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Techniques for Testing, Analyzing and Rehabilitation of Terra-Cotta

Techniques d'essai, d'analyse et de réparation de la terre cuite

Versuchsmethoden, Analyse and Instandsetzung von Terrakotta

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SUMMARY

Terra-cotta was often used as wall cladding for the early American skyscrapers. The material went out of fashion around 1930, but many ornate terra-cotta structures are still in service. Deterioration has resulted from design deficiencies and lack of understanding of material properties. Field investigation of terra-cotta failures and tests of the material are discussed. The cause of distress is analyzed and techniques for rehabilitation introduced.

RESUME

La terre cuite a été très employée comme revêtement de façade de gratte-ciels aux Etats-Unis. L'emploi de ce matériau a diminué vers 1930, mais il reste en service un grand nombre de structures en briques. La détérioration a été le résultat de déficiences dans le projet et d'une mauvaise compréhension des caractéristiques de la terre cuite. La méthode d'investigation insitu et des essais en laboratoire sont décrits. L'origine des dégâts et les techniques pour la remise en état sont présentés.

ZUSAMMENFASSUNG

Die Terrakotta wurde beim Bau der ersten amerikanischen Hochhäuser oft als Wandverputz verwendet. Um 1930 kam der Gebrauch des gebrannten Tons aus der Mode aber viele mit Terrakotta-Verputz gezierte Bauten versehen noch ihren Dienst. Infolge unsachgemässer Gestaltung und fehlendem Verständnis für das Material resultieren Verfallserscheinungen. Die Untersuchung der Terrakotta-Verfallserscheinungen und Materialversuche werden diskutiert. Die Ursache der Schäden werden analysiert und Verbesserungsvorschläge für die Problemlösung werden vorgeschlagen.

1. INTRODUCTION

The use of terra-cotta as an architectural material coincided with the building of the great American cities and the rise of the skyscrapers. The usage declined with the change in building technology, but a large number of outstanding terra-cotta structures are still in service [1]. Terra-cotta is durable and permanent because of the excellent weathering properties and the hard surface of the glaze, but the cladding on many high-rise buildings has deteriorated due to inherent deficiencies in the design and a disregard and lack of understanding of the material. The historical significance of these buildings and the unmatched richness of their detailing and vivid coloring of the terra-cotta make preservation of these structures important.

Terra-cotta was sometimes used as load-bearing masonry, but more often as a cladding anchored to the structural framing system. No provisions were made for movement, either absolute or differential, in the back-up framing or in the cladding. Moisture expansion and thermal fluctuations of the clay body and the glaze often resulted in cracking of the terra-cotta blocks. Water entering the cracks then accelerates the weathering and deterioration of the terra-cotta and causes corrosion and distress in the complex support and anchoring system [2].

Rehabilitation originates with a field survey and a program of field testing to detect the extent and the nature of the distress. Strain measurements reveal stress concentrations in the masonry and a stress map evaluates if cutting of expansion joints will relieve the build-up of stresses. Laboratory tests of terra-cotta samples measure properties of the clay body and the glaze and indicate the extent of decay and deterioration of the material.

Replacement of damaged pieces with new terra-cotta or with substitute materials requires a careful match of appearance and material properties. Laboratory tests establish strength, expansion and rate of absorption of the replacement material and accelerated weathering tests question the long-term performance and rate of degradation.

2. TERRA-COTTA CONSTRUCTION

The typical terra-cotta cladding material is about 10 cm thick and from 1000 to 2000 cm^2 in surface area. The blocks were fabricated by hand pressing the clay into wood forms. The back is open with internal webbing to stiffen the block. The glaze, an aqueous solution of metal salts, was sprayed or brushed on the unfired clay. It was fired to cone 4 to 5 (about 1130°C), resulting in good glaze hardness and high clay strength. The blocks were supported vertically at each floor level by shelf angles. Z-shaped steel straps were fastened into slots in each block and anchored the terra-cotta horizontally to the back-up walls of masonry or concrete. Ornamental units generally had multiple anchors, as seen in Figure 1.

The terra-cotta was installed with solid joints of cement/lime mortar. Joints were narrow, often about 5 mm. The walls had no expansion joints either in the back-up or in the cladding and they had no internal flashings or weepholes.

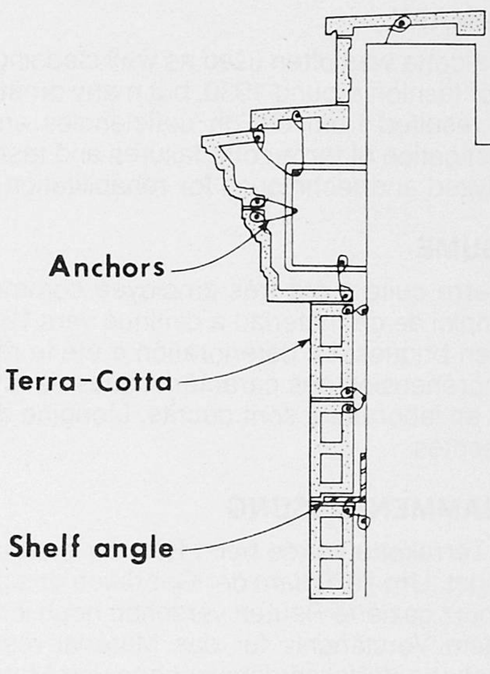


Fig. 1: Terra-Cotta Anchors

3. TERRA-COTTA FAILURES

Terra-cotta failures are often interrelated and progressive in nature. Water entering through cracks caused by differential expansion accelerates the weathering of the terra-cotta and corrodes the metal anchors and shelf angles [3].

3.1 Glazing Failures

Environmental exposure to temperature fluctuations can result in glaze crazing if the thermal coefficient of expansion of the glaze and the clay body is incompatible. Crazing, or the formation of small random cracks in the glaze, allows water to enter the clay body causing pinhole spalling of glaze when water in the clay pores freezes. More water will then enter the block resulting in general glaze spalling and the loss of the entire glazed surface [4].

3.2 Expansion Failures

Terra-cotta buildings with concrete frames often experience long-term shrinkage of the frames, but most terra-cotta failures result from temperature and moisture expansion of the clay body. Thermal and wet/drying cycles are often associated with permanent lengthening of the terra-cotta blocks, and this, plus the absence of expansion joints in the facade, creates high compressive stresses. Failure can be in the form of buckling of block units, as seen in Figure 2, or crushing at the base of the facade where expansion stresses are combined with compressive gravity loads.

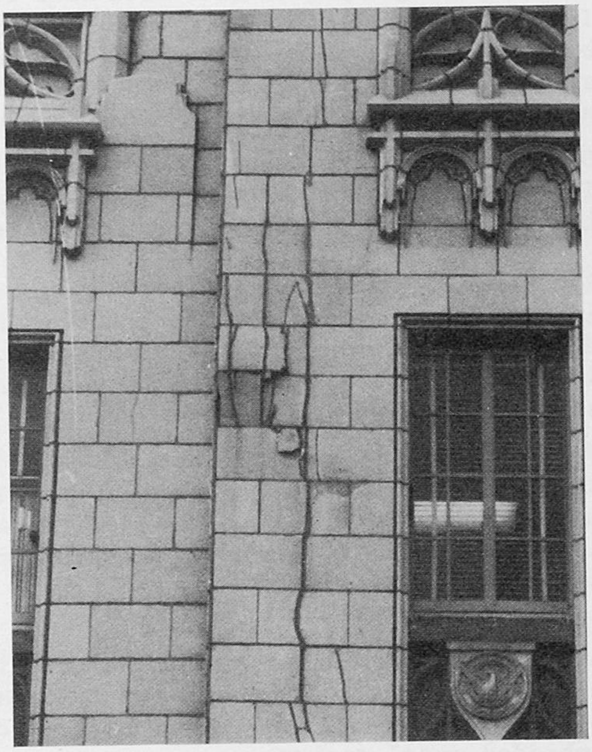


Fig. 2: Expansion failure

3.3 Moisture-Related Failures

Spalling of the glaze and cracks caused by expansion allows water to enter the wall and results in further damage to the terra-cotta from freeze/thaw action. The moisture corrodes the anchors and the pressure from the volume expansion of the rust cracks the blocks, as seen in Figure 3.

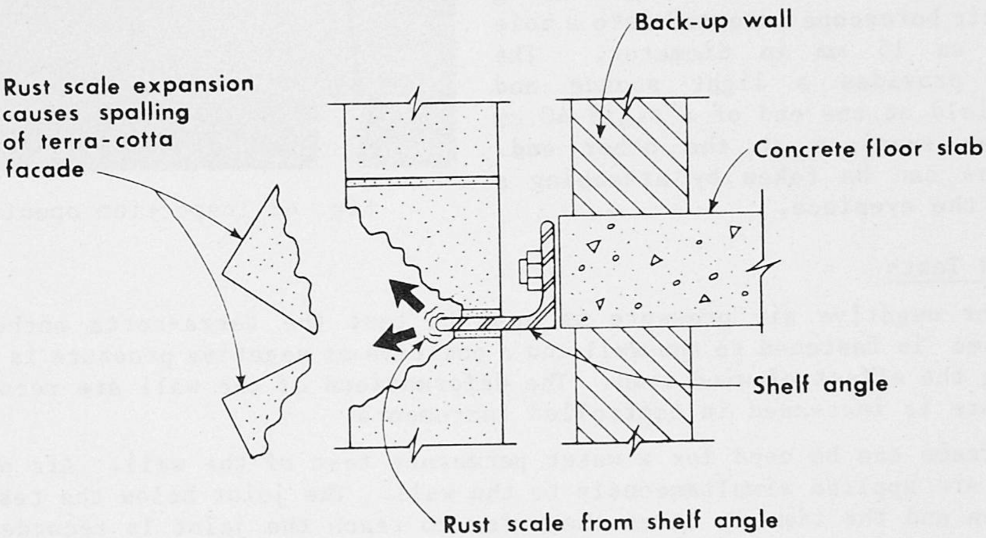


Fig. 3: Terra-cotta spalling caused by corrosion of shelf angle.

4. FIELD INVESTIGATION

The extent and the nature of the distress is evaluated by a field survey and by field testing of the terra-cotta.

4.1 Field Survey

Visual observations are made of the entire structure from the ground with binoculars or close-up from scaffolding. Photographs and drawings document the observatons and aid in detecting failure trends.

Tapping the wall with a wooden mallet can detect internal cracking. A terra-cotta block with cracks sounds different from an undamaged block when hit with a hammer. Metal hammers ruin the glaze and should not be used.

Infrared image systems have been used to detect internal cracks and delaminations. Infrared scanning or infrared photographs detect sources of heat loss in the building facade. Internal cracks in the terra-cotta or voids in the masonry backup create a temperature difference which become evident on the infrared scan. Metal anchors can also be detected this way because of their high thermal conductivity.

Crack movements are measured by installing gages or by monitoring the crack width. The cracks can have both daily and seasonal changes, as well as long-term growth. Long-term surveillance is often required to detect any significant movement.

Soniscopes have been used to locate internal cracks in the terra-cotta, but only with limited success. The many voids in the blocks tend to create patterns very similar to those produced by cracks.

Pachometers are used to detect embedded steel members and terra-cotta ties. The metal detector is used to verify the location of shelf angles and structural steel supports.

Inspection openings, as seen in Figure 4, are the best method to verify the location and the condition of the wall supports, and especially, to detect corrosion of the embedded metal anchors.

The inside of a wall can be examined using a fiberoptic borescope inserted into a hole as small as 15 mm in diameter. The borescope provides a light source and viewing field at one end of a rigid 40 cm rod and an eyepiece at the other end. Photographs can be taken by attaching a camera to the eyepiece.

Fig. 4: Inspection opening

4.2 Field Tests

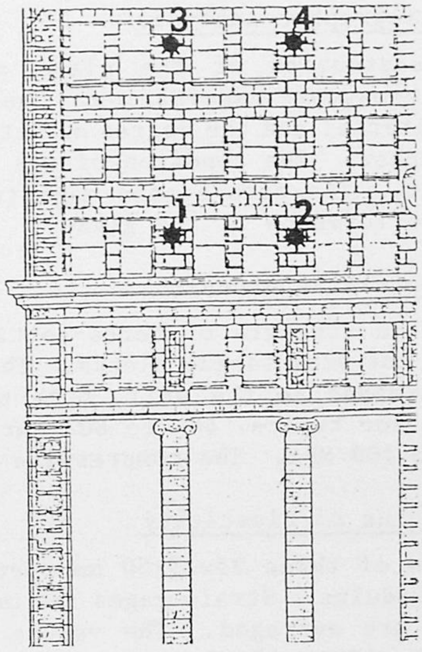
Positive or negative air pressure is used to test the terra-cotta anchors. A closed frame is fastened to the wall and a positive or negative pressure is applied simulating the effect of wind load. The deformations of the wall are recorded as the pressure is increased in controlled increments.

The same frame can be used for a water permeance test of the wall. Air pressure and water are applied simultaneously to the wall. The joint below the test frame is cut open and the time it takes the water to reach the joint is recorded. The absorbed quantity of water is measured as the weight loss of water circulating in the frame.

5. STRESS MEASUREMENT

Expansion of the terra-cotta and absence of expansion joints often cause high compressive stresses in the cladding. Strain relief testing is the best method to measure the magnitude and direction of the built-up stresses, as seen in Figure 5.

Electrical resistance strain gages are attached to the terra-cotta surface and the gages are read. Then the terra-cotta block, with the gages attached, is cut loose from the wall and the gages are read again, as seen in Figure 6. The change in gage reading is a measure of the strain in the block. The stress in the block is found by multiplying the measured strain difference by the modulus of elasticity, as determined by laboratory tests.



STRAIN RELIEF TEST DATA

GAGE	VERTICAL STRAIN μ cm/cm	VERTICAL STRESS kPa	HORIZONTAL STRAIN μ cm/cm	HORIZONTAL STRESS kPa
1	450	9315	50	345
2	283	5858	24	497
3	320	6624	30	621
4	171	3540	7	145

Fig. 5: Strain relief test

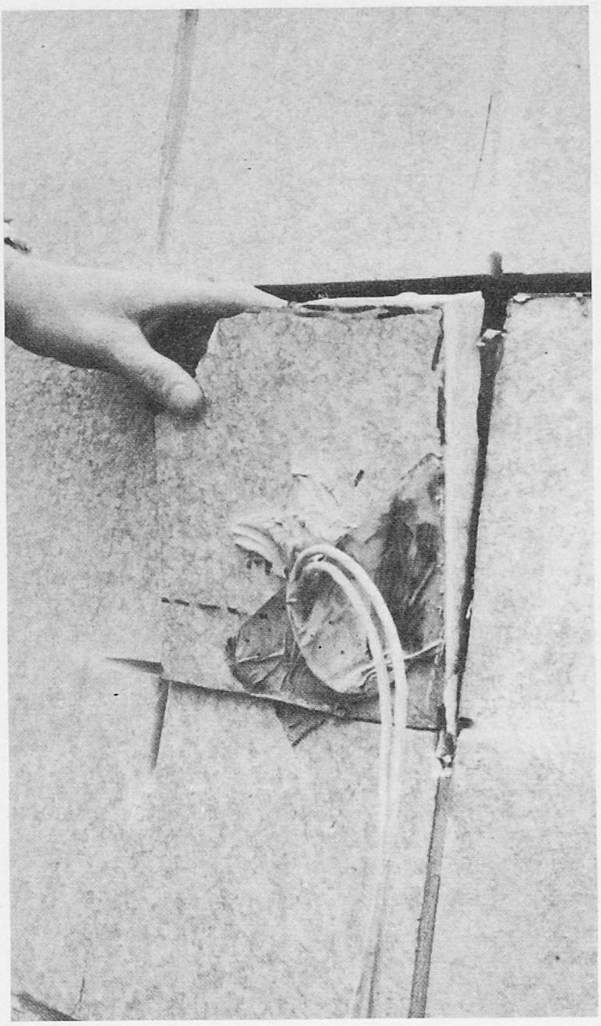


Fig. 6: Terra-cotta block, with strain gages attached, is cut loose.

The glaze in the test area should be firmly attached to the clay body and no glaze cracks should occur under the gage. Temperature variations during the day can affect the readings and should be established before the block is cut.

Compressive vertical stresses as high as 23 MPa have been recorded. This is close to the compressive strength of the terra-cotta wall. From multiple strain measurements, a stress map can be made for the exterior elevation. The map is used to evaluate if cutting of expansion joints into the facade will relieve the built-up terra-cotta stresses.

6. LABORATORY TESTS

6.1 Petrographic Analysis

The consistencies of the glaze and the clay body are evaluated through a stereomicroscopic examination. The density of the glaze surface, the composition of the material and the degree of deterioration can be established by an experienced petrographer. The conditon of the boundary layer between glaze and clay body is important. The nature, the magnitude, and the depth of the cracks predict the future performance of the glaze.

6.2 Compressive Strength

Compressive strength of terra-cotta is tested in accordance with ASTM C67 on 25 mm cubes cut from facade blocks. The load is applied in the two directions of the major stresses in the wall, both parallel to the glazed face. The compressive strength for typical 40- to 80-year old terra-cotta has been found to range from 40 MPa to 100 MPa. The compressive strength appears not to deteriorate with time.

6.3 Modulus of Elasticity

A minimum of three 25x25x50 mm specimens are tested in compression to determine Young's Modulus. Strain gages are mounted on three faces of each specimen and the readings are averaged. The values of the modulus of elasticity for terra-cotta range from 13 to 40 GPa.

6.4 Absorption

The absorption test is a modificaton of ASTM C67 and it compares the performance of glazed and unglazed specimens. On one sample, the glaze is ground off while an identical sample has the glaze intact. The sides are soaked face down in water for 24 hours. The weight gain of the glazed compared to the unglazed sample is a measure of the absorption characteristics of the glaze. Ideally, a glazed specimen should produce zero absorption if the glaze is intact, sound and craze-free. New glazes are normally impervious, but tests of 40- to 80-year old terra-cotta structures found that, at best 67%, and in the worst case, only 10% of the moisture was prevented by the glaze from penetrating the clay body [5].

6.5 Thermal Coefficients

Tests are performed both on the complete terra-cotta block and on separate pieces of glaze and clay body. Strain gages are mounted on the samples which are then subjected to temperature ranges representing the normal wall exposure. Strain readings are taken at the high, the low, and an intermediate temperature. The thermal coefficient of expansion can be established after a few cycles, but to find evidence of permanent elongation from thermal fluctuations requires a minimum of 25 cycles.

A difference in thermal coefficients for the glaze and the clay body causes a state of tension when temperature varies from normal. Such tension often causes glaze crazing [6]. The terra-cotta glaze can also experience crazing during the kiln cooling if the thermal coefficients of the glaze at high temperatures are greater than that of the clay even though the coefficients are similar in the normal range of temperature exposures.

6.6 Chemical Resistance

Different portions of glazed terra-cotta are exposed to a 10% solution of hydrochloric acid or a 10% solution of potassium hydroxide. After 3 hours, the specimens are rinsed, dried, and examined for change of color.

6.7 Moisture Expansion

During the firing, the free water is removed from the terra-cotta. As it again absorbs moisture, the clay body expands. Some of the expansion is cyclic, but a portion is nonrecoverable. A general magnitude of the moisture expansion can be determined by a reheat test. A terra-cotta sample is measured at 21°C. The sample is then heated to 1000°C, again allowed to cool to 21°C and then measured. The measured shrinkage is an indication of some of the long-term moisture expansion of the terra-cotta.

Moisture expansion of the clay body is the cause of much of the cracking, spalling, and build-up of stresses in the terra-cotta walls.

7. TERRA-COTTA REHABILITATION

Restoration of terra-cotta cladding is both difficult and expensive. The causes of distress must first be eliminated by cutting of expansion joints. The wall is made watertight by installation of flashing and joint sealants. Corroded anchors and supports are repaired and damaged terra-cotta blocks are replaced.

7.1 Expansion Joints

Vertical expansion joints are generally cut near corners and wall returns, while horizontal expansion joints are cut below reliveing angles,as seen in Figure 7. The joint location is determined from stress measurements of the terra-cotta. The joints are made watertight with elastomeric sealants. Cutting of expansion joints can disturb the fastening of the terra-cotta and will often require the installation of new anchors.

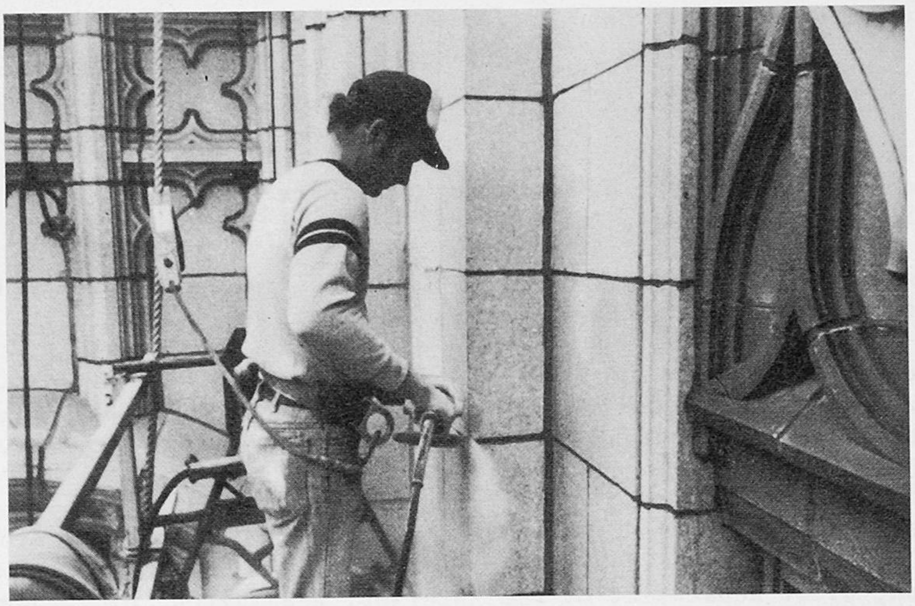


Fig. 7: Cutting of new expansion joints.

7.2 Terra-Cotta Supports and Anchors

Corroded or missing shelf angles and wall anchors are replaced. New anchors and angles should be given rust protection or be of stainless steel, especially in walls with past leakage problems. Consideration should also be given to installing flashing and weep holes in the wall cladding.

7.3 Joints

Sources of water penetration should be corrected. Roofing, flashing and capping are repaired and deteriorated sealant around windows and doors recaulked. The joints between terra-cotta blocks should be tuckpointed and not caulked since the mortar allows trapped water to dissipate without appreciably increasing absorption. Tuckpointing should be with a mortar of lower compressive strength than the terra-cotta. Application of waterproofing coatings to the terra-cotta, and especially the mortar, is not recommended. Such coating will prevent trapped water to dissipate through the joints. This will cause spalling and deterioraton of the terra-cotta.

7.4 Replacement with New Terra-Cotta

New terra-cotta is the preferred replacement material from the point of esthetics and durability. Plain ashlar blocks can be extruded, but decorative pieces require field forming and hand casting. Matching of color and texture should be verified by test firing of several full scale terra-cotta blocks. Quality testing of the material includes compressive strength, absorption, imperviousness, chemical resistance, acid and base resistance, crazing tests and glaze adhesion tests.

7.5 Replacement with Other Materials

Materials other than terra-cotta have sometimes been used for reason of economy. Fiberglass is lightweight and lends itself to decorative pieces, but it will discolor with age and is not fireproof. Precast concrete, sometimes reinforced with glass fibers, can be cast to reproduce terra-cotta details. The concrete color is matched to the existing material and surface coatings will duplicate the gloss of the terra-cotta glazing. The long-term performance of these replacement materials should be checked using accelerated weathering tests with samples subjected to repeated wet/dry and hot/cold cycles and to exposure of ultraviolet light.

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