



1986

Architectural Terra Cotta: On-Site Evaluation and Testing

Ella Webster Aderman
University of Pennsylvania

Follow this and additional works at: http://repository.upenn.edu/hp_theses

 Part of the [Historic Preservation and Conservation Commons](#)

Aderman, Ella Webster, "Architectural Terra Cotta: On-Site Evaluation and Testing" (1986). *Theses (Historic Preservation)*. 327.
http://repository.upenn.edu/hp_theses/327

Copyright note: Penn School of Design permits distribution and display of this student work by University of Pennsylvania Libraries.

Suggested Citation:

Aderman, Ella Webster (1986). *Architectural Terra Cotta: On-Site Evaluation and Testing*. (Masters Thesis). University of Pennsylvania, Philadelphia, PA.

This paper is posted at ScholarlyCommons. http://repository.upenn.edu/hp_theses/327

For more information, please contact libraryrepository@pobox.upenn.edu.

Architectural Terra Cotta: On-Site Evaluation and Testing

Disciplines

Historic Preservation and Conservation

Comments

Copyright note: Penn School of Design permits distribution and display of this student work by University of Pennsylvania Libraries.

Suggested Citation:

Aderman, Ella Webster (1986). *Architectural Terra Cotta: On-Site Evaluation and Testing*. (Masters Thesis). University of Pennsylvania, Philadelphia, PA.

STORAGE

NA

02

1986

A232

UNIVERSITY
PENNSYLVANIA
LIBRARIES



ARCHITECTURAL TERRA COTTA: ON-SITE EVALUATION AND TESTING

Ella Webster Aderman

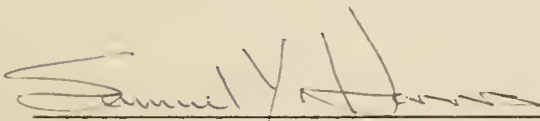
A THESIS

in

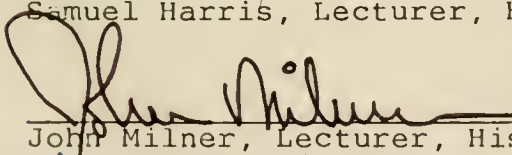
The Graduate Program in Historic Preservation

Presented to the faculties of the University of Pennsylvania
in Partial Fulfillment of the Requirements for the Degree of

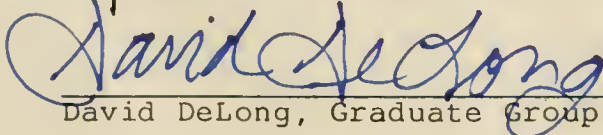
MASTER OF SCIENCE
1986



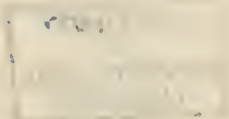
Samuel Harris, Lecturer, Historic Preservation, Advisor



John Milner, Lecturer, Historic Preservation, Reader



David DeLong, Graduate Group Chairman



FINE ARTS / NA / 02 / 1986 / A252

UNIVERSITY
OF
PENNSYLVANIA
LIBRARIES

TABLE OF CONTENTS

	Page
Extract	ii
Introduction	1
Definition of problem	1
Approach.	2
Background Information on Material	4
Manufacturing.	4
Installation	9
Design	11
Tests and Techniques for Evaluation of Problems	14
Historical Evaluation	14
On-Site Techniques of Evaluation	16
Analysis	22
Visual Inspection	22
Sounding.	23
Conclusions and Recommendations	29
Appendix A - Consultants and Contacts	31
Appendix B - Test Descriptions.	41
Endnotes	44
Bibliography	45

EXTRACT

The intent of this thesis is to investigate the evaluation and testing techniques used currently and in the past to determine the condition of architectural terra cotta as it exists on a building. The origins and objectives of the techniques, as well as the procedures, verification and results of the testing techniques are researched and evaluated. The purpose is to establish what current practice is, and to relate the limitations and possible liabilities of the available diagnostic techniques used for the analysis of terra cotta.

INTRODUCTION

Definition of Problem

Architectural terra cotta was used extensively as a decorative and structural material on buildings constructed in the United States between 1870 to 1930. Many of the buildings on which it was used are now candidates for restoration. The on-site evaluation of architectural terra cotta is necessary prior to restoration, repair or replacement in order to provide a plan for the work. The evaluation should determine the condition of the material and structure, and provide guidelines for its care and treatment during the restoration process.

The analysis of terra cotta is currently being done by a variety of individuals, including architects, masonry contractors, structural engineers, and architectural historians. The techniques being used depend on experience or observation rather than science or proven theory and vary with the individual, the geographic location, the structure to be evaluated and the client. The testing techniques, therefore, are subject to question in terms of the validity and interpretation of the testing results. The interpretation has a direct impact on the level of intervention used in the restoration plans.

Decorative architectural terra cotta is a unique material in the construction industry. It is a ceramic material which is similar to brick in composition, but terra cotta is different in form, surface coating, method of application, and most importantly, how it performs once installed on a building. Its unique characteristics require some special considerations when a building on which it has been used is to be evaluated. This thesis will relate the unique performance characteristics of terra cotta to the testing and evaluation procedures which are used on it, in order to provide a guide to those individuals who are charged with the responsibility of determining a reasonable approach for the restoration of terra cotta.

Approach

The two main approaches used to provide information were a search for published information on testing procedures and interviews with practitioners. The review of printed material included texts with information on terra cotta's performance mechanisms, tests conducted by manufacturers and the National Bureau of Standards in connection with the National Terra Cotta Society, and reports in trade journals.

Because of a lack of published information on the evaluation process, it then became necessary to gather information from the only other available source - practitioners. This involved determining who had done work on terra cotta through jobs involving replacement manufacturers and, subsequently, other referrals. In-depth interviews were conducted to determine how the practitioners evaluate the material, and their insights into the assessment process and problems of testing terra cotta.

A list of basic questions for the practitioners was made in order to have a standard for comparing information. Many of those consulted were very free with their information and opinions on particular aspects of discussion. This focusing reveals the differences in the individual experiences and practices in this field, as well as some unique approaches and problems encountered. A list of the persons who were contacted and a synopsis of the interviews are provided in Appendix A. In some cases, a more detailed transcription is available from the author.

Site visits with practitioners were also made to observe the evaluation of terra cotta being conducted.

BACKGROUND INFORMATION ON MATERIAL

There are three main aspects of terra cotta which make its use on a building different from other building materials and which subsequently affect its evaluation. These are 1. the process and problems associated with its manufacture, 2. the installation of the material, and 3. the concepts used in its original design. All three of these areas, separately or in combination, can contribute to the deterioration of the material once it is on a building. It is the interrelationship of the unique characteristics of terra cotta which has made it necessary to develop special methods of detecting problems on the site. This chapter will briefly describe the main aspects of terra cotta which are relevant to its evaluation.

Manufacturing

The fact that architectural terra cotta could be manufactured and formed into a wide variety of shapes and sizes was one of its main selling points as a building material. It was intended to be a product that could replace and simulate carved stone, but be cheaper to produce

and reproduce.(1) Ornamental terra cotta can be manufactured in three ways; it can be extruded, pressed or hand-packed into a mold. The hand-packed units are the earlier, larger and more ornate pieces. They can be up to eighteen by twenty four inches in size,(2) and weigh several hundred pounds. The decorated surface which is seen after installation is only one face of a block which has four sides, internal vertical webbing and is open on the back side. One problem that can develop with hand-packed units is delamination at seams or layers of clay where they are joined or pressed into the mold, particularly when the layers are parallel with the finished surface.(3)

Extruded and pressed terra cotta tend to be thinner and smaller than hand-packed pieces. They were used as a cladding material, particularly on the taller buildings of the 1920's and 30's. Extruded terra cotta is hung or tied to the backup structure with metal ties. Problems related

1. The rivalry between the stone and terra cotta industry over the relative merits of their products was conducted throughout trade magazines at the turn of the century. See American Architect and Building News, Architect and Engineer, Brickbuilder, or Stone magazine editorials. The fact that terra cotta so often looks like stone has led to it being mistaken for it, and (adversely) cleaned.

2. Nancy D. Berryman and Susan M. Tindall, Terra Cotta, Chicago: Landmarks Preservation Council of Illinois, 1984, p.4.

3. John Fidler, "The Conservation of Architectural Terracotta and Faience." Association for the Studies in the Conservation of Historic Buildings, Vol. 6, 1981, p. 7.

to the metal ties will be discussed later under installation and design.

All three types of terra cotta are prone to manufacturing faults which include inadequate firing, poor body mix and/or glaze properties, and warping. Once the units are formed and dried, they must be fired (heated) to a temperature which is sufficient to vitrify the clay which has been used. Underfiring will leave the material more porous, and thus less resistant to weathering.(4) Another aspect of firing that can affect the quality of the end product is the rate at which the ware is allowed to cool. Cool cracks are internal and difficult to detect. They may only break through to the surface "after the piece has been set in the building" (5) or is either struck or otherwise jarred.(6) The possibility that there are undetected cool cracks in a piece of installed terra cotta should not be overlooked when terra cotta is to be evaluated.

A poor mix of the clay body used to make terra cotta

4. Edward P. McNamara, Ceramics Volume III : Clay Products and Whitewares, State College, Pennsylvania: Pennsylvania State University, 1952, p. 471.

5. E.C. Hill, "Some Experiments on the Firecracking of Terra Cotta." American Ceramic Society Journal, Volume 5, June 1922, p. 299.

6. Hewitt Wilson, "Monograph and Bibliography on Terra Cotta." American Ceramic Society Journal, Volume 5, February 1926, p. 122.

can result in units that are not homogeneous, and are therefore more susceptible to failure due to internal and external pressures.(7) A poor body mix can also lead to a product that contains an excess of soluble salts, or iron impurities. The presence of salts can contribute to efflorescence (8), and the presence of iron and other impurities can result in staining.(9) The presence of salts in a terra cotta clay body will also adversely affect the glaze "fit", causing it to "shiver".(10)

One of the main characteristics of architectural terra cotta that makes it unusual as a building material is that it is often glazed. The glaze is a glass-like coating which is applied to the surface of a formed piece of terra cotta in a liquid state to alter the surface color or textural appearance. The interrelationship between the clay body, and the glaze which may be used on it, is critical. The modulus of elasticity of the clay body must be compatible

7. R.L. Clare, "Causes for the Failure of Terra Cotta in the Wall." Transactions of the American Ceramic Society, Volume 19, 1917, p. 593.

8. W.E. Brownell, "Fundamental Factors Influencing Efflorescence of Clay Products." American Ceramic Society Journal, Volume 32, December 1, 1949, p. 375.

9. C.W. Hill, "Notes on Green Staining." American Ceramic Society Bulletin, Volume 1, June 1922, p. 51.

10. Merle A. Coats, "The Influence of Soluble Salts in a Clay Upon the Behavior of a Slip and Glaze." Transactions of the American Ceramic Society, Volume 16, 1914, p. 167.

to the modulus of the glazes which are used on it. If the materials do not expand and contract at a comparable rate, they will separate. This is referred to as "fit" or glaze adhesion.(11) In addition, the glaze is under compression when it is taken from the kiln, and that stress is released if cooling takes place slowly. However, if the ware is cooled too quickly, cracks (crazing) in the glaze will result. The stress between the body and the glaze will vary with the thickness of the glaze and body, as well as with the composition of the glaze and body.(12) This is one source of cracks in the glaze which may have been present when the terra cotta was installed. The glaze adhesion qualities are also important in relation to the tendency for terra cotta units to spall.(13)

Warping of the terra cotta units may have been caused by too much water in the clay mix,(14) or improper handling of the formed, but flexible unit before complete drying. The amount of warpage which an individual piece of terra

11. "What Causes Stresses in Glazes." Brick and Clay Record, Volume 66, March 3, 1925, p. 355.

12. National Bureau of Standards, "Progress Report Number 88." Washington, D.C., February 1928.

13. Theodore H.M. Prudon, "Architectural Terra Cotta: Analyzing the Deterioration Problems and Restoration Approaches." Technology and Conservation, Volume 3, Fall 1978. p. 33.

14. Fidler, p. 7.

cotta may have had upon its original manufacture is difficult to determine. The use of warped terra cotta units in a building can create an illusion that there is a more serious structural problem than actually exists.

Installation

There are three main installation practices that are related to how and why terra cotta may fail, (1) the use of tanking or backfill in the units, (2) the type of mortar that was used, and (3) inconsistent or sloppy workmanship. During installation, the basically hollow terra cotta blocks were often filled with "a concrete packing of cement/crushed ballast in a ratio of 1:7 or 8."¹⁵ Because this mixture expands considerably more than the terra cotta, the terra cotta will crack. The problem is compounded by irregularities in the practice. A wide variety of material was used as backfill, including breeze aggregate, straw, or paper. In addition, the units were not always completely filled, leaving voids.

A series of cracking problems on buildings in the San Francisco area led to the investigation of the mortar that was used. The mixture was found to be too high in magnesium

15. Fidler, p. 8.

hydrated lime and did not contain enough sand.(16) This mixture was too "strong", and resulted in cracking and water penetration. Another problem with mortars was the use of coarsely graded material, resulting in point loading and cracking.(17)

Irregularity in the quality of workmanship during installation may be evident in many areas. Probably the most destructive are missing metal ties or shelf angles.(18) The possibility should not be overlooked that even when the original shop specifications (when available) called for flashing, caulking, or metal ties, they may not have been installed. The lack of quality in the installation of the original mortar, as well as any subsequent repointing, can lead to water penetration through incompletely filled joints or a lack of bond between the units and the mortar.(19)

16. Fred B. Ortman, "Terra Cotta Cracking." American Ceramic Society Journal, Volume 16, December 1933, p. 641.

17. Prudon, p. 34.

18. One example is sighted by A. Richard Glance on work at the Washington County Courthouse, Pennsylvania. See "Terra Cotta: Rehabilitation of a Courthouse Dome." Bulletin of the Association for Preservation Technology, Volume 17, 1985.

19. Faulty mortar joints are considered the main cause of leaky walls by Eckardt V. Eskesen in "Water-Tight Terra Cotta Construction." American Ceramic Society Bulletin, Volume 13, 1934, p. 154-62.

Design

The design issues which cause problems with terra cotta are perhaps easy to recognize now, but when the material was first used, many of the principles which affect its use were not understood and should not be taken for granted. The basic performance of the material had not been tested, and was not documented. Because the terra cotta units were glazed, they were thought to be impermeable. They were, therefore, designed without weepholes, flashing, or any (now) standard provisions for water run off.(20) Water could easily penetrate the system and cause or accelerate weaknesses. In climates where freezing temperatures occur, the results were disastrous. Water could penetrate the individual units, freeze and crack the entire element. When lesser quantities of water are absorbed, the ice pressure within a unit causes spalling of the glaze surface. This in turn will allow more water to penetrate. Even without freezing temperatures, allowing water to sit within units or the structure, promotes the corrosion of the metal ties, metal shelf angles and possibly the steel superstructure.(21) The evidence that corrosion has

20. See National Terra Cotta Society. Terra Cotta, Standard Construction, New York: National Terra Cotta Society, 1914.

21. One example is sighted by Eskesen, where a stream of water shot out of an observation hole.

occurred may not appear on the surface at all, or it may appear several courses down from the source of the water infiltration as indicated by rust stains on the surface.

The specifications for installation that were originally published in 1914 were not improved until 1927, well after most terra cotta had already been installed. The 1927 edition adds weepholes, flashing and shelf angles. These all helped (when used), but there was still insufficient allowance for thermal and moisture expansion, wind loading, and shrinkage or loading of the structural frame.(22)

Terra Cotta cladding which is placed in a position of being a load bearing element can not withstand the pressure and will crack.(23) Thermal expansion causes considerable damage to projecting details, such as balustrades, sills, or cornices. The type of glaze used can have a correlation to a unit's tendency toward crazing. The susceptibility to craze, in descending order is: porous finish, matt glaze, vitreous finish and glossy glaze.(24)

22. Clare does recognize problems with expansion and movement in his article published in 1917.

23. Fidler, p. 8.

24. H.G. Schurecht and D.H. Fuller, "Some Effects of Thermal Shock in Causing Crazing of Glazed Ceramic Ware." American Ceramic Society Journal, Volume 14, 1931, p. 571.

Moisture expansion occurs with terra cotta the minute it is taken out of the kiln, and continues to occur with fluctuations in humidity.(25) The fact that terra cotta is set wet (26), and the glazed surface allows for little evaporation through the exposed face, means that all entrapped water must find its way out through mortar joints or out the back. In some climates, it is questionable whether the terra cotta ever dries.(27)

These design factors, in combination with installation practices and basic material performance, amplify the need to look at all the possible causes of a crack or other failure of a terra cotta unit in order to determine all of the interrelating causes before seeking a solution for any one problem.

25. H.G. Schurecht, "Methods for Testing Crazing of Glazes Caused by Increases in the Size of Ceramic Bodies." American Ceramic Society Journal, Volume 11, 1928, p. 271.

26. American Institute of Architects, Public Works Specifications: Ceramic Veneer, File number 9, October 1961, p. 6.

27. F.B. Ortman, Paper presented to the American Ceramic Society, Philadelphia, Pennsylvania, February 24, 1920.

TESTS AND TECHNIQUES FOR EVALUATION OF PROBLEMS

One might assume that as soon as problems with terra cotta started to appear, that techniques for its evaluation would have also been developed. This, however, is not the case. Because the material was new to mass production, all problems related to its use were directed toward the material properties and its manufacturers. Ceramic scientists working for the manufacturers became the sole source for identifying problems believed to be inherent with the material. The correlation of the material characteristics to structural design did not occur until the 1920's (Clare), and then it was published by the ceramic scientists and industry, not by architects.

Historical Evaluation

The first testing on the durability of terra cotta as a material seems to have been done by Olschewsky in 1885. He tested for impurities in the material and unsuitable manufacturing processes.(28) The Stevens Institute of Technology, in 1888, tested the compressive strength of

28. W.A. McIntyre, Investigations Into the Durability of Architectural TerraCotta and Faience. Department of Scientific and Industrial Research, Special Report #12, London, 1929, p.18.

three different types of clay used to make terra cotta.(29) Then, in 1895, a commission nominated by the French government adopted comprehensive methods of testing terra cotta which included physical, mechanical and chemical properties.(30)

Manufacturers in the United States organized The National Terra Cotta Society. Its purpose was primarily to promote the use of the product. However, when major problems became evident, they sponsored research through the National Bureau of Standards to develop standards for the manufacture of terra cotta. This research lasted for eleven years, from 1917 to 1928. Most of the investigations were related to material science and quality control, and did not address in-service problems until late in the proceedings.

In 1925, the Bureau of Standards investigated the freezing and weathering properties of the material, and conducted a visual inspection of 535 buildings throughout the country.(31) These inspections are the first reference

29. Walter Greer. Terra Cotta In Architecture. New York: Gaylay Co., 1891, p. 28.

30. These were published in English by Leon Lefevre in Architectural Pottery (London: Scott, Greenwood and Son, 1900).

31. "Architectural Terra Cotta Investigations." American Ceramic Society Bulletin, Volume 4, 1925, p.410.

to any on-site evaluation. The results, as published in the Progress Reports of the National Bureau of Standards (and condensed in publications of the American Ceramic Society), were directed toward the terra cotta manufacturers, not the building owners or architects.(32)

Primarily, the committee was looking for evidence on the buildings of damage caused by freezing or thermal expansion. The results tied the probability of failure to climatic conditions within zones of the country. Those areas which had the least variation in daily temperature, and received cold and wet conditions had the most failures.

On-Site Techniques of Evaluation

There are two methods of evaluating terra cotta which were most often cited by the practitioners that were interviewed, visual inspection and sounding (or tapping). These two techniques may, on occasion, be followed by tests which are used to determine more specifically the cause of deterioration.

32. A complete list of the buildings investigated does not appear. Occasionally, a few buildings are listed with a request for the manufacturer to identify themselves, so that reports on those buildings may be sent to them.

A visual inspection is the primary method of detecting problems with terra cotta. The objective is to thoroughly examine the structure to find any and all visible signs of deterioration. In this respect, the post-occupancy inspection of a terra cotta building should be much the same as the inspection of any building, as long as the inspector is aware of concerns discussed in the previous section.

The visual inspection is both a method of identifying problems and a means of recording them. The first evaluation may be only to determine the extent of damage by a general review of the building. If a more detailed inspection is conducted, it may be done from street level with binoculars, or from whatever surrounding vantage points are accessible. At this point, each unit is viewed to determine damage, and the information recorded on elevation drawings so that any patterns in deterioration may be checked with other locations on the building. Note of the mortar condition should also be made. It would always be best to view the terra cotta as closely as possible. Even hairline cracks or cracks indicating that the mortar has separated from the unit can be quite significant. This close range view would usually require scaffolding or a swing platform.

The difference in a visual inspection of terra cotta

and the inspection of other buildings lies in trying to determine hidden damage. Has the face of a unit separated from the back, or are there voids in the backfill? The technique which may be used to try to answer these two questions is sounding.

Sounding is done by striking the surface of the terra cotta unit with a mallet.(33) The object is to produce a consistent sound ("a clear ring") over the surface of the terra cotta wall. Places where a different sound is produced are supposed to indicate an irregularity in the material, such as cracks, hollow voids in otherwise solidly filled units, or a separation of the face of a unit from the back webbing. This technique invariably requires scaffolding or high-rise equipment, which may make its use quite expensive. Besides the expense, however, the author feels that there are many variables and irregularities in this technique which makes the reliability of the results and the use of the technique questionable. These concerns will be the subject of the next section.

There are several other tests which can be conducted on site which may be warranted based on questions which arise during the visual inspection. These include the use of

33. There is a difference of opinion about that type of mallet to use; wooden, acrylic, rubber or metal. See Analysis and Recommendations, or Appendix A.

probes, stress measurement, metal detection, monitoring cracks, and water leakage tests. Although the use of these tests is by no means standard, there may be individual cases where their use is justified.

Probes or inspection holes may be used to view behind the outer skin of the terra cotta to check the status of the metal ties, or shelving, and the condition of the terra cotta. This method can be destructive to the material, unless an opening is already available because of a missing or broken unit.(34) The problem of being able to evaluate the condition or existence of the metal ties can be a major concern on a bulging wall or overhanging element. Besides the use of probes, one way to determine if the ties are behind the terra cotta is by using a metal detector. It is not a definitive method to use, but it is nondestructive.

Strain relief testing is done to determine the level of stress which may exist in a wall of terra cotta. Because of the common lack of expansion joints, this test would be advisable if substantial vertical cracks exist. The testing would determine if the terra cotta has been placed in compression, and the degree of relief necessary to correct

34. Details on how all tests are actually done is provided in Appendix B.

the situation.(35) Monitoring gauges may be used when it is desirable to know whether the cracks that exist in the unit or wall are continuing to grow, and therefore, whether stress or movement is still occurring.

There are several ways a terra cotta wall can be tested for water leakage. The simplest is the use of a hand-held, calibrated nozzle. This directs water at a suspected area, and then the wall is monitored to determine how fast and where the water goes. Another approach is the use of a modified version of the ASTM E514 "Standard Method of Test for Water Permeance of Masonry".(36) This apparatus also applies water to the surface of a wall, but the water is collected and measured for the quantity lost into the wall. This test will give an indication of the leakage of the wall assembly.

There have been efforts to adapt infra-red and sonic testing to terra cotta in the hope of developing techniques that would be able to detect voids and cracks which would not be destructive to the material. So far, however, these methods have not been practical for terra cotta.

35. An account of the use of this procedure on the Woolworth Building is provided in Prudon's article.

36. This procedure has been developed by Wiss, Jenney, Elstner Associates, and is described by Stockbridge in his publications.

Further support tests may be conducted in a laboratory to determine the performance properties of the particular terra cotta that is being evaluated. These tests can include assessment of the thermal compatibility, glaze absorption and/or adhesion, moisture expansion, and tests on the compressive strength, porosity or material content of the clay body. These tests are not commonly done, but may provide information on a contributing cause for deterioration related to the product's original manufactured state. It may also be helpful in certain cases to do an analysis of the mortar.

All evaluation and tests conducted on terra cotta should be chosen to provide a maximum amount of information with as little damage to the original fabric as possible. The destructive nature of a testing technique must be weighed against what solid and clear information the test will provide. It should be noted, as stated in the Secretary of Interior's Guidelines for Rehabilitating Historic Buildings, that it is often "the cumulative effect of a series of actions that would seem to be minor interventions"(37) that can cause the loss of a building's character through a loss of original material.

37. U.S. Department of Interior, The Secretary of the Interior's Standards for Rehabilitation, Washington, D.C.: National Park Service, 1983, p. 9.

ANALYSIS

To evaluate the available diagnostic techniques, the advantages of each are considered in relationship to any possible disadvantages, be it to the material that is tested or in terms of the technique's reliability or results. As a tool to be used in the restoration profession, any techniques used to evaluate a building material should be as nondestructive as possible, be comprised of procedures that could be duplicated by others, and produce reliable results.

It is recognized that any technique in and of itself is not used as the sole determining factor for what action is taken to repair or replace a terra cotta unit; that decision will always have to be made by the evaluator based on all available information and the goals of the project. The techniques used, however, should be recognized for their limitations, and possible liabilities.

Visual Inspection

While it can not be said that the visual inspection of a terra cotta building would produce the same results with two different evaluators, the basic information available to

them both would be the same. A cracked or deteriorated unit is viewed and related to its environment to determine the cause of failure. The procedures used could be duplicated by others, and is able to be recorded and verified. Detailed photographs and measurements are possible so that the information about the building's condition would be available for later reference. There is nothing destructive about the technique.

Sounding

The sounding technique has many questionable aspects. These include 1. the origin of the technique, 2. the objectives for the test, 3. the procedures used, 4. the lack of verification, and 5. the possibility of damage to the terra cotta. All positive and negative aspects of using tapping should be considered before its use is recommended.

The tapping technique has been used in the past on a variety of materials, including the testing of steel, brick, slate and other building stones. In all cases, the tapping would be done after manufacture and before installation or use as a quality control test to detect cracks and imperfections in the material. In the ceramics industry, the technique has application, and is used after firing to

determine if the product has cool cracks.(38) However, in all cases the tapping is done on a product that is free standing or is held loosely by hand. It does not necessarily follow that a product that is in position, clamped on three sides, and quite possibly in compression, would still produce a sound that can be directly related to cracks or hollowness. Research by McGinnis and Harkins found that "the method of clamping the materials investigated influenced to a high degree the percentage of sound transmitted."(39) The tapping technique has been transposed from a quality control technique to an on-site technique without the original conditions or objectives, and without any verification.

It should be determined whether the objectives for using the technique are in fact met, what is done with the information, and whether the objectives might be accomplished by some other means. There are two reasons stated for using the tapping technique - to determine if the unit is hollow and to determine if the face has cracked away from the webbing. If one assumes that the hollowness of a

38. The earliest published reference found for the use of tapping on a ceramic product is in A Practical Treatise on the Manufacture of Bricks, Tiles, and Terra Cotta, Charles Thomas Davis, Philadelphia: Henry Carey Baird, 1889.

39. C.S. McGinnis and M.R. Harkins, "The Transmission of Sound Through Porous and Non-Porous Materials." Ph.D. dissertation, University of Pennsylvania, 1911, p. 130.

unit can be determined by tapping it, why is that significant? What is done about a hollow terra cotta unit? All of the practitioners consulted said that they would not replace a unit that tested hollow if there were no other visible signs of deterioration. So why do it? The main concern is for pieces of terra cotta that might be internally cracked. Several practitioners felt that tapping was the only way of detecting webbing cracks. As hazardous as a loose piece of terra cotta can be, especially on an overhanging element, this is a serious concern. The question remains as to whether tapping is the only way of detecting a loose face on a terra cotta unit. In many instances, there should be a separation of the mortar that surrounds the unit if the face has separated. However, it may be difficult to detect if the condition of the mortar around the majority of units is not good, or if the face has cracked, but has not yet broken away from the webbing.

The procedures and equipment which are used to do tapping are not standardized, nor are the results verifiable. Of the practitioners who specified what type of mallet they would use, six use wooden mallets, two would use acrylic, one specified a rubber mallet, and one uses a metal hammer. Several stated that they might use one other type of mallet on occasion, but felt that the use of one of the

other mallets was completely unacceptable.(40) Besides the question of what type of mallet is best, there is no measure of how hard a unit of terra cotta is hit. It would be likely that there is a difference in how hard one might have to hit a terra cotta unit based on the type of mallet used, as well as the individual doing the striking. Furthermore, there is no method currently used to record, duplicate or verify the results of tapping. The only verification currently available is to actually remove the unit to see if it is cracked. This removes the original material from its structural context, and it is therefore not available for further reference.

There is also a question of whether, in the process of tapping terra cotta, cracks are not produced or accelerated by the technique itself. None of the practitioners consulted thought that this was true; however, no one could verify that it was not. As noted on page seven of this report and by Hill and Wilson, if cool cracks are in a unit they may not appear on the surface until they are subjected to stress in the building or are struck or jarred. It would seem to be a strong possibility that a unit that is under considerable stress, as terra cladding can be for several reasons, but might not have already cracked, would be likely

40. The best alternate was not always the same type of mallet from one individual to the next, nor was the worst alternate.

to fracture when struck in the process of tapping.

Several practitioners indicated that one of the reasons that they did not use tapping was that they encountered a considerable amount of wet terra cotta which will not produce the desired "ring" when struck. A few of the practitioners who do use tapping acknowledged that they did not do tapping after wet weather, but this was not a consideration mentioned by many practitioners who are in areas of the country where this would be a concern. The fact that there may be conditions in any building where the terra cotta may be wet at all times because of water accumulation within the unit has already been discussed, but has not been considered by all.

There are aspects of the tapping technique which seem to correlate to the use of ultra-sonics on terra cotta. It is recognized in publications, and by many of the practitioners, that the limitations of the use of ultra-sonics on terra cotta testing are related to the mass of the units, as well as the inherent flaws in the material. Weinhardt in "Industrial Application of Ultrasonics" states that "any air bubbles, cracks, or other discontinuities in the material reduce the amount of

signal reaching the receiver unit."(41) He concludes that ultrasonics "will not work well on porous materials as the material scatters the sound waves too much to give a clear reading. This is also the case where a material has many flaws."(42) Do the same principles and problems of sound transmission not apply to the sounding technique?

Practitioners have "trained ears" to account for all of the possible irregularities and conditions, but is the principle of using sound as a determining factor for the condition of terra cotta valid in one application and not in another? Unfortunately, the answer is not yet available, but needs to be considered.

41. Robert Allen Weinhardt, Jr., "Industrial Application of Ultrasonics." thesis, University of Pennsylvania, 1949, p. 25.

42. Ibid. p. 33.

CONCLUSIONS AND RECOMMENDATIONS

In the search for information on the evaluation of terra cotta, questions remain. The fact that the techniques have been used for years without verification does not justify their continued use. The long term consequences are not known and a cautious approach would be better than the realization in twenty or thirty years that substantial damage has been done.

A person responsible for selecting a method of evaluating the terra cotta on a building is faced with two primary techniques for determining the condition of terra cotta - visual inspection and sounding. At this point, a visual inspection provides a substantial amount of information that is non-destructive, verifiable, and able to be recorded. The question of whether tapping should be done must be weighed against its disadvantages on an individual basis. The author does not feel that there is sufficient verification of the technique to recommend its continued use. Certainly if tapping was introduced as a new technique today, confirmation of its capabilities and questions about its reliability would have to be produced and answered before it would be recommended.

For the preservation field and all persons involved in

the evaluation of buildings, there are several areas for further research. There is a need to determine the long range consequences of the tapping technique. One way this might be accomplished is to reexamine buildings which were previously evaluated and properly documented. This would provide information on whether the techniques which were used were adequate and accurate. If it can be determined that the tapping technique does not cause any crack progression, it is recommended that at least a method of measuring and controlling the amount of impact applied be developed.

Alternate techniques for tapping should be explored. Would a calibrated suction instrument be able to detect the loose face units? Are there techniques from other industries that are adaptable to terra cotta? The development of a method of detection which is verifiable and non-destructive should be explored. Until it is, many buildings may be subjected to a process which has no scientific basis for use, and which could ultimately lead to a higher level of intervention than is necessary.

APPENDIX A
Consultants and Contacts

DAN BARTON - Pres. 215-563-7672
O.W. Ketchan
121 North 18th Street
Philadelphia, PA

Former manufacturer of terra cotta, now brick dealer.
Company records destroyed.

Dr. NANCY BERRYMAN 312-786-0229
727 South Dearborn Avenue
Chicago, IL 60605

Consultant - talked by phone 9/4/86

Visual Inspection - Look for pattern of deterioration, salt, moss, & efflorescence, particularly at roof and parapet. Look inside building & at documents or drawings. Start with nonintrusive techniques.

Other in-field - Has used boroscopes; has used chemical tests to determine if rust is from glaze or ties; has used camera & video; permeance tests possible, but not done much; has used metal detectors, & stress or crack measurement.

Tapping - Does tapping, uses a wooden mallet or possibly acrylic, not metal, it vibrates & damages terra cotta. Objective - Determine if unit is attached.

Intrusive techniques - Remove loose piece to see if anchoring is there, where, what condition; is unit mortar filled?

Support tests - If glaze is spalling, check thermal coefficient, also compression, & absorption tests.

Note: Rep for Gladding, McBean. Teaches at Univ. of Illinois. Has published on subject.

JACKIE BUHN
Growth Properties
125 South 9th Street
Suite 801
Philadelphia, PA 19107

215-925-4160

Architect - talked by phone 9/8/86

Worked on Sheraton building with M. Thomas (CLIO Group);
used binoculars for preliminary assessment; let contract to
contractor to do tapping - Melrose Waterproofing.

RICHARD O. BYRNE
Box 610
Merrickville, Ontario K0G 1N0

613-269-3676

Architectural Conservator - talked by phone 3/25/86

Visual inspection - Look for surface crazing, salts.

Tapping - Does tapping; is self-taught; uses small mallets
or anything metallic, not rubber. Objective - is unit solid
or hollow, and adhered to structure?

Note: Does not use support tests or replacement units.
Suggests more use of museum conservation techniques for
patching.

LEE ECKLES
Garcia/Wagner and Associates
555 Sutter St.
San Francisco, CA 94102

415-986-0303

Architect - talked by phone 9/1/86

Visual inspection - Tile by tile severity rating system,
noting spalls, cracks, chips & location; information in
computer for future reference.

Tapping - Does tapping with plastic hammer. Severity system
relating visual information to hollowness to determine
removal of units.

Note: Working on PP&T building, San Francisco - thinks that
removal of units has verified tapping & visual evaluation.

Dr. MARGARET HENDERSON FLOYD
59 Ash Street
Weston, MA 02155

617-899-5722

Architectural Historian - talked by phone 10/17/86

Has done some on-site inspections. Primarily interested in the history of terra cotta applications & relationship to material & design; currently working on a book.

Note: Chairman of Fine Arts, Tufts Univ. Has published on the history of terra cotta, as well as dissertation.

MAX FERRO
Preservation Partnership
345 Union Street
New Bedford, MA 02740

617-996-3383

Consultant - talked by phone 3/19/86

Visual inspection - Correlate damaged units to system.

Tapping - Does not use tapping.

Note: Teaches at Univ. of Vermont & Boston Univ.

JOHN FIDLER
Historic Buildings Architect
City of London Corp.
The Guildhall
P.O. Box 270
London, England EC 2P 2EJ

07-606-3030

Note: Has published on subject. Was not contacted.

[Indicates in writings that a rubber or acrylic mallet be used for tapping.]

DREW KROUSE
Boston Valley Pottery, Inc.
6860 South Abbott Road
Hamburg, NY 14075

716-649-7490

Manufacturer - talked by phone.

DAVID LOOK
National Park Service
Western Regional Office
450 Golden Gate Ave.
Box 36063
San Francisco, CA 94102

415-556-7741

Architect - talked by phone 3/25/86

Note: past President of FOTC.

FRIENDS OF TERRA COTTA
Box 421393 Main P.O.
San Francisco, CA 94142

415-665-1216

Note: Organization founded in 1981 to encourage preservation of terra cotta buildings. Publishes a newsletter.

THOMAS McGRAPH
High Blooms, Inc.
Suite 800
50 Staniford Street
Boston, MA 02114

617-227-0329

talked by phone 9/1/86

Visual inspection - Evaluate by appearance of unit & interrelationship with other pieces.

Other in-field testing - Uses gauges to check for movement.

Tapping - Does not use tapping; not useful for him, a lot of wet terra cotta in Boston area, wet terra cotta will not "ring". If cracked, already knows it has to be repaired depending on when building was pointed last and whether there is moisture in the terra cotta, tapping does not provide further information.

Note: Details of repairs to terra cotta in survey reports.

LOUIS MARNELLA
Louis Marnella Assoc.
956 West Arlington Road
Erie, PA 16509

814-866-1481

Conservation Technician - talked by phone 3/26/86

Visual inspection - Looking for cracks, or crazing; use magnifying glass, photos. Evaluates mortar joints.

Other in-field testing - Just got a fiber optic probe with camera.

Tapping - Does tapping with a wooden mallet or mason's hammer. Learned by experience with mason contractor.
Objectives - To find hidden cracks or broken webbing.

Support tests - If there are loose pieces, use those for testing of original material properties or other reason for failure.

Note: Works with Drew Krouse (Boston Valley). Uses patching material from Holland - JAHN.

DENNIS NEWHART
Ludowici-Celadon Co.
Box 69
New Lexington, OH 43764
also: EDWARD E. RYSER, President
RUSSELL McINTYRE, sales

614-342-1995

Manufacturer - talked by phone 1/17/86 & 3/26/86
Provides consulting service.

Visual inspection - Looks for cracks & discoloration. Sees more problems with glazed than unglazed terra cotta.

Tapping - Does tapping; learned on job.

Note: Sales rep does on-site visits.
Ludowici Co. merged with Celadon Co. (Alfred, N.Y.) in 1906.

MARY OEHRLEIN
Oehrlein and Associates
1702 Connecticut Avenue, N.W.
Washington, D.C. 20009

202-387-8040

Architect - talked by phone 9/1/86

Problems related to original manufacture & installation are still showing up. Installation without expansion, inadequate anchoring for size of piece, use of ungalvanized ties.

Note: Worked for Ehrenkrantz.

BRUCE POPKIN
Wank, Adams, Slavin Assoc.
2 Astor Place
New York, NY 10003
also: Stephen Gottlieb, Pres.

212-420-1160

talked by phone 3/19/86

Visual inspection - Looking for cracks or damage, particularly cornices.

Other in-field testing - Uses probes.

Note: information on repairs available.

Dr. THEODORE PRUDON
Ehrenkrantz Group
19 West 44th St.
New York, NY

212-730-1950

Architect - visit in his office 9/23/86

Visual inspection - Differentiate between problems with block terra cotta - easily detected (water, movement, glaze problems) and terra cotta cladding - more complex, multi-story, anchoring complex & unprotected. Many problems originating with short cuts in installation, not following shop drawings. One time expansion vs. continuous thermal.

Other in-field testing - Sonic, based on voids & solids but not clear enough; Infra-red, has possibilities.

Tapping - Does tapping with acrylic or wooden mallet; (although in his dissertation, he says a "hammer or other metal object"); first used 1976, then extensively on the Woolworth building in 1978. Objectives - Is unit backfilled, hollow or partially filled (doesn't mean much if it is); is there internal shearing; if block is too large, you can't hear distinction well.

Note: Has never uses replacement terra cotta because of time & cost, uses cast stone. Feels that terra cotta testing might benefit from correlating technologies in other fields.

Has published on subject, as well as dissertation.

F. NEALE QUENZEL
John Milner Associates
309 North Matlack Street
West Chester, PA 19380

215-436-9000

Architect - talked by phone 1/12/86, site visit 7/1/86

Visual inspection - Identify & record damage, see if pattern develops, correlate to building structure. Identify area for further investigation.

Other in-field testing - Ultrasonic has been tried; not more reliable, but more expensive.

Tapping - Does tapping with wooden mallet. Objective - Find hidden cracks. Weather conditions prior to testing critical, no damp or freezing temperatures. Preliminary test to determine where problems are likely. Not usually done tile by tile, do part to determine per cent allowance for building.

Note: Need for study of terra cotta regionally to relate how rapidly terra cotta deteriorates, under what conditions; how it has aged in different regions.

TERRY RORISON, Pres.
Terra Cotta Production, Inc.
Box 99781
Pittsburgh, PA 15233

412-321-2109

manufacturer - talked by phone 3/19/86

THOMAS SAWYER
Gladding, McBean and Company
Box 97
Lincoln, CA 95648

916-645-3341

Manufacturer - talked by phone 3/26/86, plant visit 8/19/86

Problems occur when steel gets close to terra cotta, i.e. sills, as well as with expansion and water. Equates glazed terra cotta building with a milk bottle, water gets in through the top & is trapped, freezes & expands.

Does not have much faith in tapping, may be able to detect hollow spots & loose pieces. Origin of the technique related to tapping done by manufacturers on loosely held pieces for fire (cool) cracks, sound produced will not be the same on a terra cotta piece in position on a building; sound not even the same, on the same piece, if held differently.

Sees the need for clarification of the ASTM standard (C 67) currently applied to terra cotta, in relation to the freeze-thaw test being waived for other physical properties.

LOUIS SNYDER
Studio S Pottery
1426 Avon Road
Murfreesboro, TN 37130

615-896-0789

Manufacturer - talked by phone 3/25/86

Sees problems related more to structural problems than to material.

Note: Does some site visits.

JERRY STOCKBRIDGE
Wiss, Janney, Elstner Assoc.
330 Pfingten Road
Northbrook, IL 60062

312-272-7400

Engineer - talked by phone 3/18/86

Has developed lab and support tests for terra cotta. Extensive evaluation work.

Note: Has published on the subject. [Advises in publications that a wooden mallet be used for tapping.]

JOHN STUBBS
Beyer, Blinder, Belle
41 East 11th Street
New York, NY 10003

212-777-7800

Architect - talked by phone 3/26/86

Survey of Alwyn Court (article by Fitch, Technology & Conservation): Did visual inspection noting cracks & mortar problems. Did not use tapping - units too ornate. Glaze had been etched by previous overcleaning. Owner did not follow recommendations.

DE TEEL PATERSON TILLER
National Park Service
Rocky Mountain Region
655 Parfet Street
Box 25287
Denver, CO 80225

303-236-8675

talked by phone 4/9/86

Has published on the subject. [Advises in publication, the use of a wooden mallet for tapping.]

SUSAN TINDALL
Architectural Terra Cotta and Tile, Ltd.
932 W. Washington Street
Chicago, IL 60607

312-383-1970

Consultant and manufacturer - talked by phone 1/15/86

Tapping - Does tapping.

Note: problems in general field - testing procedures adapted from brick industry, core samples sometimes taken in wrong direction. Need for correlated information on what buildings have been studied, what went wrong, why, to company records; what has worked in different parts of the country.

Has published on the subject. Has produced a video on tapping.

SUSAN TUNICK
45 Grammercy Park
New York, NY 10010

212-228-8265

talked by phone 3/26/86

Does promotional work for FOTC in NY. Sees a lot of over-cleaning problems.

MARTIN E. WEAVER
Heritage Canada Foundation
Box 1358 St. B
Ottawa, Ontario Canada K1P 5R4

613-237-1066

Conservation consultant - talked by phone 9/8/86

Tapping - Does tapping with rubber mallet. Learned in England on other masonry buildings, applied principals to terra cotta. Believes technique developed through masons. Objectives - See if unit is attached or cracked, gives indication of need for further tests, engineering or opening up building.

Note: Has details on problems with terra cotta in survey reports. Has had to remove loose pieces on all buildings inspected.

APPENDIX B

Test Descriptions

This appendix provides descriptions of the on-site and laboratory tests that can be performed on architectural terra cotta to identify contributing causes for the material's deterioration. At the end of each description the number in brackets (x) refers to the endnote number for each description. The endnotes are listed on page 44.

ON-SITE TESTS

Infra-red - Works by detecting sources of heat, scanning (photographs) with infra-red imagery of building will indicate loose or broken units which would have different temperatures than surrounding units. Provides a record of those units that are defective.(1)

Metal Detection - Electro-magnetic impulses transmitted by an oscilloscope indicate the presence of metal.(2)

Monitoring Cracks - Scratch gauge, dial gauge, or vibrating wire strain gauges are used to determine if a crack is continuing to expand.(3)

Probes - If no opening is already available, a small hole is drilled into the unit with a masonry bit and either a metal pick or exploratory wire is inserted to determine what is behind the surface.(4)

Sonoscope - Unit is penetrated with sound waves from a transmitter. A receiver is placed on the other side of the wall. Frequencies which do not sustain their strength indicate a void or crack.(5)

Stress Measurement - A pair of gauges, one installed horizontally and one vertically, are attached directly to the surface of the units and readings are taken of the existing amount of strain. Then an area around each gauge is cut out and readings are taken again. The difference in the readings indicates the amount of strain released.(6)

Water Permeance(Wall system) - Modified ASTM E 514-74 A frame is attached to the wall and water is applied to the surface. The water is collected and recirculated, then the amount of water lost is measured. (7)

LABORATORY TESTS

Absorption - ASTM C67; Sample is dried and weighed, then immersed for 24 hours in cold water, and weighed. Sample is then immersed for five hours in boiling water. The difference in weight before and after each immersion is calculated as a percentage of the original weight and indicates the amount of water absorbed.(8)

Compressive Strength - ASTM C 67-73; load is applied to the specimen parallel to the exposed face.(9)

Glaze Absorption - Modified ASTM C67; Two samples are cut from a unit. The glaze is ground off of one, the other is control sample. Both are dried and weighed. To prevent absorption through the sides, they are coated with asphaltum. The samples are then placed 1/8" face down in a tray of water. The samples are weighed again after 24 hours and the comparison of the two figures represents the ability of the glaze to prevent absorption.(10)

Glaze Adhesion - A 1"x1" vitrified test bar is adhered to the glazed surface of the sample with vinyl acetate dissolved in methyl iso-butyl ketone. The adhesive is heated by an infra-red lamp until bubbling stops. The two surfaces are pressed together until cool; the bar is then knocked off. The glaze adhesion is good if particles of the clay body remain with the glaze; if there is a clean break between the glaze and the body, the adhesion is not good.(11)

Moisture Absorption(Reheat) - Volume change is measured for the samples before and after heating to 550oC. Indicated the amount the unit might have expanded due to the absorption of moisture since its original firing. (12)

Petrographic Analysis - The homogeneity of the clay body as well as detection of planes of cleavage and size of grains are viewed microscopically. The division of particle sizes are as follows: very fine 0.2 - 0.4 millimeter, fine 0.3 - 0.8 mm, rather fine 0.5 - 1.2mm, medium 1.0 - 2.5mm, slightly coarse 2.0 - 4.0mm, coarse 3.0 - 7.0mm, very coarse 5mm and over. May also detect the presence of a waterproof coating, the level of fusion of the clay particles - indicating whether a proper original firing temperature was reached and whether crazing penetrates the clay body as well as the glaze.(13)

Thermal Compatibility - A section of glaze and a section of the clay body are removed on a unit. Strain gauges are

attached to both areas and exposed to a controlled range of temperatures. The coefficient of expansion of both sections are compared to indicate their compatibility. (14)

X-ray Diffraction - Analysis of the crystalline components within the clay body and/or glaze.(15)

X-ray Florescence - Analysis for elemental composition of the clay body and/or glaze; elements with atomic numbers over 19 can be detected indicating to some extent the composition of the clay body and glaze.(16)

APPENDIX B - ENDNOTES

1. Stockbridge, Jerry G., "Evaluation of Terra Cotta on In-Service Structures," Durability of Building Materials and Components ASTM STP 691, P.J. Sereda and G.G. Litvan, eds. Philadelphia: American Society for Testing and Materials, 1980, p. 226. and Tiller, de Teel Patterson, The Preservation of Historic Glazed Architectural Terra-Cotta." Preservation Brief #7, Washington, D.C.: United States Department of Interior, 1979, p. 5.
2. Tiller, p. 6.
3. Stockbridge, "Evaluation", p. 225.
4. Prudon, Theodore H.M. "Architectural Terra Cotta and Veneer in the United States Prior to World War II: A History of Its Development and An Analysis of Its Deterioration Problems and Possible Repair Methodologies." Ph.D. dissertation, Columbia University, 1981, p. 204.
5. Ibid. p. 206.
6. Stockbridge, "Evaluation", p. 224; and Prudon, p. 211-14.
7. Stockbridge, Jerry, G., "Techniques for Evaluating the Conditions of Masonry Buildings." paper presented at International Conference, Materials, Science and Restoration, Esslingen, Federal Republic of Germany, September 1983, p. 379.
8. American Institute of Architects, Public Works Specifications: Ceramic Veneer, File Number 9, October, 1961. p. 4.
9. Prudon, p. 218-19.
10. Stockbridge, "Evaluation", p. 227.
11. AIA, p. 5.
12. Stockbridge, "Evaluation", p. 228.
13. Stockbridge, "Techniques", p. 383.
14. Stockbridge, "Evaluation", p. 227.
15. Stockbridge, "Techniques", p. 383.
16. Ibid.

BIBLIOGRAPHY

- American Institute of Architects. Public Works Specifications: Ceramic Veneer, File Number 9, October 1961.
- Anderegg, F.O. "Watertight Terra Cotta Masonry." American Ceramic Society Journal, Volume 16, December 1933, 634-38.
- "Architectural Terra Cotta Investigations." American Ceramic Society Bulletin, Volume 4, 1925, 408-10.
- Berryman, Nancy D. and Susan M. Tindall. Terra Cotta. Chicago: Landmarks Preservation Council of Illinois, 1984.
- Bourry, Emile. A Treatise on the Ceramic Industries, translated by Alfred B. Searle. London: Scott, Greenwood and Son, 1926.
- Brownell, W.E. "Fundamental Factors Influencing Efflorescence of Clay Products." American Ceramic Society Journal, Volume 32, December 1, 1949, 375-89.
- Clare, R.L. "Causes for the Failure of Terra Cotta in the Wall." Transactions of the American Ceramic Society, Volume 19, 1917, 593-96.
- Coats, Merle A. "The Influence of Soluable Salts in a Clay Upon the Behavior of a Slip and Glaze." Transactions of the American Ceramic Society, Volume 16, 1914, 162-68.
- Cobb, John W. "Note on Disintegration by Crystallization and Freezing." Transactions of the American Ceramic Society, Volume 11, 1909, 65-74.
- Davis, Charles Thomas. A Practical Treatise on the Manufacture of Bricks, Tiles, and Terra Cotta, Philadelphia: Henry Carey Baird, 1889.
- Eskesen, Eckardt V. "Water-tight Terra Cotta Construction." American Ceramic Society Bulletin, Volume 13, June 1934, 154-62.
- Everhart, J. Otis. "Some Simulative Service Tests for Glazed Building Materials." American Ceramic Society Journal, Vol. 13, June 1930, 404-10.
- "Exterior Restoration of the Brazer Building." Report from High Blooms, Boston.

- Fidler, John. "The Conservation of Architectural Terracotta and Faience." Association for Studies in the Conservation of Historic Buildings, Volume 6, 1981, 3-16.
- Glance, A. Richard. "Terra Cotta: Rehabilitation of a Courthouse Dome." Bulletin of the Association for Preservation Technology, Vol. 17, 1985, 39-45.
- Grady, R.F. "Relation of Absorption to the Crushing Strength of Terra Cotta." Transactions of the American Ceramic Society, Volume 12, 1910, 90-91.
- Greer, Walter. Terra Cotta in Architecture. New York: Gaylay Co., 1891.
- Hill, C.W. "Notes on Green Staining." American Ceramic Society Bulletin, Volume 1, June 1922, 51-2.
- Hill, E.C. "Some Experiments on the Firecracking of Terra Cotta." American Cermaics Society Journal, Volume 5, June 1922, p. 225-29; October 1922, p.299-310.
- Jones, J.C. "The Relation of Hardness of Brick to Their Resistance to Frost." Transactions of the American Ceramic Society, Volume 19, 1917, 528-76.
- Lefevre, Leon. Architectural Pottery. London: Scott, Greenwood and Son, 1900.
- McGinnis, C.S. and M.R. Harkins. "The Transmission of Sound Through Porous and Non-Porous Material." Ph.D. dissertation, University of Pennsylvania, 1911.
- McIntyre, W.A. Investigation into the Durability of Architectural Terra Cotta, Special Report #12, London: Department of Scientific and Industrial Research, Building Research Station, 1929.
- McNamara, Edward P. Ceramics Volume III: Clay Products and Whitewares, State College, Pennsylvania: Pennsylvania State University, 1952.
- National Bureau of Standards. "Progress Reports", Numbers 53 - 107, Washington, D.C., March 1925 - September 1929.

- National Terra Cotta Society. Terra Cotta, Standard Construction, New York: National Terra Cotta Society, 1914 and 1927.
- Ortman, Fred B. Paper Presented to the American Ceramic Society, Philadelphia, Pennsylvania, February 24, 1920.
- _____. "Terra Cotta Crazing." American Ceramic Society Journal, Volume 16, December 1933, 639-42.
- Prudon, Theodore H.M. "Architectural Terra Cotta: Analyzing the Deterioration Problems & Restoration Approaches." Technology and Conservation, Volume 3, Fall 1978, 30-38.
- _____. "Architectural Terra Cotta and Veneer in the United States Prior to World War II: A History of Its Development and An Analysis of Its Deterioration Problems and Possible Repair Methodologies." Ph.D. dissertation, Columbia University, 1981.
- "Report on the Restoration and Conservation of Architectural Terra Cotta, Battery March Building, Boston, Massachusetts." Report from High Blooms, Boston.
- Rhodes, Daniel. Clay and Glazes for the Potter. Philadelphia: Chilton, 1957.
- Schurecht, H.G. "Methods for Testing Crazing of Glazes Caused by Increases in the Size of Ceramic Bodies." American Ceramic Society Journal, Volume 11, 1928, 271.
- Schurecht, H.G. and D.H. Fuller. "Some Effects of Thermal Shock in Causing Crazing of Glazed Ceramic Ware." American Ceramic Society Journal, Volume 14, 1931, 565-71.
- Schurecht, H.G. and G.R. Pole. "Some Special Types of Crazing." American Ceramic Society Journal, Volume 15, 1932, 632-37.
- Searle, Alfred Broadhead. The Clayworker's Handbook, 3rd ed. London: Charles Griffen and Co., Ltd., 1911.
- Simpson, John W. and Peter J. Horrobin. Weathering and Performance of Building Materials, New York, 1970.
- Standard Methods of Testing Brick and Structural Clay Tile, ASTM Designation C67-78, 1980 ASTM Annual Book of Standards, Part 16, Philadelphia, Pa: American Society for Testing Materials, 1980.

Stockbridge, Jerry G., "Analysis of In-Service Architectural Terra Cotta Technical Support Investigations." paper presented 1985 Association for Preservation Technology Annual Conference, San Francisco, California, September 1985.

_____. "Evaluation of Terra Cotta on In-Service Structures." Durability of Building Materials and Components ASTM Special Technical Publication 691, P.J. Sereda and G.G. Litvan, eds., Philadelphia: American Society for Testing and Materials, 1980, 218-30.

_____. "Techniques for Evaluating the Conditions of Masonry Buildings." paper presented at International Conference, Materials, Science and Restoration, Esslingen, Federal Republic of Germany, September 1983.

Stover, E.C. "Delayed Crazeing and Shivering." Transactions of the American Ceramic Society, Volume 11, May 1928, 271-77.

Tiller, de Teel Patterson. "The Preservation of Historic Glazed Terra-Cotta." Preservation Brief #7, Washington, D.C.: United States Department of Interior, 1979.

Tindall, Susan M. and James Hamrick. American Architectural Terra Cotta: A Bibliography, Architectural Series: Bibliography #A 531, Monticello, Illinois: Vance Bibliographies, 1981.

Torraca, Giorgio. "Brick, Adobe, Stone and Architectural Ceramics: Deterioration Processes and Conservation Practices." Preservation and Conservation: Principles and Practices, Washington, D.C.: National Trust for Historic Preservation, 1976, 143-65.

van der Velden, Jan H. "Weathering and Frost Testing of Structural Ceramics." Ziegelindustrie International, January 1983, 18-26.

Weaver, Martin E. "The Evaluation of the Terra Cotta Facing of the McLeod Building." Report from Martin Weaver Conservation Consultant, Ottawa, Canada, October 1984.

_____. "Exterior Masonry Conservation Studies on the Bank of Nova Scotia, Portage and Fort Garry, Winnipeg, Manitoba." Report from the Heritage Canada Foundation, Ottawa, Canada, June 1986.

Weinhardt, Robert Allen, Jr., "Industrial Application of Ultrasonics." thesis, University of Pennsylvania, 1949.

"What Causes Stresses in Glazes." Brick and Clay Record, Volume 66, March 3, 1925, 355-56.

Wilson, Hewitt. "Monograph and Bibliography on Terra Cotta." American Ceramic Society Journal, Volume 5, February 1926, 94-145.

Anne & Jerome Fisher

FINE ARTS LIBRARY

University of Pennsylvania

Please return this book as soon as you have finished with it. It must be returned by the latest date stamped below.

~~FINE ARTS LIBRARY
OCT 26 1998
LIBRARY~~

~~RECEIVED
MAY 15 2003
FINE ARTS LIBRARY~~

~~FINE ARTS LIBRARY
JAN 13 1999
LIBRARY~~

~~RECEIVED
FEB 13 2004
FINE ARTS LIBRARY~~

~~FINE ARTS LIBRARY
FEB 16 2008
LIBRARY~~

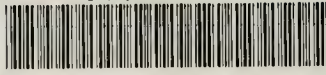
~~FINE ARTS LIBRARY
DEC 2 2002
LIBRARY 002
DEC 1
FINE ARTS LIBRARY~~

3 1198 04975 4125



N/1198/04975/4125X

3 1198 04975 4125



N/1198/04975/4125X