Masonry Veneer Failure: A Case Study of Wall Tie Corrosion

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Abstract

Long-term problems with masonry veneer often go undetected until a sudden failure occurs – a portion of the masonry falls off the building, sometimes with tragic consequences. This type of failure is of particular concern due to the frequency at which it occurs. Research by Grimm (2000) indicates that "masonry falls off a building façade somewhere in the United States about every three weeks," and that "the failures occur under normal loading conditions."

This paper presents a case study of a masonry veneer failure, which occurred under normal loading conditions. The forensic methodology included on-site examination, review of structural and architectural plans, review of maintenance, repair, and renovation history, destructive testing, review of meteorological data, and research of related events to investigate the primary cause of failure. The investigation concluded that wall tie corrosion was the cause of failure, allowing the veneer to pull away from the building at wind loads significantly lower than the design pressure. Examples of corroded masonry ties and other reinforcement are shown to illustrate the extent of corrosion at the time of failure.

Background

The Old Tower at Generic City College[2] is a 4-story administrative building with a 9-story tower centered on the East side (Figure 1). The building was constructed in 1922 and has been owned by the college since that time. The veneer is brick masonry with "university gothic" cast stone accents. Renovations to the interior and veneer were performed in 1992, but the majority of the original veneer and superstructure were retained. Previous repairs at portions of the brick veneer and many of the cast-stone decorative spires were reported and observed.

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[2] With few exceptions, building and place names have been changed in the interest of client confidentiality

On the morning of September 19, 2002, portions of the cast stone veneer were observed to be leaning away from the building. In some locations, gaps as large as 3 to 4 inches were observed (Figures 2, 3). At the owner's direction the loose stones were immediately removed using an overhead crane and were stored on plywood sheets for observation. Approximately two weeks after the failure was observed, our firm was asked to determine the cause of the distress.

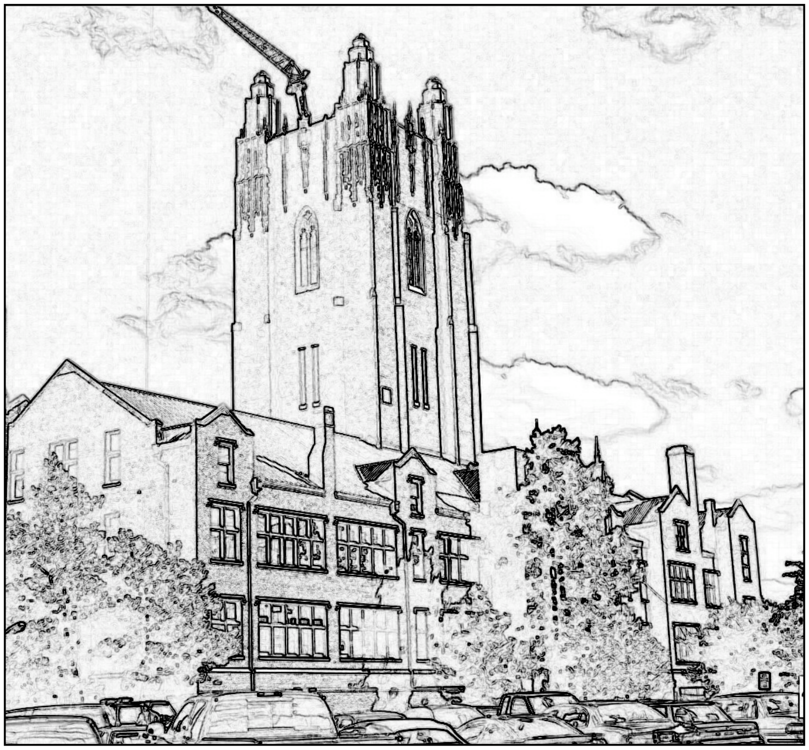


Figure 1

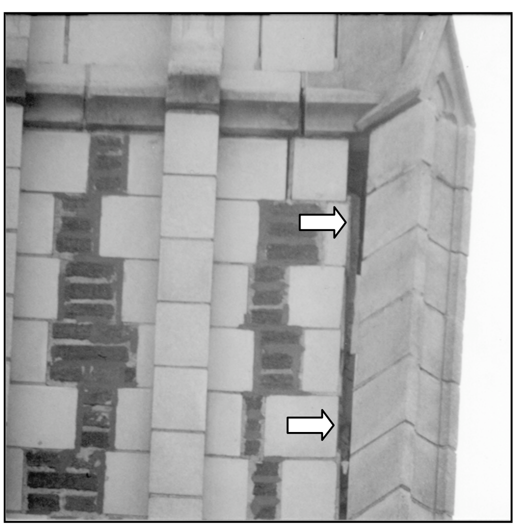


Figure 2

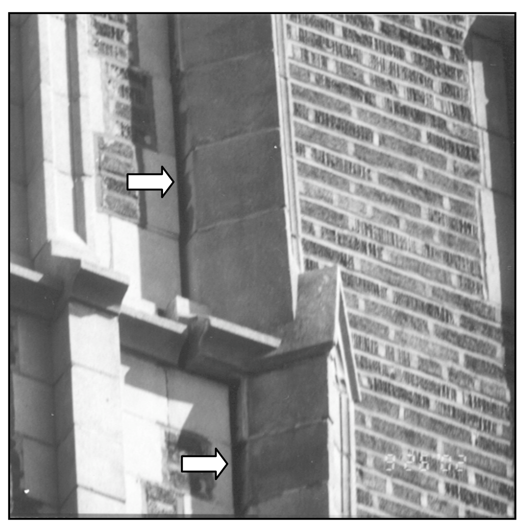


Figure 3

In a masonry façade, the condition of the veneer is function of time, weathering, dimensional stability, and long-term movement. In general, veneer distress (separations, fractures, spalling, fall-out) can be influenced by a number of variables, primarily the following:

- Foundation movement resulting in racking of the building frame or other differential movement
- Severe weather or seismic events
- Thermal movement or moisture expansion of the masonry units
- Deficiencies in original or remedial construction, including mortar application and finish work
- Weathering of the masonry units and the mortar joints, including freeze/thaw behavior
- Moisture intrusion between the veneer and the primary structural system
- Corrosion expansion of reinforcement and corrosion of wall ties
- Removal/replacement of masonry units resulting in (1) poor moisture protection at the interface with the original construction and/or (2) changes to the vertical load path in the veneer and overloading of the undisturbed masonry units
- Various combinations of the above

Our focus was to evaluate the distress of the masonry veneer and determine the primary cause of failure using walk-through, non-destructive, and destructive (mild) forensic methodology.

During the course of our on-site investigation, we were assisted by Mr. Alan Pettingale of Structural Repair Services, Inc. Mr. Pettingale assisted with the distress survey, wall tie mapping, and photography, and, based on his experience performing masonry wall repair, provided insight into the procedures and materials used during the previous repairs and renovations at the Old Tower.

Structural System

In the Old Tower, the main structural system is a reinforced concrete frame infilled with hollow-block clay masonry shearwalls. The floor slabs are reinforced concrete joist-slabs cast monolithically with the concrete frame.

The brick and cast-stone veneer is vertically supported by the foundation and horizontally supported by masonry wall ties anchored into the concrete frame and the masonry shearwalls. Wall cavities between the veneer and the primary structural system were not observed.

Foundation/Superstructure Movement

Evidence of differential foundation movement was not observed during our site visit. If present, such evidence could include stair-step diagonal fractures of masonry walls, racking of windows and doorframes, diagonal fractures at the corners of wall openings, paint lines or separations at architectural interfaces, and, in some cases, floors that are noticeably out of level. Therefore, we concluded that foundation movement was not a cause of the veneer distress.

Severe Weather

A severe thunderstorm was reported on the night of September 18, 2002. Weather data for the campus was unavailable, so data from the nearest NOAA weather stations was used to approximate the wind conditions at the Old Tower. Based on weather data for the downtown and municipal airport weather stations on September 18 and 19, 2002, the maximum wind gust speed was 48.3 miles per hour. In addition, the maximum sustained wind speed recorded at both stations was 32.2 miles per hour.

The measured wind speeds at the airport stations do not represent the exact wind speed imposed on the Old Tower. Variations in exposure due to the placement and height of surrounding buildings as well as local variations in storm intensity are factors influencing the actual wind speed.

Wind Loading: The 1991 UBC (ICBO, 1991) indicates a basic wind speed of 75 miles per hour for the building site. This wind speed is based on a fastest-mile measurement, and is analogous to a 3-second gust speed of 90 miles per hour (ICC, 2000, pp.310). On September 18 and 19, 2002, the measured gust speed of 48.3 miles per hour was approximately 54% of the 1991 UBC design wind speed. Furthermore, the pressure exerted by wind on the surface of the building is proportional to the square of the wind speed (ASCE, 1995, pp.17); therefore, the surface pressure applied by the strong wind event was approximately 29% of the design wind pressure ($0.54^2 = 0.29$).

We also considered design criteria typical of the period in which the Old Tower was built. The 1927 UBC (ICBO, 1987) indicates a design pressure of 20 psf at portions of the structure more than 40 feet above the ground. Using the wind load factors (Ce, Cq, I) from the 1991 UBC as a guide, this pressure is equivalent to a fastest-mile design wind speed of approximately 49 miles per hour. Using Figure C6-1 from ASCE 7-95 (ASCE, 1995, pp.155), this is analogous to a 3-second gust of 61 miles per hour, significantly less than the design speed from the modern code. Still, the recorded gust of 49.9 miles per hour was approximately 82% of the 1927 UBC implied design wind speed. Similarly, the surface pressure applied by the strong wind event was approximately 67% of the 1927 UBC design wind pressure.

Based on our analysis and the available information, we concluded the wind speed on September 18 and 19, 2002 was insufficient to directly cause damage to the primary structural system or veneer. However, the strong wind event may have been sufficient to precipitate damage if the veneer was not sufficiently attached to the primary structural system via wall ties. This conclusion relies on the assumption that the veneer system was originally designed and installed correctly, and the wind records for the nearby airports reflect the wind conditions at the building site.

Wind-Borne Debris or Hail: Distress consistent with impact from wind-borne debris or hail was not observed during our site visit. If present, such evidence could include broken windows or impact scars on the veneer or roof. Furthermore, the observed veneer distress was located at the upper portions of the tower; sources of wind-borne debris tall enough to allow impact at the upper portions of the tower were not observed. We concluded the veneer distress was not related to wind-borne debris or hail.

Lightning: The Old Tower is one of the tallest structures in the vicinity and has four lightning rods installed, one at each corner of the roof. Distress consistent with lightning damage was not observed during our site visit, and was not apparent from the pre-removal photos provided by the owner. If present, such evidence could include shattered masonry units or charred/scarred units. Furthermore, the presence of similar distress at three of the veneer ribs suggests that three separate lightning strikes would be required to cause the observed damage. In our opinion, the veneer distress was not related to lightning.

Seismic Loading

The Old Tower is located approximately 20 miles east of a source of moderate seismic activity. Events with Richter Scale magnitudes up to 5.0 have been recorded at this source during the lifetime of the Tower. However, distress consistent with seismic loading of the structure was not observed. If present, such evidence could include items such as stair-step "X-shaped" fractures of masonry walls (or X-shaped repairs to same) and fractures in the top and bottom sides of concrete beams at the column supports. Therefore, we concluded the distress was not related to recent or historic seismic activity.

Thermal Movement And Moisture Expansion

Bricks and other masonry units expand from exposure to moisture and to variations in temperature. Conversely, concrete shrinks as water evaporates from the material. When masonry walls are constructed with cast stone panels, the expansion of the masonry and the opposing concrete shrinkage may cause fractures in the masonry, the concrete, or both.

Fractures were observed at interfaces between the brick and cast stone units; however, previous repairs to the mortar joints have hidden the extent of this distress (Figure 4). The fractures promote water penetration of the veneer, and the repairs indicate the water penetration has been occurring for some time.

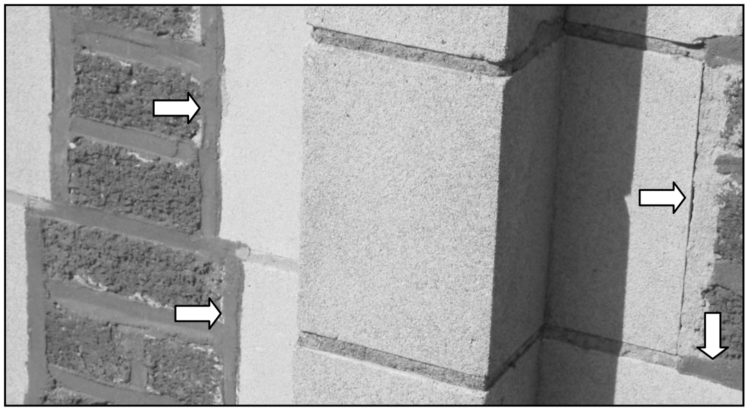


Figure 4

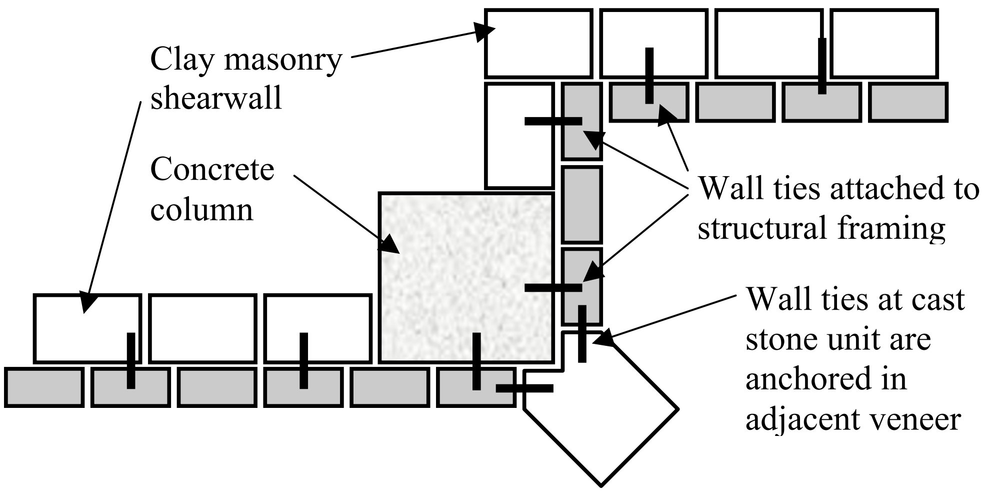


Figure 5

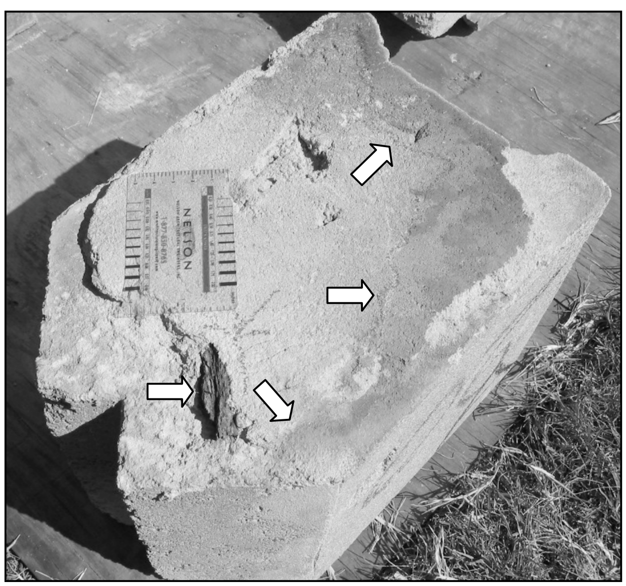


Figure 6

Construction Details

The cast-stone masonry units are attached to the building in a unique configuration: the wall ties holding the units are anchored in the adjacent veneer. In contrast, wall ties for the typical clay brick masonry unit are anchored in the structural framing (Figure 5).

The corner wall ties are more susceptible to weathering than the typical wall ties because they are anchored in the adjoining masonry, nearer to the exterior surface – there is less cover available to protect the corner ties.

Weathering, Water Intrusion and Corrosion

Discoloration, water staining, and efflorescence of the brick veneer were observed. In particular, water staining was observed on interior surfaces of some of the distressed cast stone veneer (Figure 6). Deterioration of mortar joints and roof-level cast stone spires was also noted. It is likely that the acidity of the droppings left by pigeons and similar pests has contributed to weathering of the masonry and mortar joints at the roof level, allowing additional moisture to penetrate the veneer.

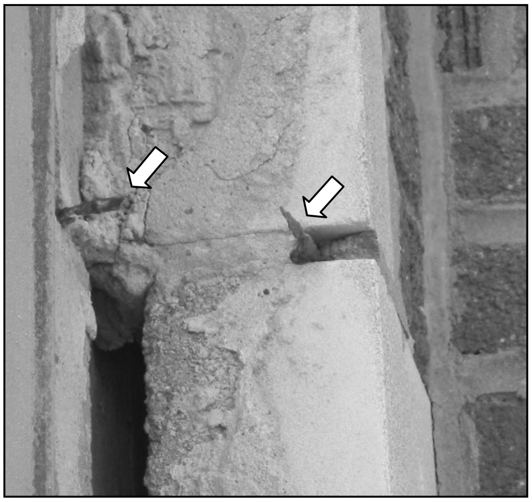
The wall ties at the veneer ribs are particularly susceptible to water intrusion because they are anchored in the adjoining veneer and have less cover – water does not have to penetrate as far in order to initiate corrosion at these ties.

Corroded and failed wall ties were observed at the corners of the tower (Figure 7), and at the interior surfaces of the exterior walls (Figure 8). Similarly, corroded and failed wall ties were noted at the removed masonry units (Figures 9, 10). Some of the corroded anchors appear to be part of the original construction, while other corroded anchors appear to have been installed remedially.

According to Grimm (2000), Corrosion causes a loss of load-bearing material in the wall tie, resulting in a smaller section with reduced load capacity. In addition, the oxidized metal expands to fill a larger volume than the original metal. The result is expansive forces in the vicinity of the anchor, which lead to additional crack formation and larger gaps in the veneer. The larger gaps lead to additional water intrusion thereby promoting further corrosion of the wall ties in a vicious cycle.

Distress due to corrosion expansion was also observed at reinforcing bars in the southwest corner of the tower (Figure 11) and at the connecting "pins" at the decorative spires at the top of the tower (Figure 12). Furthermore, corrosion expansion was noted at reinforcing bars with shallow or insufficient cover and at lintels at the first floor windows. The widespread corrosion expansion indicates that the building is exposed to an environment where moisture intrusion is common.

The loss of section and failure of the wall ties has reduced the ability of the veneer to resist lateral loads such as wind, and may also have reduced the gravity load capacity of the veneer by increasing the unbraced length, thereby reducing the buckling strength of the veneer.



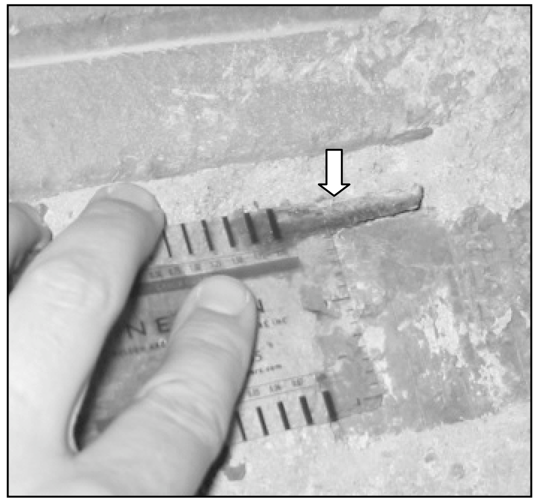


Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Remedial Work

Extensive remedial work has been performed at the tower veneer. Replaced or re-pointed mortar joints were visible during our site visit, often in the vicinity of the veneer distress (Figures 2, 3). When the mortar surrounding a brick is ground out for replacement, or the entire brick is removed and replaced, the dead load of the structure is transferred to the remaining bricks. The replacement sealant, mortar, or brick carries little or no dead load because it cures in place, with the load already transferred around it.

At the tower veneer, the remedial work may have transferred additional load to the cast stone ribs. The additional load increases the tendency of the rib to buckle out of plane, away from the building; however, the wall ties resist the buckling behavior of the rib. As the load on the wall ties increases, their remaining capacity to resist wind load is reduced.

The remedial work at the tower veneer may have partially contributed to the veneer distress by increasing the load on the wall ties; however, the primary cause of distress is the direct reduction in wall tie capacity through the corrosion process.

Summary & Conclusion – Multiple Causes of Failure

Based on the observed conditions, available documentation, and analysis, we concluded that the cause of veneer distress at the Old Tower was corrosion and failure of the wall ties. However, many conditions and processes contributed to the wall tie corrosion and failure over the 80-year life of the building.

Years of weathering of the veneer promoted water intrusion through cracks in the mortar joints. The potential for cracking was enhanced by the thermal and moisture expansion characteristics of the brick-stone interface. As water entered the mortar joints, the wall ties at the cast stone corners began to corrode. Corrosion proceeded more rapidly at the corner units, where the wall ties were anchored in the adjacent veneer – closer to the surface of the veneer than the other wall ties. Corrosion expansion of the wall ties resulted in additional crack growth, thereby promoting additional water intrusion in a vicious cycle. After 80 years of corrosion, the capacity of the wall ties was reduced to the point that on September 18, 2002 a moderate thunderstorm, with winds significantly slower than the design wind speed, was able to fail the wall ties and displace portions of the veneer.

In addition, site grading, foundation movement, wind-borne debris, hail, lightning, and seismic activity were identified as having no contribution to the veneer distress.

Epilogue

It is not surprising that the veneer failed first at the corners of the tower: the wind loads are highest at the corners, where, in this case, the wall anchor cover was the most shallow. Unfortunately, it is also not surprising that a failure was reached before the wall tie corrosion was diagnosed – the college had no formal inspection procedure to monitor the condition of the veneer. The signs of wall tie distress are often subtle (typically horizontal mortar joint separations in the plane of the ties, or localized rust staining of the veneer), and cannot easily be observed from ground level with the un-aided eye.

Due to this veneer failure, the college was made aware of a serious problem in their infrastructure, and can now take steps to investigate the condition of the masonry wall ties (and veneer in general) throughout their campus.

Based on the various ordinances established by the cities of Chicago, Ill., New York, N.Y., Boston, Mass., and Detroit, Mich., a formal inspection procedure would typically include a walk-around inspection on an annual basis, and a "hands-on" inspection every four to five years. ("Hands-on" is defined as visual inspection within arms reach.) The results of each inspection would be recorded for future reference or remedial action as required. It should be noted that the Old Tower would qualify for these ordinances because it is more than 70 to 80 feet tall and contains more than 6 stories. In our opinion, the Old Tower should be inspected even more frequently, due to its failure history and the volume of pedestrian traffic on the college campus.

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