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Aluminum Curtain Wall Panel Failure, Assessment and Repair

Rupture, évaluation et réparation d'éléments de façade en aluminium

Versagen, Beurteilung und Instandstellung von Aluminium-Fassadenelementen

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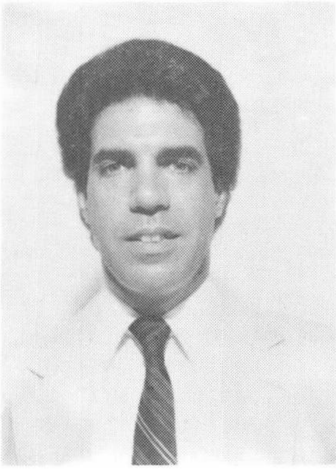

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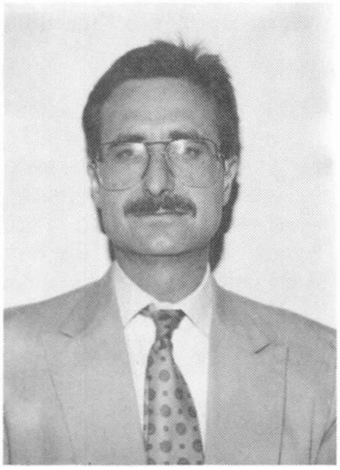

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SUMMARY

This paper summarizes an investigation of the failure of an aluminum curtain wall panel of a righ-rise building in New City. The investigation included a review of the original panel and fastening system design, metallurgical evaluation, field inspections, in-place testing, development of interim repairs, structural analysis, derivation of a cyclic wind loading spectrum, laboratory static and fatigue testing, and fatigue life analysis. A repair and monitoring program was developed which represents a prudent, yet not overly conservative, means of ensuring a very low probability of panel failure in the future.

RÉSUMÉ

Cet article décrit l'examen de la rupture d'une façade en aluminium d'un immeuble à New York. Il comprend un contrôle des éléments originaux et de leur système d'attache, un examen métallurgique, des inspections et essais in situ, le développement de réparations provisoires, des calculs statiques et la détermination d'un spectre de la charge de vent cyclique et de la durée de vie du point de vue statique et dynamique. Un programme de réparation et de surveillance a été mis en place. Il réprésente un moyen sûr, sans être trop conservatif, afin d'éviter la rupture d'autres éléments.

ZUSAMMENFASSUNG

Dieser Beitrag beschreibt die Untersuchung des Versagens einer Aluminiumfassade eines Hochhauses in New York City. Sie umfasste eine Ueberprüfung der ursprünglichen Fassadenelemente, des Befestigungssystems, metallurgische Abklärungen, Felduntersuchungen und- versuche, Entwicklung von provisorischen Reparaturlösungen, Tragwerksnachrechnung, Ermittlung eines zyklischen Windlastspektrums, statische und ermüdungsspezifische Lebensdauer. Ein Reparatur- und Ueberwachungsprogramm wurde entwickelt, welches auf nicht allzu konservative Weise eine geringe Wahrscheinlichkeit für das Versagen weiterer Fassadenelemente gewährleistet.

1. BACKGROUND

During a windstorm in December 1983, an aluminum curtain wall panel separated and fell from one of the upper floors of a high-rise building in New York City. The building was constructed in 1977 and its exterior contains more than 9,000 of these panels.

The authors' firm was retained by the building owner to conduct an investigation in order to determine the cause of the panel separation, determine the magnitude and extent of the possible problem, and report on the general structural condition of the balance of the aluminum curtain wall panels on the building.

2. INVESTIGATION

2.1 Information Reviewed

Since the building had been recently constructed, information pertaining to the design and construction of the aluminum curtain wall panels was readily available. This included the architectural design drawings and specifications, the panel manufacturer's shop fabrication drawings, and the original design calculations relating to the wall panels and fastening system which had been prepared by the panel manufacturer.

A review of the above information indicated that the wall panel and fastening system design was not unusual and in fact was commonly used on numerous buildings at the time.

The typical wall panel assembly consists of a 1.42m x 2.13m x 4.76mm aluminum flat plate with 19 aluminum clips welded to the inside surface of the plate (Fig. 1). These clips attach the plate to the perimeter mullion system and an intermediate horizontal stiffener at the approximate mid-height of the panel. In addition, the top edge of the plate fits into a continuous groove formed into the upper horizontal mullion. Since the building has approximately 9,000 wall panels, there are almost 200,000 clips utilized on the building.

The original wind tunnel test report for the building was also available. This indicated that the design wind pressure in the area of the separated panel was approximately 170 kg/m^2 suction, which was relatively high (but not the highest) as compared to other areas of the building.

2.2 Metallurgical Evaluation

A metallurgical evaluation of the separated panel and its remaining clips was conducted. It was concluded that the fatigue-sensitive nature of the clip-to-panel weld detail, combined with poor welding, resulted in fatigue cracking of panel clip weldments which caused the panel to separate from the building.

In order to provide an initial indication of clip capacity, a panel was removed from the building and selected clips were subjected to static load tests, fatigue load tests, and metallurgical examination. The static load tests indicated clip breaking strengths ranging between 110 kg and 155 kg. The fatigue test results were very erratic due to the poor and variable weld quality and the limited number of samples, and were considered to be inconclusive. Metallurgical examination of several clip welds revealed substantial lack of fusion between the clip weld and the panel surface, as well as fatigue cracks which had initiated from lack of fusion at the weld root.

Therefore, the results of clip testing and metallurgical evaluation of clip-to-panel welds from the removed panel confirmed fatigue of panel clip weldments as the cause of the panel separation.

2.3 Field Inspection and Survey

Concurrently with the metallurgical evaluation, a detailed close-up inspection of accessible aluminum panels was performed from the window washing rig on the outside of the building. The purpose of this inspection was to detect and identify any loose and/or misaligned panels which might be indicative of broken clip welds.

In addition, a field survey of several thousand existing clip welds was performed from the interior of the building. Many of the welds were found to have defects in the form of shrinkage cracks, porosity, lack of fusion, and insufficient weld size. However, only one clip weld was found to have fractured due to fatigue loading under service conditions.

2.4 In-Place Pressure Tests

In order to determine the in-place behavior of the aluminum panels, such as their load-deflection characteristics and their ability to resist design loads, five typical wall panels in the vicinity of the failed panel were selected for in-place pressure testing on the building. Most of the clip welds on the test panels contained shrinkage cracks and were considered representative of the clip welds examined in the field survey.

The accessible lower portion of each of the test panels, i.e., below the intermediate horizontal stiffener, was subjected to an internal pressure (simulating wind suction) of 266 kg/m^2, based upon New York City Building Code requirements, by using a air bag. No failures of clip welds occurred, nor was there any visual evidence of propagation of the pre-existing shrinkage cracks. No permanent deformation of the clips or panels was sustained, and the structural integrity of the tested panels was considered to be the same as prior to the test.

The results of the in-place pressure tests supported the conclusion that the clip failures in the separated panel were the result of fatigue rather than a single overload.

2.5 Interim Repair

Clips that were found to be missing or broken during the field inspection and survey were repaired by fastening either the existing clip or a new replacement clip to the panel using stainless steel screws.

In addition, stainless steel screws were installed along the bottom edge of all panels by drilling and tapping into the panels from the inside of the building. This, along with the existing continuous groove support at the top of the panel, provided basic stability for the panel independent of the clips, and was performed as an advance safety measure while the investigation was proceeding.

2.6 Structural Analysis

An analytical approach was devised using computer-assisted, finite element methods to model a typical aluminum panel and its supporting clips and curtain wall framing, in order to study the behavior of a typical panel under various loading conditions and to determine the corresponding reactions on each aluminum clip.

2.6.1 Mathematical Model

A three-dimensional mathematical model of the panel assembly was developed utilizing one-dimensional beam and two-dimensional shell finite elements. The aluminum plate was discretized into 648 triangular constant stress, linear displacement field, shell elements. The aluminum clips were modeled using one-dimensional rigid links. These rigid links connected the plate elements to the mullions and intermediate horizontal stiffener. The mullions and stiffener were modeled using one-dimensional beam elements with assigned material and cross-sectional properties equal to the actual properties of the members.

2.6.2 Loading Conditions

Three loading conditions were applied to the mathematical model. First, a uniform suction load of 197 kg/m^2 was applied to all plate elements. This represented the original panel design load.

Second, a temperature differential of 22.2°C between the plate and the mullions was applied, based upon in-place temperature measurements on the building.

Third, in order to calibrate the finite element model with the actual panel load-deflection characteristics, a uniform test load of 266 kg/m^2 was applied to all plate elements below the horizontal stiffener. This loading case simulated the in-place pressure tests performed on the accessible lower portions of five panels on the building.

2.6.3 Results of Analysis

A stiffness analysis was carried out for each of the imposed loadings using the TPS-10 program on a VAX 11/750 computer. Nodal displacements, shell stresses, beam forces and moments, and reactions were calculated. Clip reactions were obtained as axial forces on the rigid links.

For the original design load case of 197 kg/m^2, a maximum clip reaction of 56.7 kg was obtained for the center clip at the bottom edge of the panel. A maximum plate stress of 2.9 kg/mm^2 and a maximum out-of-plane displacement of 21.3mm were obtained at approximately the mid-point between the bottom edge of the panel and the intermediate horizontal stiffener.

All clip reactions and plate stresses for the temperature differential load case were found to be negligible.

2.7 Derivation of Wind Loading Spectrum

Based upon data contained in the original wind tunnel test report for the building, a cyclic wind loading spectrum was derived. This loading spectrum was utilized in the analysis of panel clip fatigue life.

2.8 Laboratory Testing

In order to determine the expected fatigue life of existing panel clips, constant-amplitude cyclic testing of numerous panel clips was performed. These panel clips consisted of existing clips removed from the building, and also new clips fabricated with "imperfect" weldments simulating the existing weldments in the building. The test results were plotted to obtain a "load vs. cycles-to-failure" curve for the clips (Fig. 2).

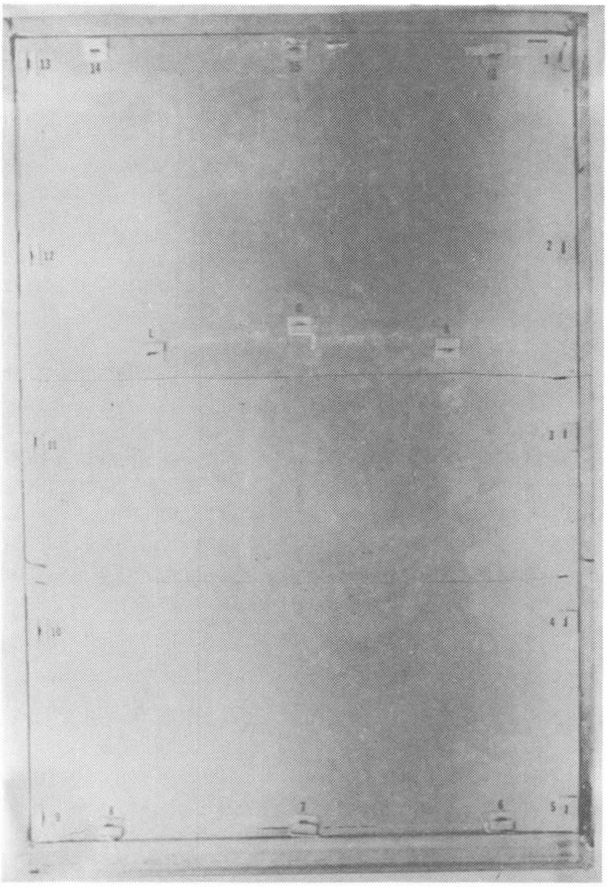

FIG. 1 Typical wall panel assembly

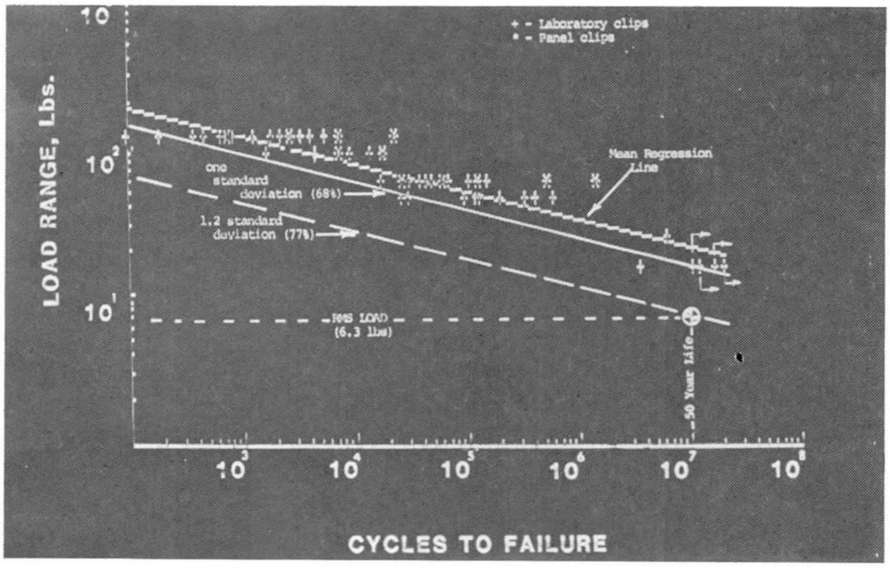

FIG. 2 Load vs. cycles to failure

In addition, laboratory static and fatigue testing of aluminum and stainless steel rivets and screws was performed in order to evaluate potential remedial fastening details.

2.9 Fatigue Life Analysis

Based upon the cyclic wind loading spectrum that was derived, a root-mean-square (rms) wind loading of 10.4 kg/m^2 at 10 million cycles, corresponding to a 50-year life, was computed. This translates to an rms load of 2.9 kg at 10 million cycles on the most highly loaded clip. Fig. 2 indicates that there is a 77% confidence level that a maximum-loaded clip weld will survive 50 years.

3. REPAIR

In addition to the repair of missing and broken clips, and the installation of stainless steel screws along the bottom edge of each panel, a periodic monitoring program was implemented in order to permit timely detection and repair of failed clips. The monitoring procedure consists of in-place testing of selected clips from the window washing rig on the exterior of the building, using a special load-deflection device.

3.1 Results of Periodic Monitoring Program

The first monitoring procedure was conducted on all panels of the building from November 1986 to October 1987. Only 46 clips out of more than 68,000 tested, i.e., less than 0.07%, were found to be missing or broken and were repaired.

A second monitoring procedure for a limited number of selected panels, to be conducted within a 2-week period, is in progress at the time of this writing. The time intervals and extent of clip testing for subsequent procedures will be determined based upon an evaluation of the results of prior procedures.

4. CONCLUSIONS

The results of this investigation indicated that the aluminum curtain wall facade structure is fundamentally sound with a confidence level of 77%. However, due to the variability of the cyclic wind loading spectrum derived from the wind tunnel data analysis, and the inherent scatter in laboratory fatigue testing results, there can be no absolute assurance (i.e., 99% confidence level or greater) that some panel clip welds may not fail in the future. Therefore, in addition to interim repairs, a periodic monitoring program was implemented in order to permit timely detection and repair of failed clips.

It is considered that the repair and monitoring program outlined in this paper represents a prudent, yet not overly conservative, means of ensuring a very low probability of panel failure in the future.