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MODERN MASONRY DETAILING IN HISTORIC TERRA COTTA CLADDING SYSTEMS: MISGUIDED INTENTIONS?

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ABSTRACT

The introduction of the skeleton frame structural system and subsequent development of the curtain wall enabled buildings to be constructed very quickly and economically and paved the way for the development of a new building type—the Skyscaper. The curtain wall or facades of the early skyscrapers evolved into an increasingly complex assemblage of various materials that are intended to act together while maintaining a weather tight enclosure and structural integrity. As these early facade systems age, damage resulting from various environmental forces has lead to an increase in repair work on these unique buildings archetypes.

The restoration of these facades presents many challenges in designing appropriate and effective repairs. Often modern detailing standards are applied to the early curtain wall systems resulting in a change in the behaviour of the system causing additional distress which is attributed to the repair itself. An understanding of the behaviour of these aging historic curtain wall systems is critical to the development and implementation of appropriate repair details.

This paper is divided into two parts. The first part will compare traditional terra cotta details with modern details and includes a discussion of the development of the modern details with respect to the evolution of the curtain wall cladding systems. The second part presents three case studies where modern details have been introduced in historic curtain wall systems and other buildings where modern details were not introduced. The rationale behind these decisions will also be discussed. The goal of the paper is to demonstrate that care should be exercised if and when modern detailing is appropriate for historic curtain wall systems.

KEYWORDS: detailing, restoration, terra cotta

INTRODUCTION

Over the past 125 years, innovations in structural engineering, construction materials, and construction techniques allowed for the construction of taller buildings. Economic and social factors, including increased population density and mechanization, provided the incentive to construct these new buildings. In order to erect taller buildings faster, the amount of material and therefore the weight of facade materials had to be decreased, and mass produced replicated ornament developed to replace custom carved facade elements. The advent of the passenger elevator, innovations in structural engineering, increase in land value and the development of the curtain wall which incorporated new ways to use traditional facade materials lead to a new building type—the Skyscraper.

Prior to the 1870s, the exterior walls of buildings functioned as both the building's structural system and the enclosure for the interior space. During this era, masonry walls were monolithic. The height of a building was typically proportional to the wall thickness and also limited to the load bearing capacity of the underlying soil.

The industrial revolution of the late ninetieth century led to the introduction of steel as a building material. With the ability to economically manufacture structural steel shapes, the skeleton frame building system soon developed. Steel frame buildings became common practice in the construction industry because of their economy, scale, and speed of construction compared to load-bearing masonry buildings. Skeleton construction allowed exterior walls to be designed "primarily for the purpose of excluding [sic] the elements, and to provide opportunity for architectural treatment" [1].

TERRA COTTA MATERIAL AND STRUCTURE

Terra cotta is a fired ceramic material used since ancient times as architectural ornament. Henry Tomlan of Worcester, Massachusetts first popularized molded terra cotta units for architectural applications in the United States in the late 1840s [2]. Terra cotta was first used on buildings for roofing, flooring, and sculptures. Subsequently, builders used terra cotta as a substitute for natural stone. Terra cotta was less expensive to manufacturer than hand carved stone; particularly when a mold could be used to reproduce the same unit type multiple times. This was important since large quantities of identical unit types (jambs, sills, ashlars, etc.) were required for skyscrapers.

TRADITIONAL DETAILING

A review of early industry details for terra cotta cladding (1890s to 1930s) reveals a subtlety of detailing to accommodate building movements. For example, horizontal expansion was generally accommodated by the lapping of spandrel areas behind piers and offsetting continuous horizontal areas of terra cotta to accommodate the movement. More significant is the issue of vertical expansion. Details included provisions for vertical expansion, but the magnitude of expansion as well as the installation of the expansion joint often resulted in ineffective, inadequate joints or the details simply were not included. Horizontal expansion joints were recommended at each floor and typically shown to match the width of the mortar joints. Often the joint was filled with a mastic or lead that had limited compressibility.

Water management detailing relied on the geometry and articulation of the facade rather than coatings, sealants and gaskets. By incorporating drip edges, water tables, cornices and recessing windows within punched openings, water was directed away from the exterior walls and openings. Early curtain wall cladding systems, like traditional monolithic masonry facades, relied on the mass of the masonry to absorb the moisture that enters the wall system and then allowed the water to evaporate and leave the wall system. The transition to the modern glass and metal curtain wall in the 1950s resulted in a dramatic shift in the water management approaches for curtain walls and the loss of rationale behind the traditional detailing. Representative details are shown in Figure 1.

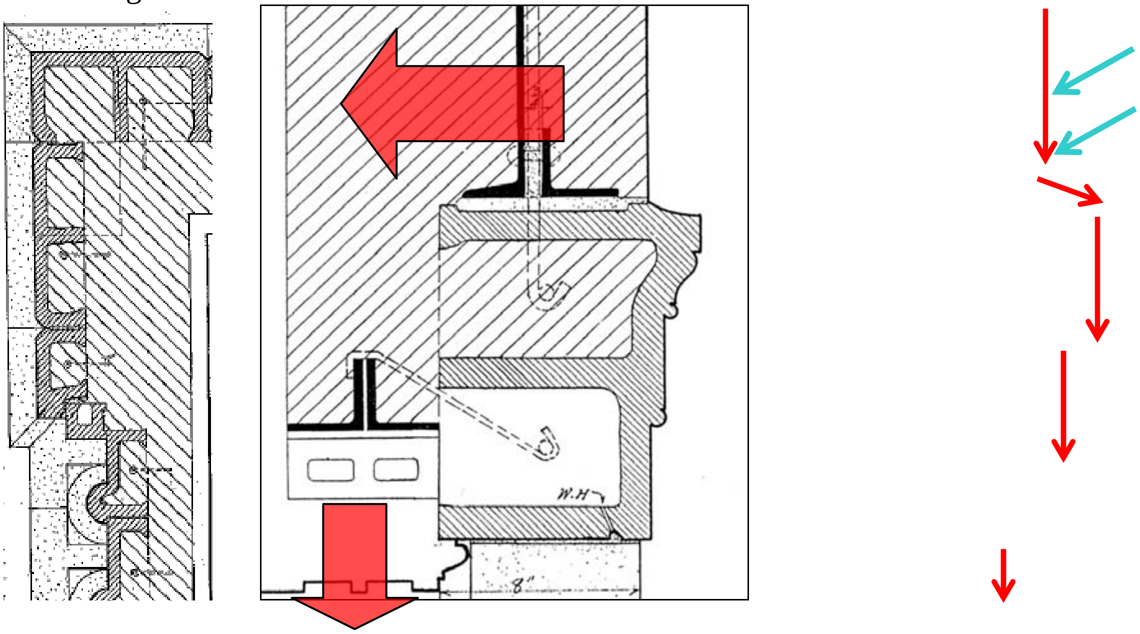

Figure 1: Detailing of terra cotta installation to accommodate horizontal expansion (left) and water management by the geometry of the units (right).

DECAY MECHANISMS

Typically, terra cotta is a very durable material and may perform well in an exterior environment. Most of the decay mechanisms of terra cotta facades are a result of deterioration of the system rather than deterioration of the terra cotta material. The main mechanisms which cause deterioration of terra cotta cladding systems include moisture infiltration, thermal cycling, and built-up compressive forces. Water inevitably enters all building facades. The amount of water entering the system typically accelerates as materials deteriorate and stresses accumulate.

Prior to the 1950s, architectural design did not adequately accommodate thermal cycling in exterior cladding systems. Physical properties of materials, color, and exposure all affect the interaction between adjacent materials. Thermal cycling on the wall systems is difficult to predict because of the complex behavior of the structure and materials within modern curtain wall systems. Temperature cycling related to seasonal and daily temperature changes may cause cracking either in the terra cotta units, the mortar, or the terra cotta and mortar interface. These conditions allow additional water to enter the cladding system and accelerating deterioration.

Fired clay masonry undergoes a permanent expansion in the first decades of service. This expansion, combined with frame shortening, was typically not properly accommodated in historic construction and leads to accumulation of compressive forces, additional cracking and subsequent water infiltration (Figure 2).

Figure 2: Representative examples of extreme deterioration due to improper maintenance.

Water infiltration contributes to the corrosion of embedded steel elements. Corrosion of embedded steel elements has long been recognized as a potential problem. The incorporation of ferrous metal into masonry construction and subsequent corrosion related distress has resulted in dramatic changes in the construction and detailing of cladding systems to address water infiltration and corrosion.

As the steel elements oxidize, corrosion forms that occupies a volume between four and ten times the volume of the original uncorroded steel. The forces resulting from the confined corrosion scale of the embedded steel elements cause visible and concealed distress in terra cotta. Numerous methods of limiting corrosion have been historically employed to protect ferrous material including boiling the element in tallow, covering it with pitch or varnish, or galvanizing it with molten tin or zinc.

The following case studies represent a range of terra cotta clad skyscrapers constructed in the early 20th century. Each building had previously undergone a major repair program and was subsequently investigated by the authors to develop repairs to address the original distress as well as the distress that developed from the previous repair programs.

MIDWEST OFFICE BUILDING- CASE STUDY 1

A 17 story steel framed office building in downtown Chicago was constructed around 1905. The facade incorporated alternating projecting and flat bays between the third and fourteenth floors. In general, the facade is in serviceable condition given the age of the building and the maintenance which has been performed in recent years. Previous repair work had included installing a flashing system above the windows in the flat portions of the wall. The repairs included removing the units above the shelf angle, installing a flashing and then reinstalling the terra cotta with a sealant joint and weep tubes at the flashing level. It was the author’s opinion that the facade distress observed was not consistent with the need to install a flashing system. No leakage had been reported and investigative openings did not indicate a significant amount of corrosion of the embedded steel supporting the terra cotta had occurred.

Based on an investigation which included visual inspections and selective removal of terra cotta units, it was concluded that the cracking and displacements are likely the result of accumulated stresses within the facade. These stresses are due, in part, to the inability of the wall construction to accommodate thermal and moisture movements of the cladding materials as well as differential movements between the masonry facade and the underlying steel structure. Limited corrosion scale was also observed which further increased the accumulated stresses.

In continuous vertical facade element such as piers and the fluted pilasters, the effects of moisture expansion, thermal expansion and corrosion scale accumulation combined with the foreshortening of the steel frame under the dead load of the building imparted stresses in the cladding system that lead to localized cracking. Cracking typically developed at points where the facade materials were restrained, such as at locations of steel supports within piers, at intersecting walls elements (piers and spandrels) and at corners of the building. Representative conditions and original details are shown in Figure 3 and 4.

In 2007 a repair program was implemented which included identifying distressed units and then repairing or replacing designated units. Following an initial inspection, the contractor removed the designated distressed units which also included units that were not distressed but had to be removed to facilitate access for installation of the replacement units. Additional terra cotta units cracked as a result of the initial removal process and subsequent release of stresses within the units. These units were also removed and replaced.

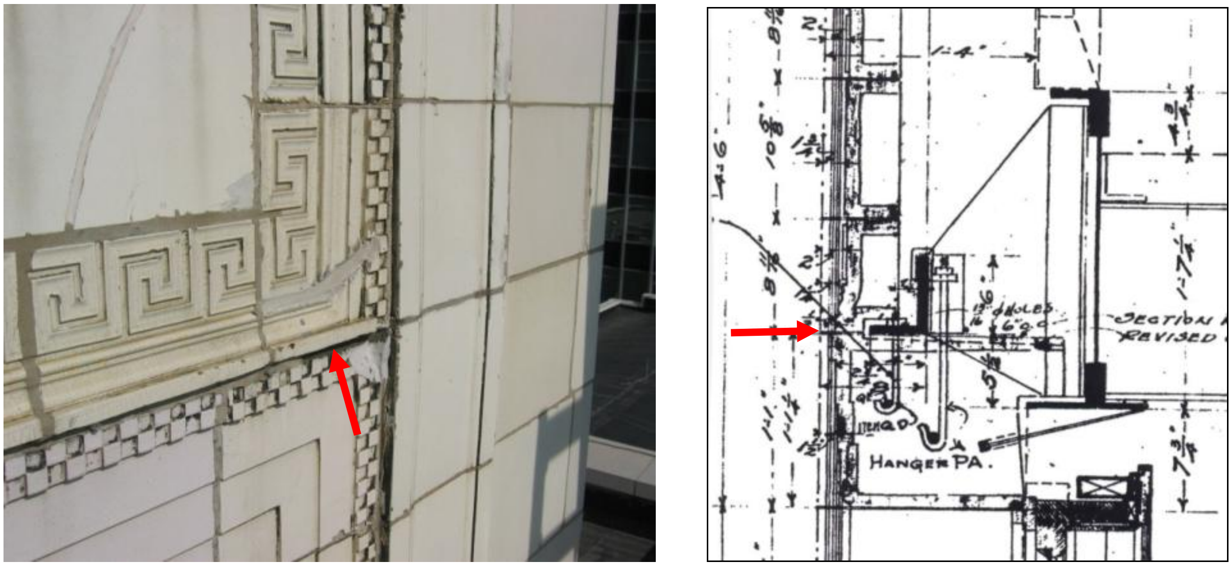

Figure 3: Representative area of flat portion of facade at previous repair location; original shop drawing. Arrow indicates bed joint corresponding to shelf angle location.

The repair program included cutting strain relief joints in the masonry across the main facades at each floor line to relieve compressive stresses within the terra cotta cladding. Approximately five days after the strain relief joints were cut, each drop was reinspected and additional units were identified to be removed and replaced as a result of cracking that had occurred due to the redistribution of the stresses within the terra cotta units. The relief joints were repointed following the removal of distressed units.

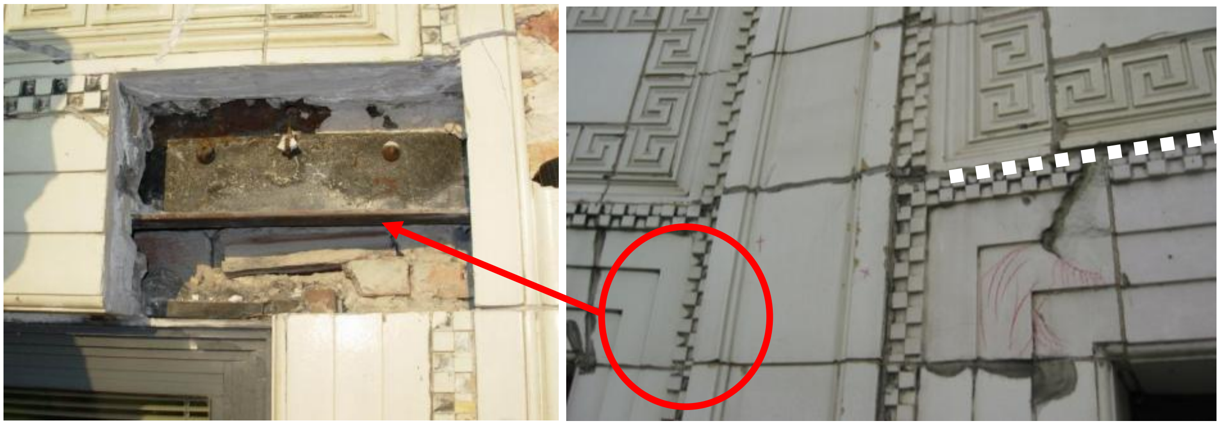

Figure 4: Representative distress in terra cotta. Inspection opening at left was created in projecting bay area. Flashing were installed only on the flat wall areas (dashed line)

The flashings which had been previously installed were essentially ineffective and unnecessary. By sealing the joint at the shelf angle it is likely that more water is actually trapped in the spandrel area than would have been the case had the supporting steel been exposed and painted and the mortar installed into the joint rather than sealant.

SOUTHERN MUNICIPAL BUILDING- CASE STUDY 2

The 25-story steel frame municipal building was constructed in 1928 and is clad entirely in terra cotta. In 1979, an investigation of the distress conditions, which primarily consisted of diagonal and vertical cracking in the terra cotta facade, was conducted. This investigation concluded that insufficient bearing of the terra cotta units at each shelf angle was the cause of the cracking and distress at the spandrel sections.

In 1980, repairs were performed to provide additional bearing at the shelf angles at many of the terra cotta spandrel units. These repairs consisted of coring two 7.6 cm (3-inch) diameter holes through the intermediate webs in each terra cotta unit, welding a stud anchor to the existing steel shelf angle at each hole, grouting both cored openings, and patching each cored hole with a thin terra cotta plug (Figure 5). Horizontal expansion joints were also installed below the steel shelf angles to prevent further cracking of the terra cotta cladding due to thermal and moisture expansion.

In 2002 an investigation of the terra cotta cladding revealed that many of the previously repaired terra cotta units, as well as adjacent units located under window openings, were exhibiting significant distress including hairline cracks radiating from the cores and more pronounced diagonal cracks in the terra cotta units below the window openings (Figure 6). The supplemental welded stud anchors were not installed in the terra cotta spandrel units located directly below the window openings; however, horizontal expansion joints were saw cut below these units. Cracks typically originated at window corners, extended through a vertical mortar joint, and continued diagonally downward, sometimes continuing to the soft joint. Cracking was also occurring between the terra cotta face shell and the vertical stiffener webs. In addition to the visual distress, many of the cored terra cotta units were found to be delaminated and loose when sounded with a rubber tipped hammer.

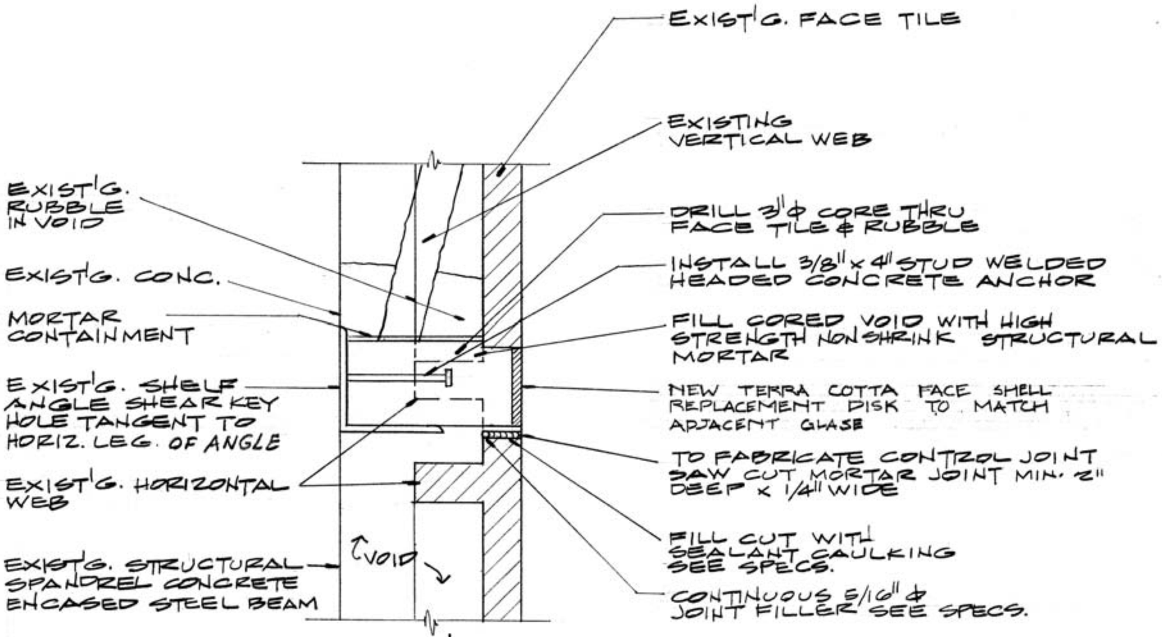

Figure 5: Original repair detail to support terra cotta ashlar units.

Figure 6: Representative distress in terra cotta. Note locations of previous repairs (arrow)

Subsequent investigation concluded that coring the terra cotta units and saw cutting of horizontal expansion joints below these units caused a redistribution of load and subsequent cracking of the units. By design, the entire gravity load of each floor of cladding was intended to be uniformly supported by the shelf angle, but in reality a portion of this gravity load was being transferred through to the floor level below. In a typical wall section, approximately half of the thickness of the terra cotta unit extends beyond the edge of the shelf angle and is unsupported. A full depth mortar joint installed under this unsupported section allows for a portion of the gravity load to be transferred to the floor below. Installation of the previously described repair appears to have altered the load path by creating point loads to the floor below since the original mortar joint was only partially removed before the soft joint was installed. The cracking pattern observed below the windows is likely the result of non uniform support across the entire shelf angle since the supplemental repair was not installed in these units.

The terra cotta spandrel units located elsewhere on the building that were not repaired during the 1980 repair program, exhibited much less distress than the repaired units. Cracking noted in these areas appeared to be due to corrosion of the encased steel support elements.

MIDWEST OFFICE BUILDING- CASE STUDY 3

This building is 46 stories in height and was constructed in 1929. The two street facades of the building are clad entirely with terra cotta. Throughout the terra cotta facades, a combination of flat and profile terra cotta units make up the exterior cladding at the columns between the windows. The columns widths range between 1.2 m (4 feet) and 1.8 m (6 feet). At each floor level the terra cotta column units are supported by a steel shelf angle that is connected to the underlying steel spandrel beam and column.

During a previous repair project, an expansion joint was installed under the shelf angle at each floor of the terra cotta columns. Sealant joint widths at the shelf angles range between 1.9 cm (3/4 inch) and 3.8 cm (1-1/2 inch). Exploratory openings revealed that the horizontal expansion joints were constructed by saw cutting the terra cotta units below each shelf angle. The original mortar was removed from the joint and a minimum clear space of .6 cm (1/4 inch) joint was created below the steel angle. Exploratory openings at the columns also revealed that the original steel shelf angle typically provided only 2.5 cm to 3.8 cm (1 to 1-1/2 inches) of bearing for the 10.2 cm (4 inch) thick terra cotta unit (Figure 7). A slightly shorter replacement unit was installed below the shelf angles, to accommodate the expansion joints, resulting in the wider sealant joint.

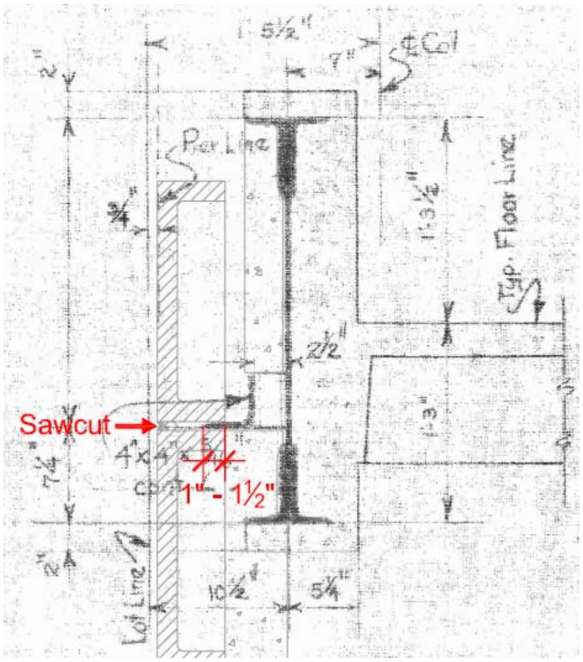

Figure 7: Original architectural detail at shelf angle location. Note bearing area dimension

During our investigation, several distress conditions were noted at the terra cotta columns where the joints had been cut including cracked and spalled units above the shelf angle. The most significant distress condition included concealed vertical cracks in the terra cotta webs, which originate where the webs of the terra cotta unit bear on the shelf angle. Representative conditions found during the investigation are shown in Figures 8 and 9.

In the original construction less than one third of the terra cotta was bearing on the shelf angle and a full depth mortar joint was installed under the unsupported section. Therefore, a portion of the gravity load was transferred through the mortar joint to the floor below; creating a mixed load path that was a combination of load-bearing and non-load bearing. When the expansion joint was cut, the gravity load of the terra cotta between shelf angles completely shifted to the shelf angle. Since a significant portion of the terra cotta unit, more than two thirds of the unit was not supported by the shelf angle, a stress concentration developed in the terra cotta unit at the end of the shelf angle where the vertical cracks were observed. It was concluded that the cracking is due to inadequate bearing and redistribution of the load after the horizontal expansion joints were cut.

Figure 8: Representative examples of shelf angle locations with minimum bearing (left) and with expansion joint having been cut below shelf angle (right).

In addition to the distress units above the shelf angle, the terra cotta units below the new horizontal expansion joints were observed to be hollow (no bond to backup materials) and some were loose. It is likely that the lateral support at the top of these terra cotta units was inadvertently eliminated when the horizontal expansion joints were cut.

Figure 9: Representative distress in terra cotta at shelf angle locations.

CONCLUSION

Effective repair and restoration of historic terra cotta facades requires an understanding of mechanisms of deterioration as well as appropriate repair techniques which do not adversely impact the facade by creating more distress or not adequately addressing the cause of the deterioration. An understanding of historical detailing as well as overall behaviour of the cladding, as originally constructed, is critical. These case studies illustrate examples of repairs which at many levels were appropriate for the distress observed, but a lack of a fundamental understanding of the entire cladding system resulted in new and potentially more extensive repairs. A comprehensive investigation by qualified restoration specialists is critical to developing a successful restoration program.

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