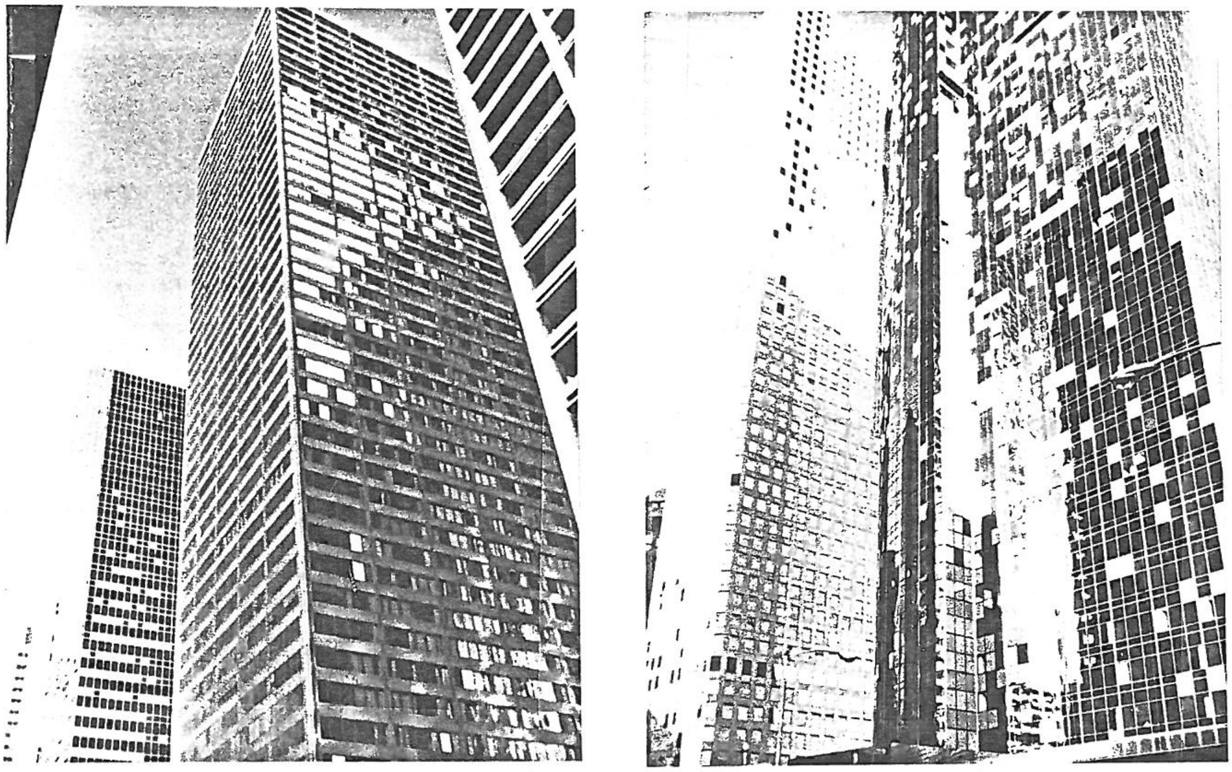
a. Stresses in ksi by Theory [11] b. Stresses in ksi by Experiment [19]

FIGURE 1. COMPARISON OF STRESSES IN 60 x 96 x 0.225 IN. (1.52 x 2.44 x .006 m) GLASS PLATE LATERALLY LOADED TO 0.70 PSI (4.83 kPa)



a. Following Hurricane Celia (1970) b. Following Hurricane Allen (1980)

FIGURE 2. WINDOW GLASS DAMAGE TO GUARANTY BANK PLAZA, CORPUS CHRISTI, TEXAS (USA) CAUSED IN PART BY WINDBORNE DEBRIS



a. 100 Milam Building (foreground) and Entex Building

b. Allied Bank Building (foreground) and Interfirst Bank Building

FIGURE 3. WINDOW GLASS DAMAGE IN DOWNTOWN HOUSTON, TEXAS (USA) CAUSED BY HURRICANE ALICIA, AUGUST 18, 1983

(1979) and Hurricane Allen (1980)[16]. Numerous additional windstorm events which relate windborne debris and window glass damage have been documented by the Institute for Disaster Research [17].

Many high-rise buildings in Houston, Texas experienced glass damage and glass breakage during the passage of Hurricane Alicia on August 18, 1983. The most dramatic glass damage and breakage occurred in a relatively small area in the city center (Ref. Fig. 3). Attention which was focused on this small area overshadowed window glass damage in other high-rise buildings which occurred throughout the city.

Media reports attributed most of the window glass damage in the city center to windborne debris, principally roof gravel, but including debris from signs, roof appurtenances, and architectural facia. Wind engineers and curtain wall authorities who participated in a special session on Hurricane Alicia at the October 1983 National ASCE Meeting [18] attributed the glass damage to five factors: (1) windborne debris, (2) wind pressure, (3) out-of-plane deflections in glass support systems, (4) in-plane "racking" of glass support systems, and (5) improper installation.

Several downtown buildings (ranging up to 77 floors in height) were glazed with fully tempered (toughened) glass. When some of these units broke, the resulting small particles were injected into the airstream, contributing missiles which broke or damaged additional units. News media photographers and eyewitnesses reported glass plates flying intact, suggesting that at least some units were removed from buildings by wind induced pressures. Post storm inspections revealed surface damage (pits, scratches) to a high percentage of unbroken units. This damage was found on all sides of several buildings and on floor levels above adjacent rooftops, indicating that debris impacts were not limited to line-of-sight trajectories from debris sources. Post storm inspections also revealed that some window units had "walked" within their frames, leaving one edge unsupported.

Window glass damage occurred to more than a score of multistory buildings elsewhere in the Houston metropolitan area. Most of this damage could be related to windborne debris. Several sloped glazing and skylight installations were damaged by debris falling from adjacent rooftops.

Conclusion

New theoretical methods of analysis for thin glass plates are providing opportunities for refinements of existing window glass design relationships. These methods are under consideration by building code and standards groups in North America.

The performance of glazing in windstorms, with particular reference to hurricanes, suggests that windborne debris is a factor that must be addressed in design. In circumstances where windborne debris constitutes a hazard, design processes should take this factor into account.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant CEE-8118214. The author also wishes to acknowledge contributions to window glass theory and performance evaluations by Drs. C.V.G. Vallabhan and H.S. Norville of Texas Tech University.

References

1. R.L. Hershey and T.H. Higgins, "Statistical Prediction Model for Glass Breakage from Nominal Sonic Boom Loads," Booz-Allen Applied Research, Inc., Bethesda, Maryland (USA), 1973 (NTIS AD 763 594).

2. LOF, "Glass for Construction," Report 4a/li, Libbey-Owens-Ford Company, Toledo, Ohio (USA) 1970.

3. L. Orr, "Engineering Properties of Glass," Publication 478, Building Research Institute, National Academy of Sciences, Washington, DC (USA), 1957.

4. "Glass Products Recommendations, Structural," Technical Services Report No. 101, Pittsburgh Plate Glass Company, Pittsburgh, Pennsylvania (USA), c1964.

5. R. Bowles and B. Sugarman, "The Strength and Deflection Characteristics of Large Rectangular Glass Panels Under Uniform Pressure," Glass Technology, Vol. 3. No. 5, 1962, pp. 156-70.

6. Pilkington Flat Glass Limited, "Wind Loading Charts: Transparent, Patterned, Wired, Rough Cast, Laminated Glass and Transparent Double Glazing," Pilkington Flat Glass Limited, St. Helens, Merseyside (England), 1979.

7. "PPG Glass Thickness Recommendations to Meet Architects' Specified 1-Minute Wind Load," PPG Industries, Pittsburgh, Pennsylvania (USA), 1979.

8. R.A. Melliere, "Finite Element Method for Geometrically Nonlinear Large Displacement Problems in Thin, Elastic Plates and Shells," Ph.D. Thesis, University of Missouri at Rolla, Rolla, Missouri (USA), 1969.

9. C.R. Tsai and R.A. Stewart," Stress Analysis of Large Deflections of Glass Plates by Finite Element Method," Journal of American Ceramic Society, Vol. 59, Nos. 9-10, 1976, pp. 445-448.

10. C.V.G. Vallabhan,"Iterative Analysis of Nonlinear Glass Plates, Journal of Structural Engineering, ASCE, Vol. 109, No. 2, February, 1983, pp. 489-502.

11. C.V.G. Vallabhan and B. Y-T. Wang, "Nonlinear Analysis of Rectangular Glass Plates by Finite Difference Method," Institute for Disaster Research, Texas Tech University, Lubbock, Texas (USA), 1981.

12. C.V.G. Vallabhan, "Nonlinear Glass Plates on Elastic Supports," Glass Research and Testing Laboratory, Texas Tech University, Lubbock, Texas (USA), (in preparation).

13. W.G. Brown, "A Load Duration Theory for Glass Design," NRCC 12354, National Research Council of Canada, Ottawa, Ontario (Canada), 1972.

14. W.L. Beason, "A Failure Prediction Model for Window Glass," Institute for Disaster Research, Texas Tech University, Lubbock, Texas (USA), 1980 (NTIS PB81-148 421)

15. W.L. Beason and J.R. Morgan, "Glass Failure Prediction Model," Journal of Structural Engineering, ASCE, Vol. 110, No. 2, February 1984, pp. 197-212.

16. J.E. Minor, "Preparing Buildings for Hurricane Winds," Postprints, Third Conference on Meteorology of the Coastal Zone, American Meteorological Society, Boston, Massachusetts (USA), 1984, pp. 61-66.

17. J.E. Minor and K.C. Mehta, "Wind Damage Observations and Implications," Journal of the Structural Division, ASCE, Vol. 105, No. ST11, November 1979, pp. 2279-2291.

18. K.A. Godfrey, Jr., "Window Glass in Extreme Winds: Design for Flying Debris?" Civil Engineering, Vol. 54, No. 1, January 1984, pp. 66-68.

19. "Dynamic Fatigue of Flat Glass, Phase II," Final Report 67039, Ontario Research Foundation, Mississauga, Ontario (Canada), 1981.