A Novel Method for Terra Cotta Repair

by Kolbjorn Saether

Abstract

At the turn of the 20th century a new form of artistic design was introduced to the facades of high-rise buildings. Terra Cotta, the Latin expression for "burned earth", was used for this endeavor. Not only was this material well suited for the creation of artistic sculptures, but it also proved to be almost indestructible when exposed to normal wind and weather. But yet, 100 years later, many of these buildings show patterns of damaged terra cotta units. Even though a great majority of the terra cotta didn't show any damage, something was happening on the inside to some of the units. J-bolts and pins fastened most terra cotta units to the supporting structure. However, some of these bolts and pins would corrode due to moisture penetrating the outer shell in to the steel. The result was a reduction in strength due to reduced cross-sectional area or cracked terra cotta due to the expansion of the steel bolts and pins. Until now, no general effective repair method had been found. Our development of the foam patch method of repair will change this situation.

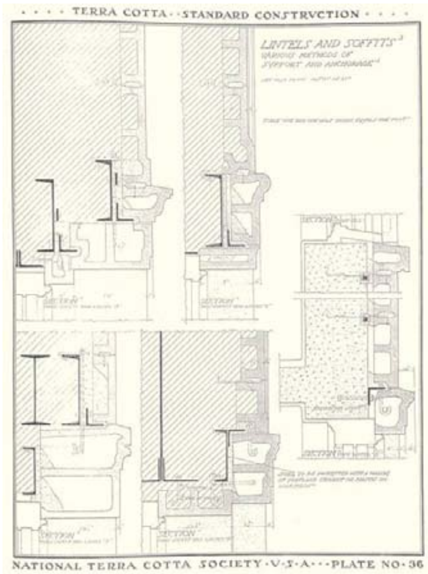
Introduction

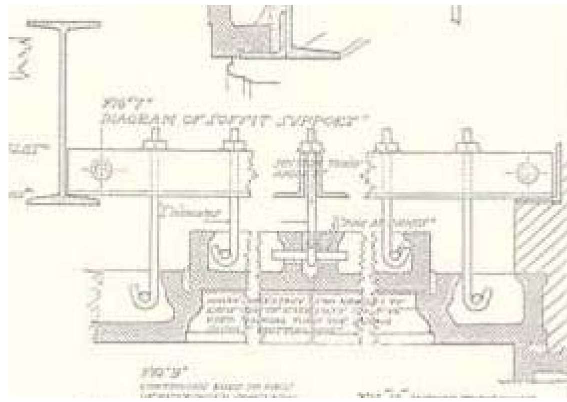
Historically, before the advent of the Miesian-style "less is more" in high-rise building designs, the original architectural movements of the Chicago School of Architecture viewed building exteriors as a canvas on which to adorn artistic features and transform practical structures into aesthetic monuments. Many of these decorative designs have been created using terra cotta facades and are present in hundreds of buildings here in Chicago alone. They have given many city neighborhoods their special architectural character. But many of these buildings are in trouble due to deterioration of the terra cotta units.

Terra cotta was once viewed as being indestructible, although there are several factors that can cause terra cotta to deteriorate. By themselves these units have proven to be close to indestructible when exposed to wind and weather. In most cases, after 100 years of exposure the units show little or no signs of damage. In spite of this, peculiar patterns of damaged units have developed on many of these buildings. The damage has in spots been so intense and so threatening and the repair so expensive that these buildings have turned into "White Elephants" for the building owners. The building damages must be repaired.

Typical terra cotta details

To understand what is happening, it is necessary to study the construction of the terra cotta. A typical terra cotta unit consists of an ornamental face shell approximately 2 thick with 4 inch to 6 inch or even 12-inch deep ribs or edges for strength and stability. These ribs are arranged to form voids behind the front surface (square, rectangular, voids, etc.). These terra cotta units in many ways are like decorative China, hung on a wall supported by steel wires and nails. They form a continuous surface, sometimes supported through mortar joints one on top of the other or tied, similar to masonry, with metal hooks and clips to the back-up wall or frame for lateral support. Pins and J-bolts, however, often furnish the vertical support. To get a hold of each unit, the steel pins are pushed through holes in the terra cotta ribbing or edgings, the pins themselves being supported by J-bolts, which then are supported by the steel framing members or the back-up masonry walls.





Cause for deterioration

Something is happening, but what? Numerous theories have been developed. Many causes have been identified. Freezing up of horizontal and vertical expansion joints would put pressure on the terra cotta units. Moisture penetrating into the terra cotta shell would cause expansion and would crease the glazed finish. Water trapped in the cavities because of clogged up or missing weep holes, would cause damage due to freezing and thawing water within the cavity. Still, the single most prominent reason for the deterioration of the units is the corrosion of the steel support system. The support system consists of hundreds of steel pins, hooks and bolts located within the cavities of the units. Moisture would cling to the steel components and cause these to corrode, expand, and weaken. This action would cause two types of damage, one the direct weakening of the supporting steel member, and the damage being the indirect destruction of the terra cotta unit through expansion of the steel member.

The architects and manufactures of terra cotta clad buildings were fully aware of the vulnerability of this cladding. Specifications, as written by the National Terra Cotta Society USA, were expressed both in the introduction to the use of terra cotta, as well as in the detailed specifications. Some samples are shown below:

> ***Protection against Corrosion (Introduction)***
> *Proper care should be exercised to prevent the corrosion of all steel supports, ties, etc. Where such protection cannot be permanently secured through encasement with mortar or concrete, or through the use of corrosion resistant metallic coatings, non-corrosive metals should be employed.*

and

> ***Supporting Anchors (Standard Specification)***

27. *All anchors, hangers, bolts, clips, straps, rods and pins for securing Terra Cotta shall be of wrought iron or non-corroding soft steel.*
28. *Anchors, hangers, bolts, clips, straps, rods and pins for securing the Terra Cotta, except where otherwise shown or specified, shall be of the following minimum sizes: (General sizes were given).*

Weep holes were routinely designed into the terra cotta details to weep out any of the water/moisture that might have gotten into the cavity. All in all, any corrosion was not supposed to occur.

For some unknown reason, however, these specifications were not adhered to. Mainly, as high-rise construction took over the field at the turn of the 19th century we find tall buildings with empty cavities (no mortar fill) and unprotected, mild steel pins and J-bolts. Was it the need to keep the skin light? It is difficult to say. The facts were as stated above: the metal was allowed to corrode.

How could mistakes like this happen? We even see cases of this happening right in our time. An example is a fence around St. Mary's Hospital in Chicago. Out of some 30 steel posts, 16 had caused the supporting concrete caps to crack. Number 10 was so bad; the concrete base had been replaced.

This cracking was due to expansion of the steel. As corrosion occurs, the effected steel layer will increase in size 6 to 8 times. As in the post/concrete top plate case, inside a terra cotta unit, if a pin is located next to or within a terra cotta unit rib, this increase can cause the unit to crack. One advantage for this type of damage, however, is that it is visible and can be identified and repaired. (One of today's accepted repair methods is the use of stainless steel pins. For this method, holes are drilled into the terra cotta unit through which pins are installed. This method, however, does not do the whole job as the corrosion of the steel within the unit is allowed to continue to corrode.)

Another and even more dangerous type of damage is the reduction in strength of the supporting steel pins, bolts and hangers. When this happens within a cavity, no outward sign of trouble is visibly developed, and the damage can go undetected for years until suddenly a heavy unit gets disengaged and comes crashing to the ground.

That this corrosion actually takes place is no myth (see pictures above). The first sample is a 5/8” ∅ J-bolt, which has been reduced to zero due to corrosion. The same is the case with the second example, the ¼“ x ¼“ tie. Again, the section is reduced to zero.

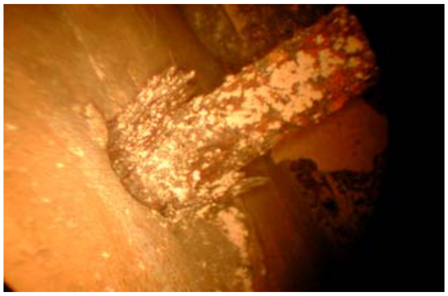
To avoid the expense of physically opening the unit for inspection, and then repairing and or replacing the unit, a cost effective and foolproof method for identifying the damage is the use of a fiber optic scope. This inspection method is minimally invasive requiring only a small hole on the order of ¼” ∅ to ½“ ∅ to be drilled into the unit.

The fiber optic scope is a simple instrument. It has an eyepiece on top to which a camera can easily be mounted. It can look straight down or, with a mirror attachment; the view can be bend 90° and rotated to give a 360° view of the cavity.

The building façades at 220 South State Street in Chicago were inspected using this scope. Except for some relatively small cracks, initially, no dramatic damage was observed from the ground or from the swing stage. When looked at with the fiber optic scope, however, the situation showed up quite differently. Corroded pins were found throughout. Slivers of corroded metal trapped in the terra cotta ribs could be seen. This then resulted in cracks through the rib and terra cotta facing.

220 South State Street.

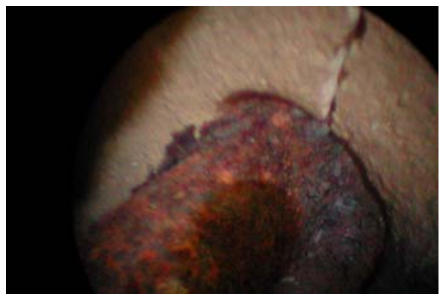
Cracked terra cotta windowsill.



Slivers of corroded metal inside a rib.

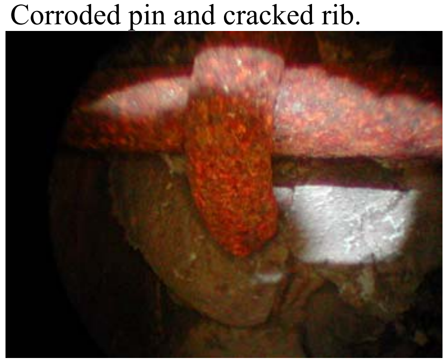
Corroded pin.

Cracked rib.



Corroded pin and cracked rib.

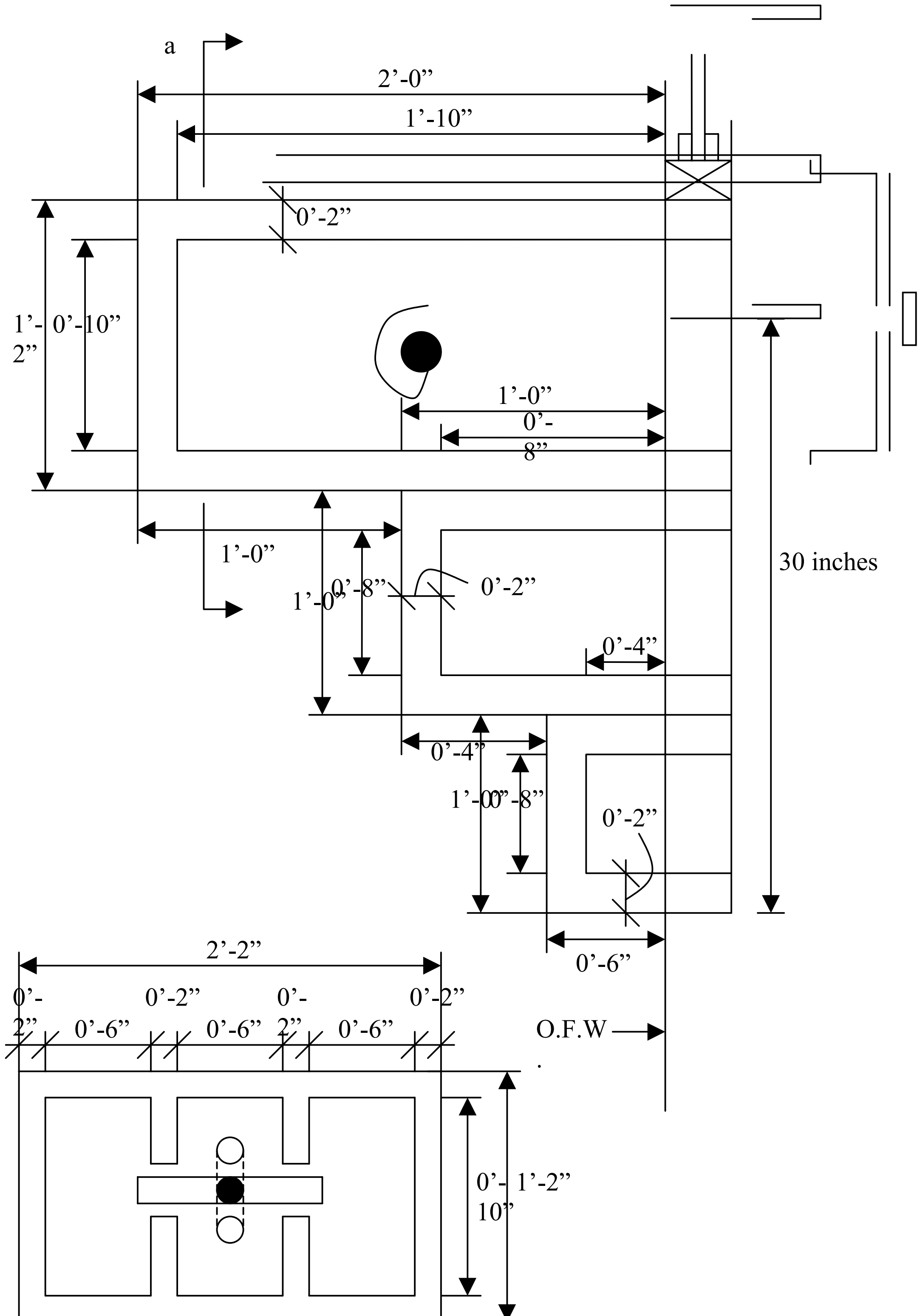
J-bolt and pin intersection.



J-bolt and pin intersection.

The inspections with the fiber optic scope can be limited to spot checks or to include only critically located units. The option of using optical fiber imaging offers a further advantage. It is inexpensive and very effective. Allowing pictures to be generated of the damaged components it gives an accurate record of what has happen, thereby allowing the required strategies to be developed.

220 South State Street



Section a.a.

<u>Unit 1 assembly</u>

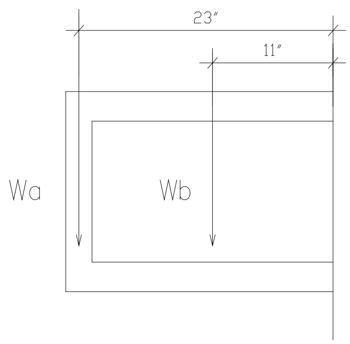
a

Design – Top Unit

Volume Va = 2” x 26” x 14” = **728 in3**
Volume Vb = [26” x 14” – 3(6” x 10”)] x 22 = **4,048 in3**

Weight Wa = 728 x 120/1,728 = **43.68 lbs.**
Weight Wb = 4,048 x 120/1,728 = **281.11 lbs.** **ΣW = 324.8 lbs.**

C.O.G.: X = (Wa a + Wb b)/ΣW = (43.68 x 23 + 281.11 x 11)/324.8
= **12.61 in**

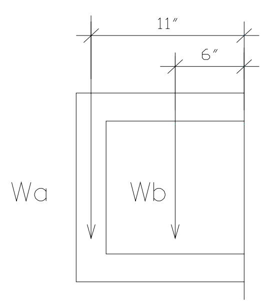


Design – Middle Unit

Volume Va = 2” x 26” x 12” = **624 in3**
Volume Vb = [26” x 12” – 3(6” x 8”)] x 10 = **1,680 in3**

Weight Wa = 624 x 120/1,728 = **43.3 lbs.**
Weight Wb = 1,680 x 120/1,728 = **116.7 lbs.** **ΣW = 160.0 lbs.**

C.O.G.: X = (Wa a + Wb b)/ΣW = (43.3 x 11 + 116.7 x 6)/160.0
= **7.31 in**

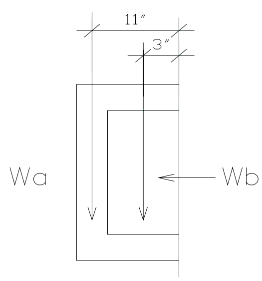


Design – Bottom Unit

Volume Va = 2” x 26” x 12” = **624 in3**
Volume Vb = [26” x 12” – 3(6” x 8”)] x 4 = **672 in3**

Weight Wa = 624 x 120/1,728 = **43.3 lbs.**
Weight Wb = 672 x 120/1,728 = **46.7 lbs.** **ΣW = 90.0 lbs.**

C.O.G.: X = (Wa a + Wb b)/ΣW = (43.3 x 5 + 44.7 x 3)/90.0
= **3.9 in**



Tensile Stresses

Total Weight: W = 324.8 lbs.
W = 160.0 lbs.
W = 90.0 lbs. **ΣW = 574.8 lbs.**

Overturning Moment M:
M = 12.61 x 324.8 = 4,095.70 in #
M = 7.36 x 160.0 = 1,177.60 in #
M = 3.90 x 90.0 = 351.00 in # **ΣM = 5,624.30 in #**

T = 5,624.30 x 1/30” = 187.5 lbs.
Foam Area = 3 (6” x 10”) = 180 in2
f = 187.5 lbs/180 in2 = **1 psi**

Total forces in unit

Bolt Strength:
½“ Φ bolt Tensile Strength: Tallow = 0.20 x 18.00 = **3,600#**
Yield Ultimate Strength: Tyield = 0.20 x 36.00 = **7,200#**

Terra Cotta Unit Weight:
W = 140 x 2 x (2 x 24 x 12 + 4 x 14 x 10 + 24 x 18) x 1/1,728 = **254 lbs.**

Urethane Holding Power:
Polymeric Urethane Bonding Agent: fr = **5 psi**
Tensile Strength of three 5” x 6” foam patches:

T = 3 x 5 x 5 x 14 = **1,050 lbs.**

Tensile Strength of one 20” x 14” foam patch:

T = 5 x (24 – 4) (18 – 4) = **1,400 lbs.**

Repair Program

Once the damage has been established and with the calculations of the forces and stresses within the units and their anchors at hand, a repair program can be developed.

With numerous theories developed in the past to explain the presence of damaged terra cotta units, a corresponding multitude of repair programs surfaced. Numerous efforts were made to repair the terra cotta clad buildings. No easy method could be found. The methods were generally incomplete, ugly, temporary or too expensive. They used pins, plastics, fiberglass, precast concrete, stone, brick, aluminum, even new terra cotta units; an exhausting array of efforts and generally at little or no avail.

The fact was, three fundamental things had not been dealt with. The repair had to do three things: 1) it had to protect the steel against further corrosion; 2) it had to repair the cracked units, 3) it had to restore the carrying capacity of the support components wherever needed.

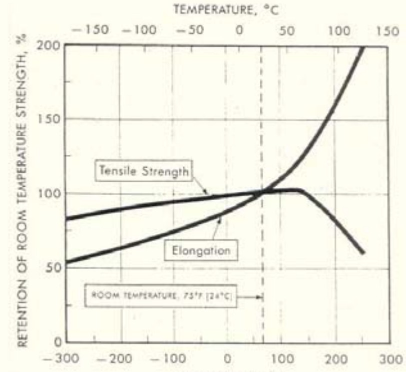
In search of an answer, the surprise solution was that all three could be obtained from a system and a material used for something entirely different. Polyurethane Foam had been used for years to seal cracks in rocks and concrete. This foam would stick to almost everything. It was waterproof, but it had a tensile strength of only 10 to 60 psi. However, when multiplied with 200 in^2, this would make a force of 2000 to 12000 lbs. A large terra cotta unit could weigh 333 lbs. A typical unit would generally have two or three open cells, approximately 5” x 14” = 70” each. When multiplied with 3, the three units would have a total area of 210 in^2. This times 5 psi results in 1000 lbs. If made to carry the unit in tension this alone would mean a safety factor of 3 to 1.

Table VI

Burial Test With Rigid Polyether Foam Slab Stock
Test Conditions: 12 x 12 x 2 in [305 x 305 x51 mm] sections buried to a depth of 10 in [254 mm] in the ground in Delaware
A control sample was aged indoors

Property	Control (Aged Indoors)	Buried In Ground
Density, lb/ft³ [kg/m³]		
Original	2.1 [34]	2.1 [34]
After 1 year	2.2 [35]	2.2 [35]
After 3 years	2.1 [34]	2.1 [34]
After 10 years	2.1 [34]	2.1 [34]
Tensile Strength, psi [MPa] (measured on buttons)		
Original	54 [0.37]	54 [0.37]
After 1 year	68 [0.46]	59 [0.41]
After 3 years	36 [0.24]	30 [0.20]
After 10 years	58 [0.40]	57 [0.39]
Elongation, %		
Original	5.1	5.1
After 1 year	6.3	7.2
After 3 years	3.4	3.8
After 10 years	6.5	6.0
Compression Strength, psi [MPa] (at yield point)		
Original	47 [0.32]	47 [0.32]
After 1 year	51 [0.35]	38 [0.26]
After 3 years	42 [0.28]	33 [0.22]
After 10 years	50 [0.34]	46 [0.31]
K-Factor, BTU · in/hr · °F [mW/m · K]		
Original	0.123 [17.7]	0.123 [17.7]
After 1 year	0.127 [18.3]	0.126 [18.2]
After 3 years	0.136 [19.6]	0.131 [18.9]
After 10 years	0.144 [20.8]	0.168 [24.2]
Volume Change, % of original		
Original	–	–
After 1 year	0	1.7
After 3 years	0	4.2
After 10 years	0	4.2

Figure 12
Effect of Temperature on Tensile Strength and Elongation
Density: 1.8 lb/ft³ [29 kg/m³]
High Crosslink Density Foam
(Calculated average molecular weight between crosslinks = 350<)



To hold a two-inch thick piece of terra cotta, with full foam back up, only 0.15 psi would suffice.

In other words, these repairs could be done with polyurethane foam. This material having the consistency of maple syrup could be injected through a ¼” ∅ hole as a liquid, expanded 10 to 20 times its original volume, squeezed into every crack and crevice and void, allowing the excess foam to be squeezed out of the inlet hole and then, once cured after approximately 15 minutes, bonding itself to the inside of the terra cotta unit. It would hold any cracked and loose pieces in a firm grip and would stick to the backup masonry wall with a force 3 times or more than the weight of the unit itself. It would surround any exposed steel and encapsulate and rustproof this steel preventing further corrosion. If there should be any water present in the cavity, the polyurethane, which is hydrophilic, would make use of this to develop the foam. Actually, for a successful application the installer would add given amounts of water. To recap: The foam encapsulates the steel. It protects this against corrosion. It solidifies broken terra cotta units. It fastens the units to the back-up wall. It dries up any moisture. It costs very little to buy, and it costs very little to apply.

The foam in the final product is tested by the use of an oscillating, small diameter, thin wall split-spoon core drill. The resulting cores may be subjected to direct observation for this entire length, including the condition of the interface along the back-up structure. Similarly, the walls of the hole itself can be evaluated by the use of the fiber optic scope.

Combined with the fiber optic probe for determining the condition of the terra cotta units and the support systems and documenting the damage as well as the repair, one has a new method of repairing terra cotta cladding. It is permanent and would preserve the terra cotta clad buildings for years to come. Terra cotta repair offers the possibility of large savings as compared to conventional repair methods.

Of the so-called accepted repairs, besides cleaning, caulking, sealing, painting, etc. the most common is the use of stainless steel rods. These rods are various types of expansion or chemical anchors. None will stop the ongoing corrosion, as they do not encapsulate the steel. The expansion anchors would normally have unknown anchor capacity when expanded in the back-up wall. The chemical anchors are difficult to install across a cavity specially if placed overhead or on an upward slope. Each type requires the drilling of several holes in the cracked terra cotta pieces. This could lead to further cracking. If based upon an inspection that is limited to visual observation and tapping, the entire problem of corroded hanger strength reduction is ignored and could consequently cause life-threatening conditions to go undetected. Still, this repair program is routinely approved by the Chicago Building Department.

On the other hand, the suggested foam repair approach has been turned down by the Chicago Building Department. It criticizes several points in its approach. The City has stated that the foam could crack the terra cotta during the expansion phase. This is not possible since each cavity is vented by the inlet hole. Furthermore, it has stated that the foam may not protect the steel from corrosion, even though in reality the product is marked as a waterproof material. Numerous tests have been made on this topic. The polyurethane foam is fundamentally used as waterproofing. Therefore, no water can penetrate through the foam and thusly it will prevent the steel from further corrosion. The city has further claimed that the foam would not necessarily fill the cavity. So far tests have proven it is almost impossible to prevent it from filling the cavities involved. As a means of getting this method approved, it was suggested by the city examiner that the method should to be evaluated by the City Committee on Standards and Tests.

After presenting the approach before this committee, the method was once again turned down. This committee consists of a chairperson and 9 members from the industry including 2 structural engineers. One member pointed out that the foam would loose 50% of its strength if exposed to 350 degree Fahrenheit temperature. To reach this kind of temperature, which is hot enough for one to fry a steak, there has to be a fire. If this should be the case, the safety factors which are 3, 5 or more than 10, would be adequate to handle the 50% reduction in strength, meaning that before any terra cotta units would begin to fail, other critical parts of the façade would have been destroyed by the fire, such as all glass windows, etc.

Another member of the committee pointed out that the foam contained the chemical Freon (as referred to and used in Dupont's tests). Today carbon dioxide is used, a gas that forms a part of the air we breathe.

The committee further pointed out that the tests were not for the present product because of the reference to Freon. A written statement from a 30-year veteran chemist is available where he attests that the present polyurethane foam is of the same quality as that tested. Only the gas Freon, which was located within the closed cell bubbles in the foam, had been replaced with carbon dioxide. In other words, even though the tests were not for this particular product the properties were the same as those tested. These same test results are by the way used throughout the industry as a base for the polyurethane foam evaluation.

In conclusion, the use of polyurethane foam serves the triple purpose of bonding the terra cotta pieces together as well as bonding the total unit to the interior walls and encapsulates the steel components, arresting any further corrosion. The combined use of a minimally invasive inspection method with polyurethane foam injection provides an ideal repair strategy for the repair of terra cotta clad buildings.