**US Army Corps
of Engineers**
Waterways Experiment
Station

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Repair and Maintenance of Masonry Structures: Case Histories

by   Edward F. O'Neil

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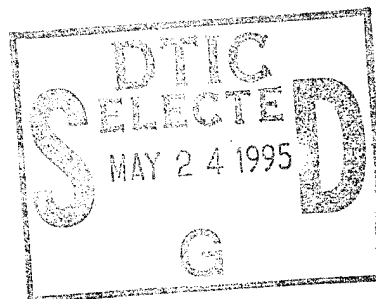
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Prepared for   Headquarters, U.S. Army Corps of Engineers

The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area			Problem Area
CS	Concrete and Steel Structures		EM	Electrical and Mechanical
GT	Geotechnical		EI	Environmental Impacts
HY	Hydraulics		OM	Operations Management
CO	Coastal			

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Technical Report REMR-CS-46
March 1995

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by Edward F. O'Neil

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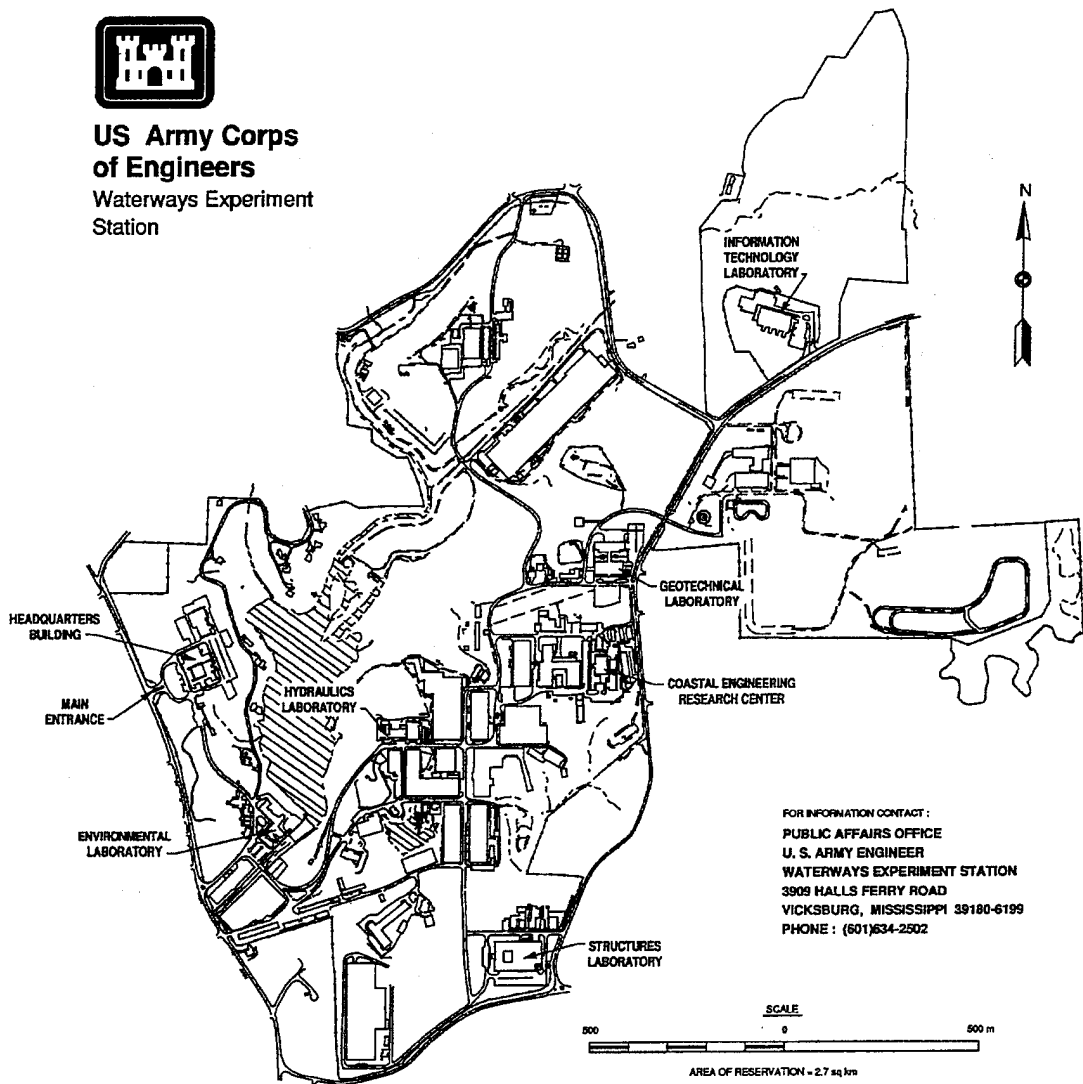Final report

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**US Army Corps
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Waterways Experiment
Station

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STRUCTURES
LABORATORY

SCALE

500   0   500 m

AREA OF RESERVATION = 2.7 sq km

Contents

Preface

The study reported herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit 32636, "New Concepts in Maintenance and Repair of Concrete Structures," for which Mr. James E. McDonald, Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), is Principal Investigator. This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program.

The REMR Technical Monitor is Dr. Tony C. Liu, HQUSACE. Mr. William N. Rushing (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. James E. Crews (CECW-O) and Dr. Liu (CECW-EG) serve as the REMR Overview Committee. Mr. William F. McCleese, SL, WES, is the REMR Program Manager. Mr. McDonald is the Problem Area Leader for Concrete and Steel Structures. This report was prepared by Mr. Edward F. O'Neil, Concrete Technology Division (CTD), SL, under the general supervision of Dr. Liu, Acting Chief, CTD; and Messrs. Bryant Mather and James T. Ballard, Director and Assistant Director, SL, respectively.

The following individuals provided information for this report and their help in compiling data is greatly appreciated:

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Mr. Norm Hatcher, USAED, Rock Island
Mr. Rich Todd, USAED, Rock Island
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Mr. Michael Bray, Lantz-Boggio Architects, Englewood, CO
Mr. Kurt Dathe, Dathe Masonry, Arvada, CO

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	2.471	hectares
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
inches	25.4	millimetres
miles	1.609347	kilometres
pounds (force)	4.44822	Newtons
pounds (force) per square inch	0.006894757	megapascals
square feet	0.09290304	square metres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9) (F - 32) + 273.15.

1 Introduction

Background

The Corps of Engineers is responsible for the upkeep of thousands of brick and stone masonry structures in its building inventory. Many of these structures have strong historical significance to the country. Repair and maintenance of these structures is an important component in managing Corps property and preserving the nation's historical heritage. While brick and stone masonry construction is inherently durable, older structures do deteriorate from exposure to stress and the environment. Proper execution of repair and restoration techniques in rehabilitating these structures will ensure that they endure and remain useful for many years.

Restoration techniques range from temporary stop-gap measures to full restoration programs. The level of effort that is expended will depend on the significance of the structure, the severity of the damage, and the funds available for the project. One goal that should be followed regardless of the level of effort is to accomplish the restoration goal with as little modification of the structure or further damage to it as is possible. Understanding the reasons for good restoration techniques will make the application of these methods easier to achieve.

Purpose

The purpose of this study was to develop, review, and report case histories of repair and restoration to damaged brick and stone masonry structures for the purpose of presenting many acceptable repair and restoration techniques in use today. It is designed to familiarize the reader with some solutions to masonry restoration as well as provide further reference material for more detailed study.

Scope

This study is organized to give a background of each structure, the general climatological data for the area in which the structure is built, a description of the problems the structure was experiencing or the reason for the rehabilitation, a review of the solutions and techniques used to accomplish the restoration, and the performance to date of the repairs that were made. In several cases, additional research information on repair techniques and repair goals have been provided to supplement the data on the repair. The case histories have been chosen to give a broad review of different types of deterioration to brick and stone masonry construction and the chosen solutions. The cases reviewed cosmetic restorative work as well as structural restoration and structural upgrading to earthquake resistant standards. Table 1 below has been provided for a quick reference to sections of this report which deal with specific areas of repair.

The information reported here was obtained through (a) visits to project sites, (b) discussions with project personnel, (c) discussions with designers, contractors, and material suppliers, and (d) review of the literature on materials, and repair and restoration techniques applicable to brick and stone masonry structures.

Table 1
Repair Quick Reference

Type of Repair	Case History
Paint Removal	U.S. Capitol, Mississippi River Commission Bldg.
Stone Strengthening	U.S. Capitol
Stone Replacement	U.S. Capitol
Water Repellent Coating	U.S. Capitol, Mississippi River Commission Bldg.
Slate Roof Replacement	Mississippi River Commission Bldg.
Brick Repair	Mississippi River Commission Bldg., Fort Norfolk, Tallmadge Boyer Block Bldg., Ft. Sam Houston Gift Chapel, Hotel Oakland
Mortar Replacement	Rock Island Arsenal, Fort Norfolk, Tallmadge Boyer Block Bldg., Ft. Sam Houston Gift Chapel
Masonry Cleaning	U.S. Capitol, Rock Island Arsenal, Tallmadge Boyer Block Bldg., Ft. Sam Houston Gift Chapel Fort Norfolk
Building Restoration	Fort Norfolk
Wall Stabilization	Tallmadge Boyer Block Building, Hotel Oakland
Sandstone Repair	U.S. Capitol, Rock Island Arsenal, Tallmadge Boyer Block Bldg.
Expansion Joint Design	Bershire Place
Crack repair	Bershire Place, Ft. Sam Houston Gift Chapel
Structural Repair	Ft. Sam Houston Gift Chapel, Hotel Oakland

2 Case Histories

United States Capitol

The basic architectural design of the United State Capitol was conceived by an amateur architect, Dr. William Thornton, in 1793 (Allen 1990). The design consisted of a domed center section based on the Roman Pantheon, bounded by identical north and south wings treated with Corinthian pilasters. One wing was for the Senate and one wing was for the House of Representatives. The central domed section was accented by a seven-bay portico standing on a one-story arcade. Figure 1 is a drawing of the early structure.
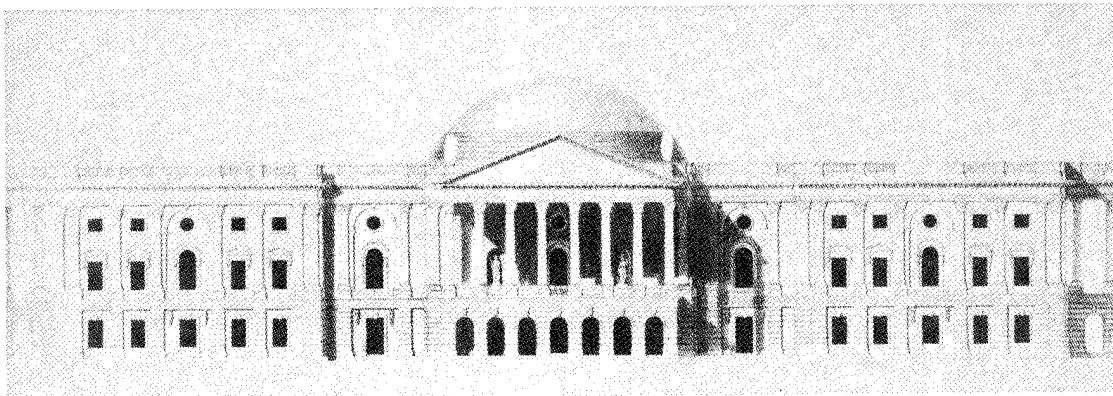
(Ca. 1796 drawing courtesy of the Architect of the Capitol)

Figure 1.   Drawing of the Capitol as conceived by Dr. William Thornton

The construction began in August 1793. The North and South Wings were to be constructed according to the Thornton's basic plan by the Architect of the Capitol (AOC) James Hoban. The construction was first focused on the North Wing because of a shortage of funds. Construction continued to the end of the decade when a temporary brick structure called "The Oven" was built as a meeting room for the House of Representatives. It was connected to the North Wing by a wooden passage. The South Wing design included carved stone columns of the Hall of the House, a marble floor, sculptures,

one hundred skylights, luxurious draperies, and central heating. Before the South Wing construction was begun in 1804, AOC Benjamin H. Latrobe demolished the building called "The Oven" and rebuilt the old foundation.

While this was underway, the architect discovered that the North Wing was in a serious state of deterioration. The condition of the Senate Chamber located on the ground floor was considered serious due to falling plaster and rotting floor, and restoration was needed.

The first Capitol restoration

The interior of the North Wing was rebuilt with a vaulted construction to match that of the South Wing. The Senate Chamber was raised to the main level and a room designed especially for the Supreme Court was constructed on the ground floor below. In 1811, only the eastern half of the North Wing was rebuilt, because funds had to be shifted to the national defense to prepare for the second war with Great Britain. The war took a heavy toll on the Capitol. In 1815 when Latrobe came back to Washington, he discovered the Capitol had been seriously damaged by fires set by the British troops.

Capitol restoration (1815-1819)

The AOC started this restoration of the North and South Wings by cleaning the smoke from the exterior stone and evaluating the fire damage. All stone that could not be repaired had to be replaced. In the rebuilding, the Senate Chamber was expanded to provide additional committee rooms as a half-domed semicircle similar to the amphitheaters of ancient Greece and Rome.

In 1818, AOC Charles Bulfinch was appointed to continue the repair and restoration of the North and South Wings. The Supreme Court Chamber and the rooms for the House and Senate were completely restored in 1819. The construction of the Central Building was begun in 1818. The newly appointed architect redesigned the Central Building according to his own idea and taste. In his opinion, the copper-covered wooden dome was too high. He designed a lofty dome more appropriate for the nation's most prominent building. He worked at finishing and perfecting sculpture, landscaping, fencing, and gate houses for 4 years. In 1830, the Capitol was completed after 37 years of construction.

Restoration of 1851 - The cast iron dome

In 1851, the Library of Congress was gutted by fire caused by sparks from one of the stoves. This fire destroyed the Library's valuable collection of manuscripts. AOC Thomas U. Walter restored the Library. He had the room constructed of cast iron which is fire resistant. The room remained in use until 1897 when the Library of Congress moved into its new quarters.

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After the enlargement of the House and Senate Wings, the length of the Capitol was more than doubled. Because of this enlargement, the appearance of the original dome was small and underscale. These facts, coupled with the facts that the dome was made of wood and vulnerable to fire, prompted the AOC to remove the old dome and replace it with a new dome of cast iron.

Cast iron was the only available material that would permit such a dome to be added without completely rebuilding the rotunda. Because of the massive weight the new dome would add to the existing structure, the old foundations and walls were tested and were strong enough to carry the additional load without reinforcement. In 1856, the construction of the new dome was begun by removing the original wooden dome, installing over 5,000,000 lb[1] of new masonry on top of the rotunda walls, reinforcing them with strong iron bands, and tying them to the existing structure. Nearly 9,000,000 lb of ironwork were subsequently placed on this new masonry base.

Modernization

Edward Clark, AOC from 1865 to 1902, introduced many modern improvements to the Capitol. In 1866, electricity was used to start the gas jets that in turn lit the dome. Steam heat replaced the crude gravity hot-air furnaces in the cellar used to warm the old Capitol. In 1874 came installation of the first elevator run by a giant screw. Gas lighting was replaced by electric lighting in the 1880's because of the gas explosion that rocked the Capitol in 1898, and the roof of the North and South Wings were rebuilt with fire resistant materials. These roofs were lowered to enhance the overall appearance.

Between 1902 and 1954, extensive modernization to the interior of the Capitol was done. The interior stonework was cleaned, and some of the plaster was replaced with imitation stone for appearance sake. In 1949, the House and Senate Chambers were remodeled, but most of the work dealt with the deteriorated iron and glass ceiling in the chambers.

Marble cladding was added to the East Front of the Capitol between 1958 and 1962. This extension to the Capitol was considered essential to correct the illusion that the dome was swaying over the void of the East Portico and was therefore inadequately supported.

Recent restoration

In 1971, in anticipation of the coming bicentennial in 1976, the AOC restored the old Senate Chamber and the original Supreme Court to their midnineteenth century appearance. The Supreme Court quarters, which had been stripped of its decoration and used as an all purpose meeting room when

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[1] A table for converting non-SI units of measurement to SI units is presented on p vi.

the court moved to new quarters, was restored to its original grandeur. The old House of Representatives Chamber was restored above the level of the marble floor. Included in that restoration work was draping of the colonnade, reproduction of the historic lighting fixtures and mantles, and interior repainting.

Restoration of the sandstone walls of the West Central Facade, the only elevation of the old Capitol that had not been covered by marble, is the central focus of this case history study.

Washington, DC, weather

The climatic conditions in the Washington, DC, area are hot summers with periods of high humidity and moderately cold winters with a mean seasonal temperature around 40 °F. Summer temperatures extend from June through September with average temperatures in the upper 80's and the high temperatures ranging up to 103 °F. July and August are generally the hottest and most humid months. Winter conditions are generally present from mid-November through mid-March. Winter temperatures are generally in the low 40's but can get as cold as 10 to 0 °F. Fall and spring are moderate seasons with average temperatures in the 40's to 60's. The rainy season is generally the spring with an average annual rainfall of 40 in.

Description of the recent problems

The AOC had known for many years that the West Facade of the Capitol was in need of repairs. For 2 decades the colonnade on the West Front of the building had been braced by huge timber trusses, Figure 2, to prevent the weakened structure from collapsing. The sandstone veneer of the facade was crumbling from deterioration largely due to freezing and thawing of a relatively weak porous material and age and falling pieces could be dangerous.

On April 25, 1983, the House Appropriations Committee approved a $70.5 million bill to buttress the deteriorating walls. This was a timely appropriation, since 2 days later on April 27, 100 sq ft of sandstone veneer from the braced colonnade fell to the courtyard. Immediately it was decided that something must be done. From the collapsed area, it was obvious that the stone was cracked and soft from years of exposure. These same symptoms that showed up in the area where the facade had failed were present on much of the west face of the building. It was apparent that more than just the colonnade area needed repair.
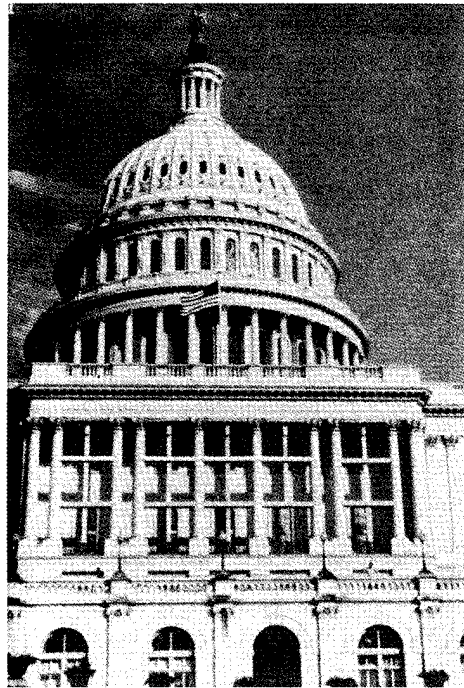
Description of the solutions

The AOC consulted with engineering firm Ammann and Whitney, New York, to determine the scope of this problem and to develop a solution. After

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much consultation, it was determined that the sandstone of the facade had to be stripped of its paint coatings to determine the true condition of the stone. It was known that the stone used in this portion of the Capitol was an inferior grade from a quarry on Aquia Creek in Stafford County, Virginia. Stripping the stone of its coatings would make more obvious any structural cracking and areas of crumbled stone and serve as a diagnostic tool in determining the undamaged portions of the facade and what portions needed to be repaired or replaced.
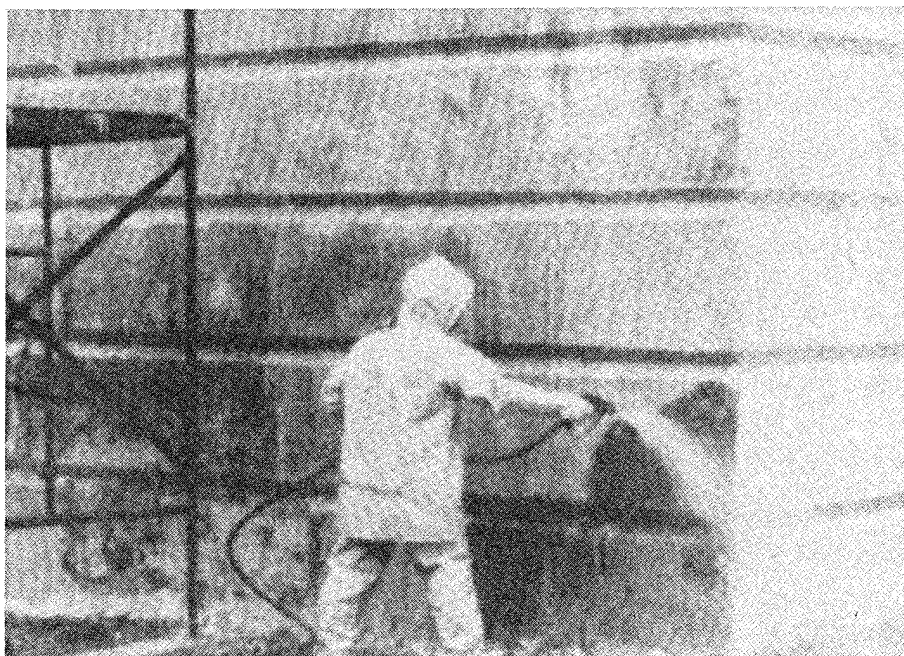
The engineers from Ammann and Whitney first discovered the scope of the task by determining how many coats of paint must to be removed. For nearly 150 years, beginning around 1818, the Capitol was painted every 4 years. During these years, the old paint on the sandstone was not removed before each new coat was applied. This amounted to an accumulation of 35 coats of paint which had to be removed before the sandstone could be examined. This was an enormous amount of hardened paint considering that some of the coatings were greater than 1/8 in. thick. It was interesting to note the evolution of the popular painting products over the years. Linseed oil based paints were found closest to the stone, since they were used at the time the building was first painted. These were followed by lead-based paints used around the turn of the century and into the first half of this century. The outermost coats were acrylic or synthetic-resin-based paints.

(Photo courtesy of ProSoCo)

Figure 2. View of West Facade Colonnade showing supporting timbers

The AOC had to determine what chemicals would remove all these paints without further damaging the delicate sandstone beneath. Field tests were conducted on an inconspicuous, lower part of a courtyard wall shown in Figure 3. The tests were limited to turpentine-based solvents, chloride-based paint removers, and alkaline-based paint removal products. Other products which would soften the paint would also destroy the matrix of the sandstone. After much testing, a two-step process was selected to effectively remove the paint and clean the surface of the sandstone with the least amount of damage to the material beneath. The first step involved a heavy-duty, alkaline-based paint stripper to soften and remove the paint. This stripper contained potassium hydroxide and had a pH of 14. Potassium hydroxide is a very strong alkali and is deleterious to wood and metal surfaces. To protect these

(Photo courtesy of ProSoCo)

Figure 3.   Field test of chemicals on courtyard wall

surfaces, they were covered with polyethylene sheeting before the stripper was applied.

Two applications of the stripper were required to remove the 35 coats of paint on the sandstone. Each application was sprayed on with the use of a commercially available airless spray system. This system had to be refitted with caustic resistant seals because conventional sprayer seals would be destroyed by the chemicals. The pressure setting on the spray system was set high enough so that the stripper would not clog in the delivery nozzle, yet low enough so that it would not atomize when expelled from the nozzle. The stripper was applied in a heavy coat that was built up to a thickness of 1/8 in. during application. This coat was allowed to dwell on the paint surface for 24 hr. The formulation of the stripper was such that it would continue to have a softening effect on the layers of paint for that period of time. After the first application of the stripper was completed, a second application was made without cleaning the debris of the first pass. The second application remained on the surface for an additional 24 hr before both applications were removed. The walls were rinsed with pressure rinsing equipment to remove the dissolved paint and chemical residue from the stripping operation. The pressure rinsing is recommended because masonry surfaces are porous and caustic materials can penetrate into their pores. The use of water at moderate pressures (particularly warm or hot water) will force these materials from the masonry surface. However, care should be taken to use only the pressure that

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is necessary. Excessive pressure can damage the substrate and drive unwanted chemical cleaners into the pores of the material rather than off of the surface.

The second step of the operation was to neutralize the surface of the sandstone to stop the further action of any alkalis that may have been left on the stone. The product used contained acetic acid to neutralize any remaining alkali. This acid was the weakest of the appropriate chemicals and would do the least damage to the fragile sandstone. The acetic acid concentrate was diluted with water and applied to the surface of the sandstone with an airless spray system. This spray application was done with very low pressure. High application pressures would have driven the acid into the pores of the sandstone from which it would have been difficult to remove. This acid solution was allowed to dwell on the surface of the sandstone for 3 to 5 min before it was washed off with water under pressure. The water rinse was applied from the bottom of the treated area to the top, making sure each portion of the surface was covered by the clean water. The entire surface was kept wet during this operation to prevent any streaking of materials being washed from the surface.

This process removed the bulk of the paint from the sandstone. Further attention was needed in areas such as those between the ornamentation on columns (Figure 4), window decoration, and in the joints between the blocks of sandstone. The many years of paint that had built up in these areas obliterated the detail in some cases. These areas were spot treated with the alkali stripper before the paint removal portion of the process was completed.

The paint-removal portion of the restoration was completed by February 1984, and the condition of the sandstone could clearly be seen. The AOC officials and the engineering team could then determine the amount of repair that was needed. An extensive survey of the surface was conducted (Clifton 1987). Cracks in the stone were fully exposed, and areas where the stone was weak and deteriorated could be identified. The survey showed that the deterioration to the facade was random and not associated with locations that were highly susceptible to severe weather. The deterioration of the stone was generally confined to the top 1/2 in. of the surface. There were areas where the deterioration was deeper than 1/2 in., but these were generally less than 1 in. deep. The deeper deterioration would generally be in areas such as cornices and where carved stone was used.

The sandstone in the West Facade apparently began deteriorating very soon after it had been put in place. Benjamin H. Latrobe, the AOC during Thomas Jefferson's first term, wrote that the stone began to deteriorate almost immediately (Clifton 1987). He recorded that it cracked and would crumble on exposure to air and sun. It would expand when wetted and contract when dried. It was not until 1818 that these walls were first painted. The present speculation is that most of the deterioration to the walls occurred prior to painting and that the paint slowed the exposure of the stone to moisture. The deterioration was due to moisture in the surface of the sandstone that froze before paint was first applied or froze periodically in the 160 years since.
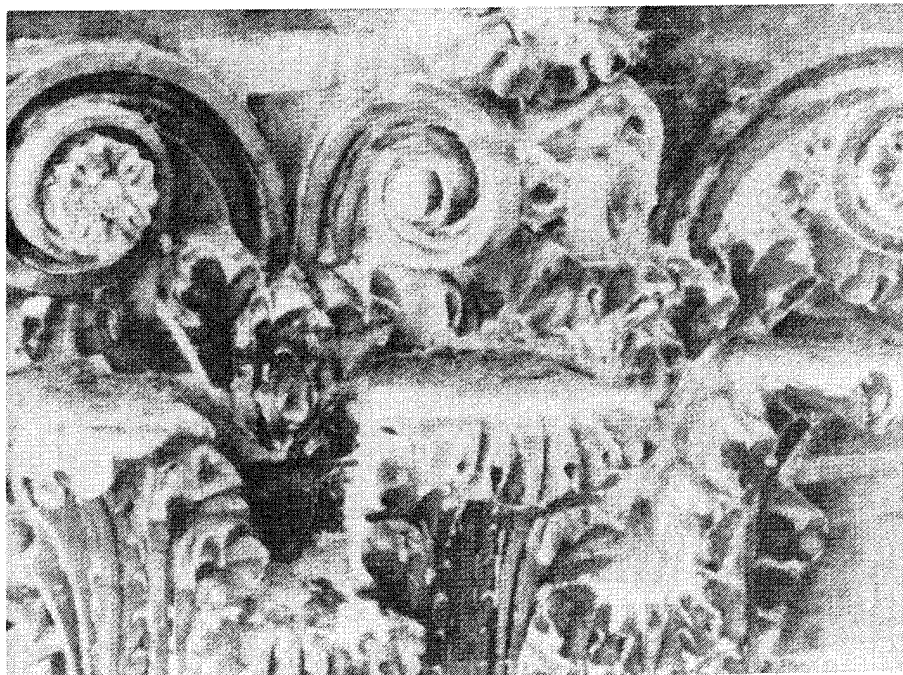
(Photo courtesy of ProSoCo)

Figure 4. Ornamental detail requiring extra cleaning

During the inspection of the surfaces, the sandstone was classified as material that had deteriorated beyond the point of reclamation and material that could be saved and preserved. From the early inspection reports, it was recommended that up to 40 percent of the facade needed to be replaced.

Tests conducted by National Bureau of Standards

The former National Bureau of Standards (NBS, now the National Institute of Standards and Technology) conducted extensive testing on the stone of the Capitol to help develop technical criteria that would aid in deciding whether or not to treat the stone (Clifton 1987). The tests they conducted are given in Table 2. Specimens of the sandstone were cut from stones taken from the Capitol after the paint had been removed. These specimens were tested with five different candidate strengthening materials chosen by the AOC. The materials included four silanes (S1, S2, S3, S4) and one acrylic coating (A). The manufacturers of each of the materials or the application representatives of the materials were asked to treat the specimens with their product to most nearly reproduce the techniques that would be used with each product in the field. Only in certain circumstances did the NBS personnel actually apply the material to the samples. All testing that was conducted on the specimens was done in accordance with the applicable American Society for Testing and Materials (ASTM) standard, if one existed.

Table 2
Tests Conducted by NBS
Water absorption
Water vapor transmission
Sodium sulfate tests
Consolidation ability
Depth of penetration
Accelerated, combined deterioration tests

Water-absorption tests. Treated and untreated 2-in. cubes of sandstone were subjected to water absorption tests in accordance with ASTM Designation C 97, "Standard Test Method for Absorption and Bulk Specific Gravity of Natural Building Stone" (ASTM 1990b). The cubes were immersed in water and data were calculated as mass was gained during the water immersion. All of the materials reduced water absorption, but the silanes (S1 through S4) were much more efficient at excluding the water. The acrylic gained 53 percent in mass while the silanes only gained between 4.3 and 8.6 percent in mass due to the immersion.

Water-vapor transmission tests. Treated and untreated 3-in.-diam, 1/4-in.-thick specimens were tested for water vapor transmission according to ASTM Designation E 96, "Standard Test Method for Water Vapor Transmission of Materials" (ASTM 1992b). The tests were conducted at 88 percent relative humidity (R.H.) and 90 °F. The results were recorded as the ratio of the mass of water vapor passing the treated specimen to the mass of water vapor passing the untreated specimen. The results indicated that all the materials with the exception of S4 had ratios of about 1. Thus indicated that the treated and untreated specimens passed about the same mass of water vapor in a given time. S4 had a ratio of approximately 0.73, signifying that the treatment material reduced the amount of water vapor that could pass through the specimen.

Sodium sulfate soundness tests. In this test, treated and untreated specimens were soaked in saturated sodium sulfate solution in accordance with ASTM Designation C 88, "Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate" (ASTM 1990a). The specimens were immersed in the saturated solution, allowed to come to equilibrium, and then removed and dried in an oven. This evaporates the water, precipitates a sodium sulfate hydrate, and then dehydrates it. The cycle is then repeated until failure. The accumulation of dehydrated salt in the pore structure causes a pressure on the surroundings when it rehydrates. This force may exceed the tensile strength of the material. The amount of breakdown after a specified number of cycles is a measure of the "soundness." i.e., the frost resistance of the material, since the expansion of the anhydrous salt on rehydration simulates the increase in volume of water when turning into ice on freezing. The volume is increased by 9 percent. The tests revealed that all

the treated specimens protected against the ingress of the sodium sulfate better than the untreated specimens. The specimens treated with the S3 and S4 material offered the best protection, increasing the number of cycles before destruction from 7 to 13.

Consolidation ability. The effect of the consolidants on the strength of the stone was tested by applying the consolidants to 2-in. cubes of the stone and then determining the compressive strengths of these cubes according to ASTM Designation C 170, "Standard Test Method for Compressive Strength of Natural Building Stone" (ASTM 1990c). The specimens were treated by the manufacturers in the first round of tests, and the results of those tests showed that there was a decrease in the strength of cubes treated with materials S1, S2, and S4, the same strength for cubes of material A, and an increase of 16 percent for cubes treated with material S3. The data for material S1 was originally based on only one test, so the tests were again done with the coating of the specimens applied by the NBS personnel. These results revealed that the strength increased for the specimens coated with the S1 material and that the earlier results were probably in error due to weak stone. The overall conclusions were that the strength of the material with consolidant depended on how deep the consolidant penetrated the specimen.

Depth of penetration. Additional penetration tests were conducted to determine how deep each material would penetrate into the stone. Specimens, 2-in. cubes, were coated with each material and then tested in compression. The broken surfaces of the specimens were treated with water to find out where the water would absorb and where it would bead. The depth to which the consolidants penetrated were determined in this manner.

The results of laboratory studies showed that the range of penetration went from 0.3 to 1 in. The depth depended on the application material. Brushing on the consolidant was the poorest method and immersion of the specimen and pressure injection performed the best. Specimens immersed in S2, S3, and S4 had a penetration of 0.8 in., while brushing on of S1 penetrated to 0.3 in. The 1-in. depth was achieved by pressure injection of material A.

Similar tests using A, S1, and S4 were conducted on portions of the West Facade of the Capitol in field tests. Consolidants were applied according to manufacturers' instructions and, after 48 hr, cores were taken. The penetration ranged from 0.7 in. to greater than 3.5 in. Further, after 30 days the depth of penetration of all materials was greater than 1 in. Again, the method of application was critical to the depth of penetration, pressure injection being greater than saturation and saturation being greater than brushing.

Accelerated, combined deterioration tests. The NBS also conducted a series of tests in which deterioration was to be measured from the effects of a combination of tests. The tests included rapid temperature change, wetting and drying, and immersion in water. The tests were conducted on both treated and untreated specimens and lasted for greater than 1,600 cycles. The

results showed no cracking or deterioration for any of the specimens under this testing and was discontinued without conclusion.

As a result of the exhaustive testing done by the NBS, the AOC and Ammann and Whitney indicated that the sandstone blocks that could be restored were in need of strengthening and that they should be coated with a breathable coating to protect them from further ingress of water. The strengthener chosen was a silicic ester that forms natural binders in place.

Masonry related repairs

Efforts to replace and repair stone went on concurrently. Masons replaced the badly deteriorated sandstone with limestone while restoration crews worked to repair and preserve stone that was considered good enough to save. Due to the proven limitations of the Aquia Creek sandstone and the architects' intentions to paint the facade after the restoration was complete, Indiana limestone was used as the replacement. This material was more durable than the sandstone, and since it was going to be painted after the repair, the color and material characteristics did not need to match.

The stone that could be repaired was treated with a stone strengthener and a breathable water-repellent coating. The stone strengthener replaces natural binding materials within the stone that have been lost to weathering and the water-repellent coating prevents water from penetrating into the stone while at the same time allowing water vapor to move out of the stone through the coating.

The stone strengthener in this case contained a silicic ethyl ester which is the active ingredient that adds strength to the stone. It has an extremely small molecular size coupled with a viscosity which is less than that of water. These two attributes help allow the material to penetrate deeply into the pores of the sandstone.

In the process of effective masonry consolidation and strengthening, one of the most important functions is to restore the integrity of the decayed stone by reestablishing the bonds between the adjacent grains. This is done by depositing the binding material well within the pore system (Clifton 1980). Any binding material that is used must fully penetrate any deteriorated, weathered, surface layer and establish itself in the sound material beneath. Consolidation in any weak surface layer only tends to harden the surface layer and form a crust (Boyer 1986). These crusts generally have lower vapor permeability and different thermal characteristics than the stronger base layers. The different thermal characteristics and the lower vapor permeability tend to cause moisture to collect beneath the surface crust, and there is a tendency for this material to spall and cause further deterioration to the base material. To this end, the viscosity of the binder should be low to facilitate its penetration into the pore structure of the stone and to take advantage of the natural capillary action of the pore structure of the stone to draw the binder deeply into it.

The strengthener should not form a barrier to the natural transmission of water vapor through the stone or the strengthener. It should have no adverse chemical or physical reactions with the stone it is intended to strengthen. Formation of unwanted substances as a result of chemical interaction between the strengthener and the stone could actually cause more damage than the strengthener was intended to fix. Additionally, any material that is added to the masonry to strengthen it should produce no aesthetic changes to the base material. As an illustration, a strengthener that when hardened would remain tacky would have a tendency to darken with age because of the airborne particulate matter that would cling to the sticky surface.

The silicic ethyl ester strengthener has a neutral catalyst which aids reaction with water and moisture within the stone to product a glass-like substance deep within the structure of the stone. The glass-like substance is the silicic ethyl ester converted to silicon dioxide which is of the same chemical composition as some natural binding materials. Most of the silicic ester will convert to silicon dioxide within 2 weeks curing time under average climatic conditions (68 °F and 50 percent R.H.). This material has its limitations, however. Due to its nature, there is a strong need to control wind and temperature. This restricts application unless precautions are taken. The product has a limited shelf life. It will deteriorate even in a sealed condition after 12 months. It will bond to many materials that are used to make molds for replacement stone and makes their use difficult, and it is unsuitable for some use with some forms of marble. It is very volatile, having a flash point of below 21 °C.

The task of strengthening the stone began in earnest in February 1987. To achieve the proper penetration of the strengthener, the material was applied in multiple passes over small areas of the building, Figure 5. These repeated applications were referred to as cycles. Each cycle consisted of three saturating passes of the material applied bottom to top over small portions of the building. Each building portion was approximately 72 ft long and 7 ft high. This application area was the largest that would allow the material to be applied easily and to fully penetrate before it began to catalyze. In each pass, the material was sprayed onto the stone and allowed to saturate for 10 to 15 min before the next pass in the cycle was applied. The strengthener was applied by airless spray equipment. This equipment provided a controlled, low-pressure spray of the material over the surface of the building. Between each cycle, there was a waiting period of 45 min to be sure that the material in each cycle had fully penetrated. The cycles were repeated until excess material remained visible on the surface at the end of the 45-min waiting period. Five cycles of treatment were applied to the sandstone. The replacement limestone took three cycles before the stone was properly saturated.

With the beginning of application in winter, the appropriate application temperature (a surface temperature of between 40 °F and 85 °F) was not always obtained. The ambient temperature and that of the stone surface had to be monitored constantly. To ensure that moisture had been completely removed from the stone and the surfaces were at the proper temperature when
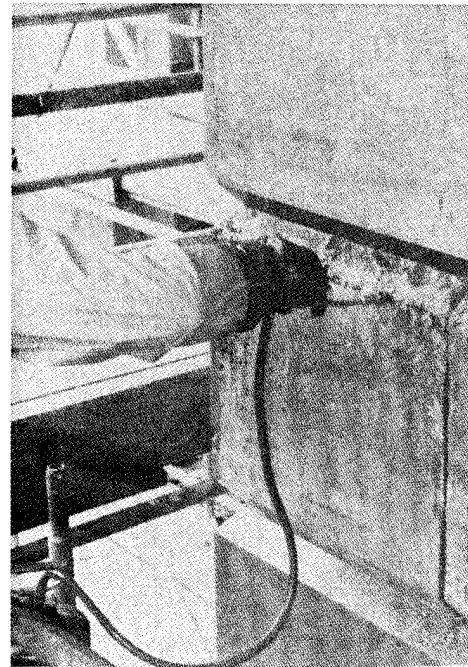
the strengthener was applied, radiant heaters were used near the stone surface at night during the winter. The scaffolding in the area of the work was enclosed with sheets of polyethylene, and the heaters were turned on after the work day was complete, Figure 6. Surface thermometers were installed on the stone and checked each day to make sure that the temperature of the stone was above the minimum 40 °F. The heaters were then disconnected, the polyethylene removed, and the day's work begun.

Small-diameter cores were taken into the sandstone and limestone to determine the depth of penetration of the stone strengthener. The penetration was better than expected, between 1-1/2 and 4 in. on the sandstone and 1 to 1-1/2 in. on the limestone, due in part to the nightly heating of the walls. As a result of the very successful penetration, the amount of stonework scheduled for replacement was reduced from 40 to 25 percent.

(Photo courtesy of ProSoCo)

Figure 5.   Application of stone strengthener to sandstone

After the stone strengthening was completed, the building was given a water-repellent coating to complete the job. The coating is a breathable masonry coating that repels water but allows water vapor to pass through the coating. It is a water-based coating suitable for exterior masonry surfaces that can be pigmented to match a number of different color applications. Generically it is a silicone emulsion with a silicone-resin binder that, when dry, exhibits a high degree of water-vapor permeability due to many small (0.005-in.) pores in the dried coating. These pores allow the water vapor to exit the stone and penetrate through the coating. The pores are so small that they will not allow water into the stone.

Seventeen test panels were coated with pigmented versions of the coating to determine the coverage of the material over strengthened sandstone and limestone and to exactly match the color of the marble in the adjoining House and Senate wings. The panels were evaluated in morning and afternoon direct sun and shade, as well as on cloudy and clear days. A formulation for the best color match was chosen and the coating was begun.

Before the coating was begun, the stone was cleaned to ensure that no loose material was left on the surface. The coating material could be applied by brush, roller, or airless spray but was applied by the later method because of all the detail in the carvings of the stone. Since it was to be sprayed on, it was diluted with up to 15 percent fresh water to thin it for even application through the spray nozzle.

(Photos courtesy of ProSoCo)

Figure 6.   Enclosed scaffolding and heaters

The first coating was applied in a thickness of approximately 15 mils. This is a wet thickness and, due to the 60 percent by mass of solvent and vehicle, will reduce to approximately 6 mils when dry. To ensure full coverage of the surface and a satisfactory application of the coating, it was backrolled once before letting the coating dry. The first coat was allowed to dry for 24 hr before a second coat was applied by the same techniques described in the first application. This coat was also allowed to dry for 24 hr before the coating was considered cured.

Performance to date

At the time of this writing, all restorations to the West Facade of the Capitol have performed well. The sandstone that was repaired shows no signs of further deterioration, and there has been no deterioration of the paint which was placed over the stone to complete the restoration.

Mississippi River Commission Building

The Mississippi River Commission (MRC) Building is located in downtown Vicksburg, MS, at the intersection of Walnut and Crawford Streets.

The structure is owned by the General Services Administration (GSA) of the U.S. Government and leased by the U. S. Army Corps of Engineers to house the offices of the MRC as well as parts of the Lower Mississippi Valley Division of the Corps.

The building is shown in Figure 7. The foreground portion of the building was built in 1890 as a Post Office, a custom house, and as offices for the Signal Corps. It was built in the then popular Romanesque revival style. In 1912 the portions of the building shown in the background of Figure 7 were built as an addition to the original structure. They were built in the same style as the original building.

Figure 7. General view of Mississippi River Commission Building

The building is constructed of load-bearing brick above the first floor. Below the first floor line, it is constructed of Ohio blue sandstone block around the entire building. Trim is predominantly wood, and architectural details around the building are of a variety of materials including copper, cast iron, terra cotta, and wood. The roof is slate.

Vicksburg weather

The climatic conditions in the Vicksburg area are hot humid summers and moderately cold winters. Summer temperatures extend from June through September with the high temperatures ranging up to 100 °F. July and August are generally the hottest months. Winter conditions are generally present from late November through mid-February. Winter temperatures are

generally in the 40's but can get as cold as 10 to 15 °F. Fall and spring are moderate seasons with average temperatures in the 60's and 70's. The rainy seasons in this part of Mississippi are generally in the winter and spring with between 45 and 60 in. of rain a typical amount of annual rainfall.

Repairs have been made to the building throughout its life, but the first major repair was conducted in the early 1950's. At that time the building was beginning to develop moisture problems and needed cleaning. The repair solution was to clean the brick by sandblasting, apply a thick grout coating to the mortar joints (called at that time striping), and paint the sandstone with a coat of cement grout to help waterproof it. In the 1980's, a new slate roof was put on the building because it was beginning to show signs of leakage from the roof area.

In 1991, the building underwent its current renovations. This time the repairs were done to alleviate moisture problems that were causing deterioration of the brick and mortar joints as well as preventing paint and paper from adhering to the interior walls.

Description of the problems

Problems were first noticed on the interior surfaces of exterior walls throughout the building. A number of the walls began to show signs of peeling paint, mold, and moisture. Signs of soft plaster beneath the wall coverings were also noted. Glued wallpaper would not adhere to some surfaces. The wood in the window sills and frames were old and were rotting due to excessive moisture streaming down the outside of the building. These conditions were not confined to one location, but were spread over the entire building. On the north facade of the building, the moisture related deterioration was the worst because of lack of sunlight exposure which would aid in drying.

Further examination of the building turned up deteriorating brick work on both the outside of the building as well as the inside. Bricks that were soft and crumbling were found as well as bricks that turned to powder when touched. In addition, mortar between the bricks was soft, deteriorating, and crumbling. Most of the brick damage was found on the inside and outside of exterior walls. However, in a number of cases there was deterioration to the brickwork at the base of interior walls in the basement.

In addition to the deterioration of the brickwork, the entire surface of the building was dirty from the years of grime and soot deposited on the surface since the last cleaning in the 1950's.

The sandstone on the outside of the building had experienced bad spalling during the years subsequent to the application of the cement grout. Even in its best condition, the sandstone used in this building was a soft material and was falling away in layers sometimes close to 1 in. thick. Figure 8 shows some of this damage to the sandstone.

Solutions to the problem

In evaluating the condition of the building, it was discovered that the slate roof that had been installed in the 1980's had been put on incorrectly and was the cause of much of the moisture running down the walls and rotting the wood on the windows. The slate sheets had not been correctly lapped when they were originally installed and they were not functioning as they had been designed. The roof had to be totally removed and replaced in the correct manner.

The cause of the peeling paint and wall paper, deteriorating brick, and spalling surfaces of the sandstone was excess moisture taken into the walls of the building. Moisture was coming from a number of different sources. Primarily, the exterior brick was taking in great amounts of water through the surfaces that were damaged by sandblasting during the 1950's. The blast cleaning had destroyed the vitrified surface of the brick. This vitrified surface tends to shed water rather than absorb it. Figure 9 shows some of this damage. This figure shows that the nozzle operator varied the distance of the nozzle from the surface of the wall such that when the nozzle got very close the damage of the sand hitting the brick was so bad that even 40 years later the path that the nozzle took is still visible.

Figure 8. View of wall showing spalling damage to sandstone

Water coming into the walls through the brick surface was making the interior surfaces of exterior walls wet. The dampness was making plaster weak and rotting the wood casement work. Water was also running down the facade of the brick and further deteriorating the woodwork.

It was determined that the roof must be installed correctly, the brickwork should to be repointed, cleaned, and a water repellant applied to prevent any further moisture from penetrating the brick and to allow any moisture created on the interior of the building to escape; the sandstone needed to have the paint and grout removed to allow moisture to escape; and a water repellant was required on the sandstone as well.

The first chore for the architects was to choose the method of cleaning. Government architects studied National Park Service documents on restoration techniques and adopted a "gentlest means possible" philosophy in dealing with cleaning the surface of the bricks. This philosophy says begin with a low pressure water treatment supplemented with mild, nonionic detergents and scrubbing with soft brushes. If the gentle method does not work, the next step is to choose chemicals that won't harm the material (Grimmer 1988). The architects conducted site tests and determined that the amount of dirt and
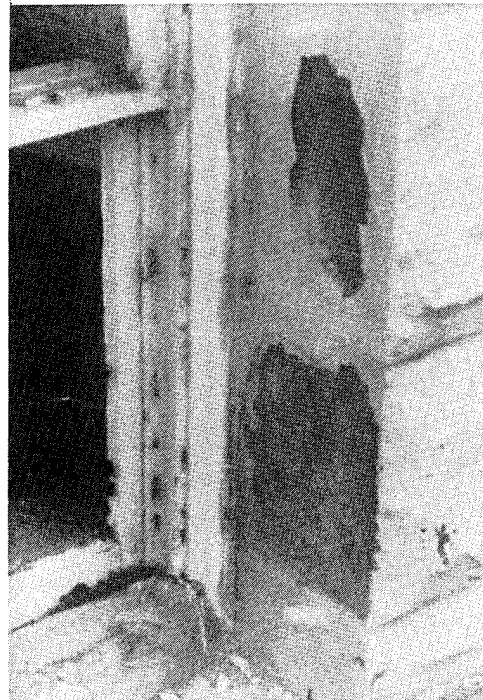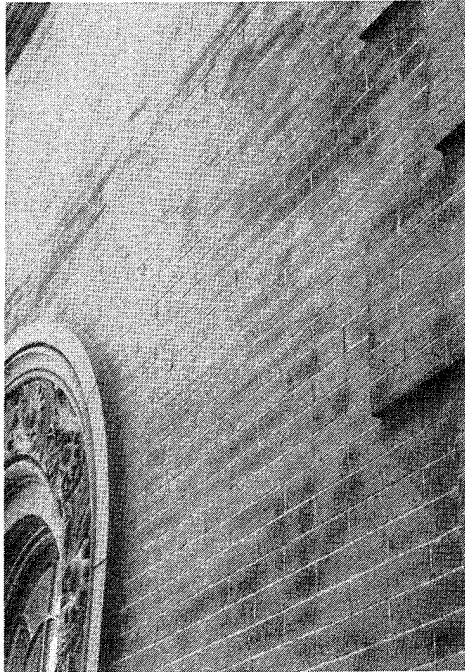
Figure 9. View of brick showing nozzle damage

grime on the building was too severe for the use of water and detergents. As a result, they chose a number of chemical cleaners which would clean the surface of the brick while not damaging the brick or sandstone in the process. The product chosen was a hydrofluoric acid-based material which effectively loosens carbon bonded to the siliceous surface. The paint on the sandstone was removed with heavy-duty paint strippers that had minimal effect on the stone.

Before cleaning could be accomplished, all the deteriorated mortar joints had to be tuckpointed. Repairing the joints before doing the surface cleaning is more cost effective, because the tuckpointing process creates residues that will soil the building facade. Newly sealed joints will also prevent cleaning chemicals from entering the building through the joints. Some of the mortar in the joints was completely deteriorated, and some of it was still in good shape. In the 1950's cleaning, a cementitious coating material was applied to the mortar joints which was meant to seal them against the penetration of water. This coating process, called striping, was still present on some of the joints and had protected the joints which remained covered over the years. The rest of the joints were raked to a depth of 1/2 in. to remove the deteriorated mortar in preparation for tuckpointing.

The contractor wanted to use a mechanical grinder for removing the mortar from the joints, but the specifications did not permit this. The architects did agree to let him use mechanical tools if he could demonstrate on a test panel that he could remove the mortar without damaging the brick. This technique was subsequently demonstrated by the contractor, and the use of mechanical grinders was authorized. The contractor used a small 3.5-in.-diam grinder with a 3/16-in.-thick diamond-tipped blade (Figure 10). This was the widest diameter blade he could use without damaging the brick. Special care was taken when removing mortar from the head joints since the grinder could potentially damage the bricks above and below this joint. The contractor would stop the grinder before crossing the bed joint and remove any remaining mortar with hand tools to prevent damage to the bricks.

The mortar used for the repointing was composed of 4 parts lime, 1 part portland cement, and 12 to 14 parts sand. This mixture was submitted and approved by the architect. The use of lime as binder in repointing mortar is encouraged because it produces a softer mortar than one made entirely from portland cement. Exactly matching a mortar to one that has been removed is not necessary (Mack, Tiller, and Askins 1980). The important points to remember about the replacement mortar are:
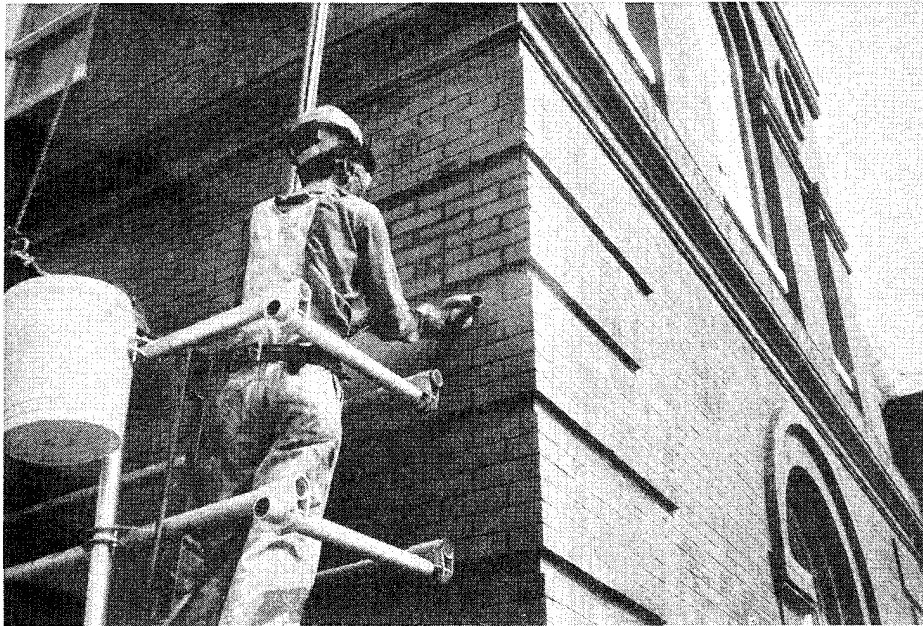
Figure 10. Worker routing bricks with small saw

a. Match the mortar in color, texture, and detailing.

b. Be sure that the mortar is softer than the brick.

c. Be sure that it is as soft as the original mortar.

A number of the bricks in the exterior of the building had been damaged over the years. This was mostly through freezing and thawing damage to the water-saturated bricks. An example of this damage is shown in Figure 11. Because a replacement brick that was the same color, size, and shape could not be found, the contractor carved bricks for the replacements. Damaged bricks were removed before the repointing, and others that did not show on the face of the building were located. These bricks were ground to powder and mixed with epoxy binders to make bricks to fill in where the damaged bricks had been removed. There were only a small number of such areas that needed this type of treatment, and they were typically in areas that were near the top of the building, around flashing or parapets. As a result, the bricks blended well with the old brick and could not be easily distinguished from them.

Pretreatment testing of masonry. The process of cleaning the brick and sandstone required that the chemicals be tried on a sample of the material before being used on the building. It is important to identify the materials that will come in contact with the chemicals to ensure that they will not be damaged by those chemicals (Grimmer 1988). The architects sent samples of the material to a testing laboratory to have them conduct analyses on the physical and material properties of the building components. Samples of
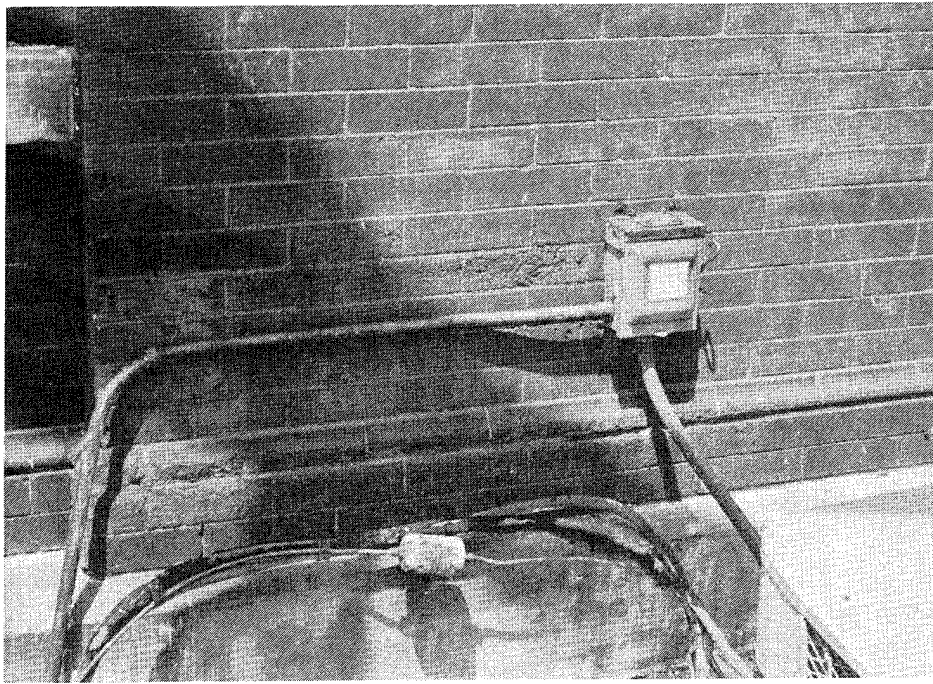
Figure 11. View of brick damage due to weathering

brick, limestone (some of the window sills were made of limestone), and sandstone were sent to the lab. Pretreatment tests were conducted on these materials first.

The brick sample consisted of one partial brick measuring 4 by 2-1/2 by 4-1/4 in. Two samples, 2-1/2 by 2-1/2 in., were cut from this sample. Tests for water absorption, hygroscopic moisture uptake, presence of water-soluble and acid-soluble salts, as well as anionic salts were conducted. The remaining portions of the samples were used for chemical and physical testing. A similar set of tests were conducted on the limestone and the sandstone. Table 3 gives these results.

Posttreatment water-absorption tests. The samples sent to the laboratory were also tested for water absorption after they had been coated with the chemicals that were to be used in the restoration cleaning and sealing. The samples were coated as per manufacturer's recommendations and allowed to absorb water for 10, 30, 60 min, and 24 hr. The results of these tests were studied before approval for use on the building was given. They are reported here in Table 4.

With these tests reported, the contractor was required to clean a 4- by 4-ft test panel of the brick on the south face of the building near the rear. The manufacturer's product data sheet for the cleaning chemical recommended that the area be tested to determine dilution rate and compatibility with masonry surrounding the areas to be cleaned. The recommended procedure for determining the dilution depended on the porosity of the brick. If the brick is porous, then it is recommended to use the cleaner in its concentrated strength. If the concentrate cleans effectively, tests should be run with diluted solutions until the mildest solution that will clean the surface is found. With surfaces

Table 3
Pretreatment Chemical and Physical Tests

Brick

Water absorption %	
after 10 min	2.7
after 30 min	3.6
after 60 min	4.8
after 24 hr	8.8
Hygroscopic moisture uptake %	0.1
Water-soluble salts %	0.00
Acid-soluble salts %	0.89
Anionic salts %	0.00
X-ray diffraction %	
Quartz	95
Feldspar	3
Hematite	2

Limestone

Water absorption %	
after 10 min	4.6
after 30 min	6.8
after 60 min	8.1
after 24 hr	11.9
Hygroscopic moisture uptake %	0.1
Water-soluble salts %	0.00
Acid-soluble salts %	36.18
Anionic salts %	0.00
X-ray diffraction %	
Dolomite	90
Quartz	10

Sandstone

Water absorption %	
after 10 min	6.8
after 30 min	7.4
after 60 min	8.9
after 24 hr	12.1
Hygroscopic moisture uptake %	0.6
Water-soluble salts %	0.00
Acid-soluble salts %	1.89
Anionic salts %	0.00
X-ray diffraction %	
Quartz	80
Microcline feldspar	10
Kaolinite	2
Calcite	1

Table 4
Posttreatment Water Absorption Tests

Brick (with siloxane treatment)

Water absorption %
after 10 min	2.4
after 30 min	2.9
after 60 min	3.3
after 24 hr	3.9

Brick (with silane treatment)

Water absorption %
after 10 min	1.3
after 30 min	1.5
after 60 min	1.8
after 24 hr	2.5

Limestone (with siloxane treatment)

Water absorption %
after 10 min	2.7
after 30 min	3.6
after 60 min	4.9
after 24 hr	6.3

Limestone (with silane treatment)

Water absorption %
after 10 min	2.0
after 30 min	2.6
after 60 min	3.7
after 24 hr	5.0

Sandstone (with siloxane treatment)

	Test 1	Test 2
Water absorption %		
after 10 min	4.8	3.0
after 30 min	5.6	3.4
after 60 min	7.1	4.6
after 24 hr	8.9	5.8

Sandstone (with silane treatment)

	Test 1	Test 2
Water absorption %		
after 10 min	3.4	2.3
after 30 min	4.6	2.9
after 60 min	5.3	3.8
after 24 hr	6.7	4.6

that are not very porous (such as glazed brick or polished granite), the dilutions should be tried first. Since cleaning a test panel will also tell what effects the solution will have on surrounding materials, it is probably prudent to approach the concentration of the cleaner from its most dilute to least dilute direction. This also follows the philosophy of "gentlest means possible."

The owner's specifications for the cleaning work dictated that acid cleaners for removal of normal atmospheric staining would not use hydrochloric acid and that the hydrofluoric-acid content would not be greater than 5 percent. A similar specification for the removal of heavy atmospheric staining would not exceed 16 percent hydrofluoric acid. The hydrochloric acid is not a completely effective cleaner, and it leaves salt deposits behind that can be detrimental later on.

Cleaning a test panel would also tell what effect pressure rinsing will have on the cleaned brick. The higher the rinsing pressure, the greater chance of damage to the old brick. The pressure should be high enough to clean the surface and not leave any acidic residue but weak enough not to damage the brick.

The specifications also required that the chemical manufacturer's representative be present during the test panel cleaning. This was to ensure that his chemicals were being used correctly by the contractor. The test revealed that the chemicals would clean the brick but not damage it or other masonry materials in the vicinity.

As mentioned above, the chemical cleaner contains hydrofluoric acid. This is corrosive and will damage glass and architectural aluminum and is harmful to wood, painted surfaces, and foliage. Before the chemicals could be used on the building, the contractor had to protect all such surfaces. The only materials in the building that would be damaged by this chemical were the windows and the wooden frames around them. They were effectively protected by flooding the surfaces with water before applying chemicals near them.

The chemical cleaner used to remove the surface dirt was applied by low-pressure spray equipment (< 50 psi). The use of high pressures in applying the chemicals can force the chemicals into the pore structure of the material and make them difficult to remove after they have done their work. The chemicals were applied from the top of the building down. This procedure prevents chemicals and loosened dirt from coming in contact with surfaces that have already been cleaned and allows the chemicals washing down the surface to start cleaning the areas below. During the application process, care was taken to prevent the sprayed-on chemicals from being spread by wind drift. This could cause damage to areas nearby that were not intended to be cleaned such as automobiles or other buildings. The cleaning solution was allowed to remain on the wall for 3 to 5 min before being rinsed off. Figure 12 shows the brick surface as the spray is being applied.

The rinsing procedure starts by flooding the treated area with a low-pressure water stream that removes the bulk of the acidic residue from the brick surface. This is followed with a medium pressure water spray (1,000 to 1,200 psi). The area to be rinsed is flooded from the bottom to the top. This ensures that the residues removed from the area will travel over surfaces that are already wet with water, and this will further dilute the chemicals in
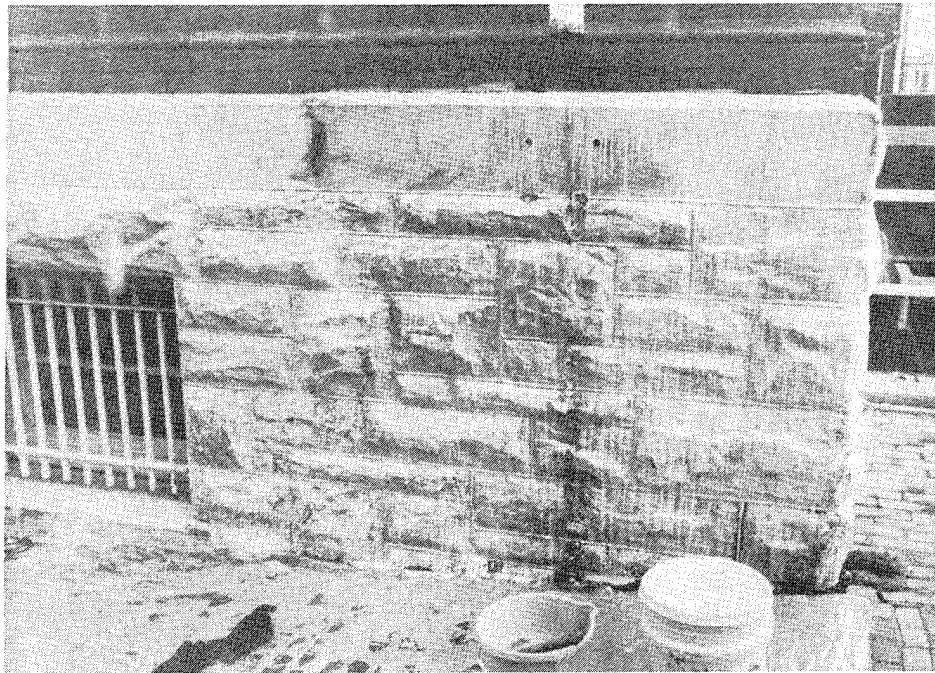
Figure 12. Limestone being cleaned with chemical spray

the waste stream. The areas beneath the areas being cleaned should also be kept wet and flushed with water to prevent streaking from the chemicals and dirts being washed from the above areas.

If the above procedure did not clean the surface the first time, it was repeated until the desired result was achieved (Figure 13).

The sandstone had been damaged over the years by applications of mortar and paint. These coatings needed to be removed before the sandstone could be sealed. The first step in the reclamation of the sandstone was to remove the paint that had been applied over the years. This was removed with chemical paint stripper. The product used was one that would dissolve high-strength paints and coatings. Epoxies, polyurethanes, and enamel paints are included in this group. The product is a thixotropic material that is brushed on and removed with water rinses.

The stripper was applied to dry, clean surfaces of the sandstone with brush and roller, taking care to lay down a uniformly thick coating. It was left in place for approximately 20 min to allow it to soften and loosen the paint from the stone. After the allotted loosening period, the paint was stripped from the surface by water pressure delivered at medium pressures (800 to 1,200 psi). This effectively removed the paint from the sandstone. The pressure water treatment also helped remove any loose cement paint and the freeze/thaw damaged layer of sandstone. However, the paint stripper was not formulated to remove cement grout. This material had to be removed with other products.

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Figure 13. View of cleaned MRC Building

A chemical used to restore limestone was used to remove the cement grout from the sandstone. The material used for this purpose was described by the manufacturer as a liquid blend of inhibited acidic ingredients and wetting agents. The acids in this liquid attack the calcium-based materials in the grout and dissolve them away. Because the sandstone beneath the grout is resistant to acid attack, this chemical was effective in removing the grout but did not harm the sandstone. This method was used to remove over 80 percent of the grout paint.

The limestone restorer was diluted with water before application. The dilution rate ranged from the strongest concentration of 2 to 1 water to concentrate down to a weak solution of 6 to 1. It was applied to the sandstone by prewetting the surface with water and applying the cleaner with a low pressure spray. The application of the water to the surface further diluted the acidic solution when it was mixed into the wet surface. The solution was allowed to stay on the surface for 3 to 5 min. Rinsing of the surface was done by washing with water in a stream that had low to moderate pressure. The manufacturer recommended a pressure of greater than 400 psi. The surface was rinsed from bottom to top to ensure that the washed chemicals would travel over an already wetted surface to prevent streaking.

A side effect of the use of the limestone restorer was that it combined with iron deposits in some of the sandstone and eventually produced a rusty colored

stain on the cleaned surface. When this was encountered 7 to 10 days after the first application, the use of the restorer was discontinued. However, by this time enough of the mortar paint was removed to allow the sandstone beneath to breath.

Treatment of the surfaces. The brick and sandstone were treated with a water repellent after all the repairs were completed. The specifications for the coating called for a colorless, clear, penetrating water repellent for above-grade brick, natural stone, and concrete surfaces. Before the contractor could choose an appropriate material, he was required to provide the following:

a. Manufacturer's product data.

b. Manufacturer's instructions for application.

c. A protection plan for surrounding materials.

d. A quality assurance plan.

e. Test reports.

f. Certificates of compliance.

The contractor chose a low-viscosity, deep-penetrating, water-repellent, and consolidating material to do the job. The sealer is a liquid with 40 percent solid content. The active solids were silane water repellents and silicone binding materials to ensure attachment of the water-repellent materials to the interior surfaces of the masonry pore structure. The solvent carrier for the solids is a ketone with a very low viscosity. The low viscosity and small molecular size of the materials provides for high penetration of the material into the pore structure of the masonry and high coating of the interior pore surfaces. This material does not rely on filling the pores in the masonry to achieve its water repellency but by coating the walls of the pores. This means that water vapor can freely travel through the pores while water is repelled. The breathability of such a coating will prevent water vapor from migrating to the back of the coated surface, condensing, and then being trapped under the coating. Freezing of trapped water such as described is the cause of much of the damage that results from coating masonry surfaces.

As with the cleaners, a test panel treated with the sealer was prepared for the architect's approval before it was applied to the building surface.

The application of the sealer was accomplished from the top of the structure down. The surface of the brick and sandstone was completely repaired and allowed to dry before the sealer was applied. It was applied with a low-pressure airless spray applicator that was outfitted with hoses and seals that would not be deteriorated by the solvents in the carrier. The sealer was applied in two wet-on-wet coats to the brick and sandstone. It was applied in flooding applications from the bottom of the area being treated up to the top.

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This was done to ensure that runoff from the spray application would flow over an already wetted surface. Sufficient material was applied to allow for an excess coating to run down below the application point for approximately 6 in. The first coat was allowed to penetrate into the pores of the masonry for about 5 min before the second coat was applied. The sealer will dry in 4 to 6 hr and will be water repellent after 72 hr. The manufacturer states in his product data that the water repellency rating is 99.8 percent allowing only 0.2 percent water absorption.

Performance to date

At the time of this writing, the repairs to the MRC Building have been completed for 1 year. Structural repairs to the roof are functioning properly, and there is no new leakage. The repointing and brick repair to the facade as well as the ancillary woodworking repairs have stopped any further ingress of water into the building from these sources, and the coating and masonry strengthening are performing as expected with no color change due to the materials applied to the brick.

Rock Island Arsenal

The Rock Island Arsenal is a complex of stone masonry structures built on Arsenal Island, a 929-acre island in the Mississippi River at Rock Island, IL. The arsenal was built for the purposes of military ordnance development and production in the late nineteenth century. The plan for the complex was conceived in 1865 by General Thomas Jackson Rodman, and the majority of the buildings which comprise the facility were constructed over the next 26 years. These structures form a highly significant example of military construction of the period.

The climatic conditions in the Rock Island area are hot humid summers and cold winters with a mean annual temperature of 50 °F. Summer temperatures extend from June through September with average temperatures in the low 70's, the high temperatures ranging up to 107 °F. July and August are generally the hottest months. Winter conditions are generally present from mid-November through mid-February. Winter temperatures are generally in the low 20's but can drop to as cold as -10 to -20 °F. Fall and spring are moderate seasons with average temperatures in the 40's to 60's. The rainy season in this part of Illinois is generally the spring with an average annual rainfall of 29 in.

The buildings under discussion in this case history are three buildings built between 1877 and 1918. The three buildings are all connected. Buildings 108 and 110 were built between 1877 and 1883, while Building 109 was built between these two buildings in 1918.

Buildings 108, now used as a printing plant, and 110, now used as an administration building, are identical U-shaped structures consisting of a 90- by 60-ft central section to the north flanked by two 60- by 300-ft wings on the east and west sides of the central section. Each building has two 60- by 15-ft pavilions attached to the outer faces of the east and west wings. These buildings are shown in Figures 14 and 15. Their foundations and load-bearing walls are constructed of ashlar limestone block. They also have limestone water tables. The buildings are two and one-half stories above ground level with a single basement level. The walls are 3 ft thick at the basement, decreasing about 6 in. in thickness with each successive story.

Major entrances are located in the center of the north wing of each building, in the pavilions, and in the north and south ends of the east and west wings. Entrances and windows in the buildings are arched openings with rusticated stone surrounds and keystones. Some of the stone sills surrounding the windows in Building 108 were made of rough cut sandstone instead of limestone.

Metal Fink trusses provide support for the cross-gable roof of these buildings. The ends of the roof are stone pedimented gables above stone entablatures. Stone pilasters rise from the water table to the entablature.

Building 109 is a rectangular structure, 90- by 60-ft, and two and one-half stories high. It was designed by Stone and Webster Engineering Company to match the original stone Buildings 108 and 110. It was built in 1918. It joins Building 108 at its northeast pavilion and Building 110 at its northwest pavilion.

It has a concrete foundation and stone water table. It is a reinforced concrete structure clad with coursed stone veneer. Entrances and windows are arched openings with rusticated stone surrounds and keystones as in the other buildings. It has a seamed metal gable roof on steel beams. It is shown in Figure 16.

### Description of the problem

These buildings are only three of many such stone buildings at the Rock Island Arsenal complex. They have survived well. Primarily due to environmental pollution and the deteriorating effects of freezing and thawing over the winters, these buildings were in need of cleaning and repair of the joints between the stone masonry units. The freezing and thawing of the mortar in the joints as well as the deterioration caused by water running over the stones and eroding the mortar necessitated removal of the deteriorated mortar and replacement with fresh mortar.

Over the years, the soot and pollution of an urban environment had coated the stone and darkened the surface of both the limestone and sandstone. The later, being a more porous stone, was blackened by the soot to a greater
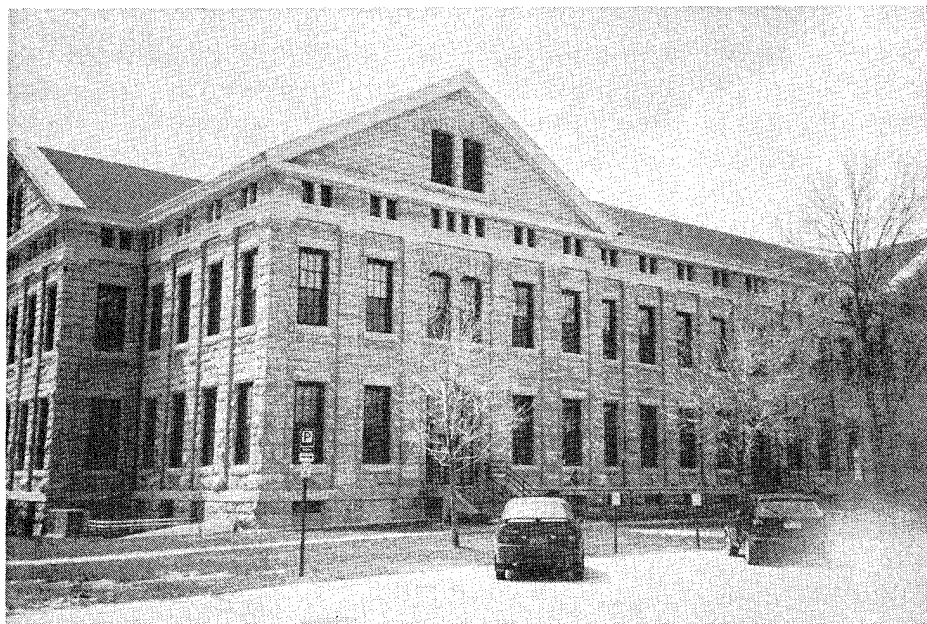
(Photo courtesy of U.S. Army Engineer District (USAED), Rock Island)

Figure 14. General view of Building 108
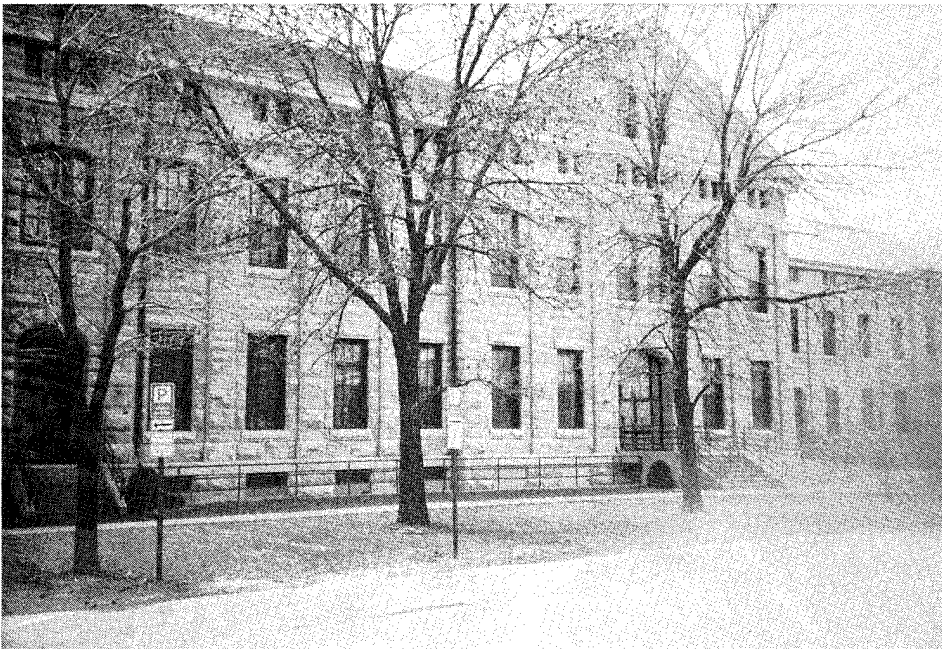
(Photo courtesy of USAED, Rock Island)

Figure 15. General view of Building 110

(Photo courtesy of USAED, Rock Island)

Figure 16. General view of Building 109

degree than the limestone. As a result, a contract was let to clean the stone and repoint the mortar in all three buildings.

Description of the solution

Repointing of the stone was the first task. It is important to make repairs to the mortar before cleaning the stone to prevent any of the cleaning chemicals from penetrating the joints where they could aggravate the existing damage. If the building is cleaned before the joints are repaired, chemicals can get deposited on surfaces that will later interfere with bond of the repair mortar or chemicals can get into surfaces and pores where they can not be easily cleaned with rinse water. Cleaning chemicals left behind or left on the structure longer than desired can cause damage to the concrete.

All the joints in the three buildings were repointed. This was a large job because of the size of the buildings. The linear footage around the buildings was approximately 3,200 ft and given the number of bed and head joints in each building as well as the number of buildings, the total linear footage of joints to be repaired increased to over 27 miles. As is standard, the mortar in the joints was removed to a depth of two and one-half times the width of the joint. Since the joints were as wide as 1-1/2 in. the mortar in them had to be removed down to 3-3/4 in. in extreme cases. In the bed joints they used a combination of tools for mortar removal. A grinder with diamond tipped

blade was used to remove most of the mortar. However, where the depth had to go to 3-3/4 in., the blade was too shallow, and additional cutting had to be done with a thin-bladed chisel. The grinder could be used in the head joints because the masonry of the building was large limestone blocks. However, when the grinder came close to either adjacent bed joint, the mechanical chisel had to be used to prevent damage to the blocks above and below.

The replacement mortar was designed to be weaker than the limestone. It was formulated to fall within the requirements of ASTM Designation C 270, "Standard Specification for Mortar for Unit Masonry (ASTM 1992a)." Within this specification, the mortar was made to conform to the requirements for Type N. The actual proportions used were 1 part portland cement, 1 part hydrated lime, and 6 parts sand. A colorant was used in the mortar to help it match the color of the stone and the original mortar that remained. Repointing techniques that were used were similar to those described in case histories of the MRC Building (case history 2) and Fort Norfolk restoration (case history 4) elsewhere in this report.

When the repointing was completed, the next task was to clean the stonework. The contract called for cleaning the soot from 125,000 ft^2 of stone. The process began by cleaning test panels of the limestone. Water with detergents would not clean the panels, so it was necessary to move to chemical cleaners. A strong alkaline-based cleaning compound with no abrasive was chosen because of the success that it had in cleaning similar limestones without damaging the stone itself. It was important to the state historic preservation office that the cleaning process not damage the character of the tool markings on the stone. The alkaline cleaning compound would remove dirt, carbon, and other atmospheric pollutants without eating away at the surface of the stone.

The cleaning procedure consisted of prewetting the area to be cleaned with water, followed by application of the cleaner with a soft-bristled nylon brush. Due to the highly alkaline nature of the chemicals, the use of natural fiber bristle brushes was not suitable. The manufacturer recommends against using high-pressure spraying to apply the cleaner, since the high pressures could force the cleaning chemical into the pores of the stone and make it difficult to remove. The cleaner was allowed to dwell on the surface for 30 min before being rinsed off. A low-pressure water rinse was used to remove the chemicals from the surface of the stone. The low-pressure rinse was used to further prevent driving the chemicals into the stone. After the low-pressure rinse, the surface was again flooded with a high-pressure rinse to remove any remaining diluted chemicals.

To neutralize the pH of any further alkaline chemicals on the masonry, they followed the cleaning chemicals with an afterwash of an organic acid cleaning compound formulated for use with the limestone cleaner. The afterwash was spray applied to the cleaned surface using a low-pressure spray system fitted with a fan tip applicator immediately after the final rinse of the limestone cleaner. It was allowed to dwell on the surface for 3 to 5 min and

then pressure rinsed from the surface. The pressure rinsing was done from the bottom up to ensure that any chemicals would wash onto water-wetted surfaces and would become even more diluted as a result.

This procedure was used on all the limestone with very good results. Figure 17 shows some of the limestone before and after it had been cleaned. It wasn't until workers began cleaning some of the sandstone sills in Building 108 that there was any problem. The manufacturer of the chemicals used to clean the limestone recommended against using the product with sandstone because it would damage the structure of the stone. A different kind of cleaner was used to clean the sandstone parts of the buildings.
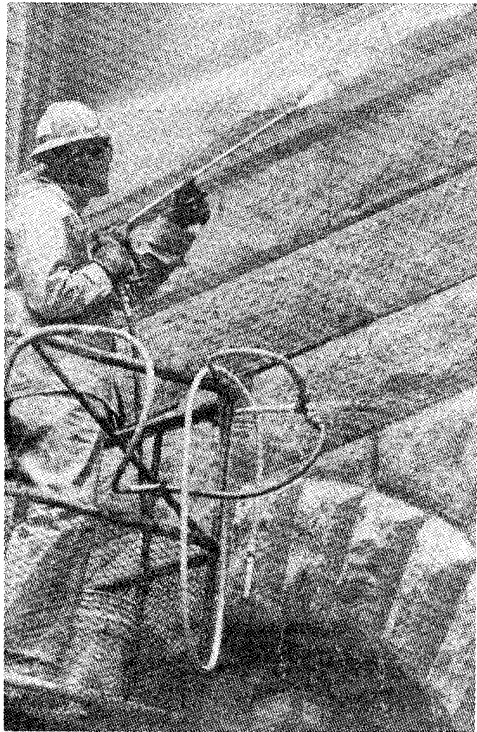
(Photo courtesy of USAED, Rock Island)

Figure 17. Limestone facade during cleaning

The Director, Engineering and Housing (DEH), was insistent that the sandstone be cleaned regardless of the amount of soot and dirt in the stone. The contractor worked with a number of trial chemicals on test panels. All these chemicals were designed to work with sandstone, but all the tests failed to clean the stone. The next request of the DEH was to use sandblasting to clean the sandstone surface. The DEH contacted the Illinois State Historic Preservation Office (SHPO) to determine if this procedure was suitable. Officials from the SHPO would not allow this procedure because the use of abrasive materials would destroy the surface of the stone and would blast away the hand tooling work of the stone along with the dirt. This hand tooling work was considered important to the identity of the stonework of the period and would be lost with abrasive cleaning. The contractor then recommended a low-pressure abrasive water wash. This technique used sand applied under a low-pressure water spray. The SHPO also rejected this approach for the same reasons as mentioned above.

The DEH called together representatives from the Rock Island District, the contractor, the DEH, and the SHPO to find a solution that would allow the cleaning of Building 108 as well as satisfy the requirements of the SHPO to preserve the stonework markings on the sandstone. During this site visit, the contractor applied a number of the potential solutions to 5- by 5-ft test panels for all participants to evaluate the results. All of the potential methods that the contractor tried were rejected either because they didn't remove the dirt or in removing the dirt the process damaged the stone.

A representative of the SHPO suggested that the contractor try a certain chemical not known to the contractor. The SHPO representative had seen this product used on another project and had seen its results. The chemical was a

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heavy-duty restoration cleaner that uses hydrofluoric acid as one of its main active ingredients. This chemical was also used to remove heavy carbon deposits on the MRC Building (case history 2).

The manufacturer describes this product as "...a concentrated compound for cleaning extremely dirty and heavily carbonated masonry typically found in large cities or high pollution areas." They further say that it can be used on brick, granite, sandstone, terra cotta, exposed aggregate, and other masonry products. It has the advantages of being very strong for heavy cleaning action, is effective in cleaning heavily carbon-stained buildings, and is safer than sandblasting because it will not damage masonry surfaces. It has several limitations. It cannot be used on limestone or limestone products since it is a strong acid (pH of 0.5) and it can etch some polished stones or glazed surfaces. It is also recommended that it not be used indoors because of its highly acidic nature. When used out of doors, surrounding surfaces (glass, architectural aluminum, wood, painted surfaces, and foliage) should be protected against wind carried product.

The contractor tested this material on a test section and found it to be effective in removing the pollutants and noninjurious to the sandstone itself. As a result, the SHPO representative approved its use on the sandstone surfaces of the buildings.

In preparation for applying the cleaner, the contractor protected all nearby materials that would be damaged by airborne spray from the cleaner. Plastic sheeting was used where it could be applied and all surrounding limestone was covered. The workers were also required to protect themselves from this strong acid cleaner. They were required to wear full-length rain gear, neoprene gloves, goggles, respirators, and plastic face shields while applying the chemicals to ensure that they would not come in contact with the acids.

The cleaner was delivered to the site in a concentrated form. The manufacturer required that the product be diluted before it was used, stating that use in its concentrated state could cause bleaching of the natural color of the stone. The manufacturer recommended a minimum dilution of 3 parts water to 1 part cleaner, adjusting according to the test panel results. Test panel results showed that the pollution could be removed by diluting the concentrate 4 to 1 with water.

The area to be cleaned was wetted with water as a first step in the cleaning procedure. The diluted cleaning solution was then applied to the sandstone using a low-pressure (50-psi) spray applicator. The chemical was applied from the top down and the area below the sandstone sills was continuously washed with water to dilute the chemical that dripped down from the sill. The manufacturer's literature says that the cleaning solution should stay on the surface for 3 to 5 min, but the intensity of the pollutants required that the chemicals dwell on the surface from 15 to 30 min and sometimes longer. When the cleaner was on the surface for a long period of time, care was taken to prevent the chemicals from drying out. This could have caused a condition

where the chemicals could have bleached the stone due to the increased concentration of the acids as the water evaporated from the solution.

When the dwell time was completed, the chemicals were rinsed from the stone with low-pressure flood rinses. As with the alkaline cleaner for the limestone, the low pressure was used to prevent driving the chemicals into the pores of the stone. The low pressure also minimized the risk of raising the acid from the surface in aerial spray that could contaminate adjacent areas. The rinsing was done from the bottom up to ensure that the chemicals would drop down into well flooded areas thereby further diluting the acids as well as preventing streaking of the surface from contact with the chemical. A second pass at rinsing the surface was made after the initial pass. This pass was made with higher-pressure equipment (1,400 to 1,500 psi) to thoroughly remove any additional chemicals.

There were several areas where one application of the cleaner didn't remove all the pollutants. In these areas, the cleaner was applied and rinsed multiple times until all the soot was removed.

Figure 18 shows the building during the cleaning process. The walls in this figure are cleaned limestone and the sills beneath the windows are the sandstone sills. The sill beneath the window on the left hasn't been cleaned in this figure while the two sills to its right have. The difference is striking.

Performance to date

In a restoration, where cleaning is the main focus of attention, the visual results of the cleaning are the best indicator of the performance. Both the limestone and sandstone have survived the cleaning in good shape. The stone mason's chisel marks have not been damaged by the cleaning, and the graphic results of the cleaning can be seen in the figures in this case history. The mortar joints that were repointed prior to the cleaning are in excellent shape at the time of this writing.

Fort Norfolk

Fort Norfolk is a military complex located at the foot of Front Street on the Elizabeth River in Norfolk, VA. Figure 19 shows an overall view of the historic site. It is currently owned and operated by the U.S. Army Corps of Engineers and is shown to the public by the Norfolk Historical Society.

It was originally constructed about 1810 as a coastal defense fort protecting the Norfolk area. It was occupied by the U.S. Army from its construction through the early 1820's. Due to movement of the task of harbor defense to Forts Monroe and Calhoun at the entrance of Hampton Roads in the early
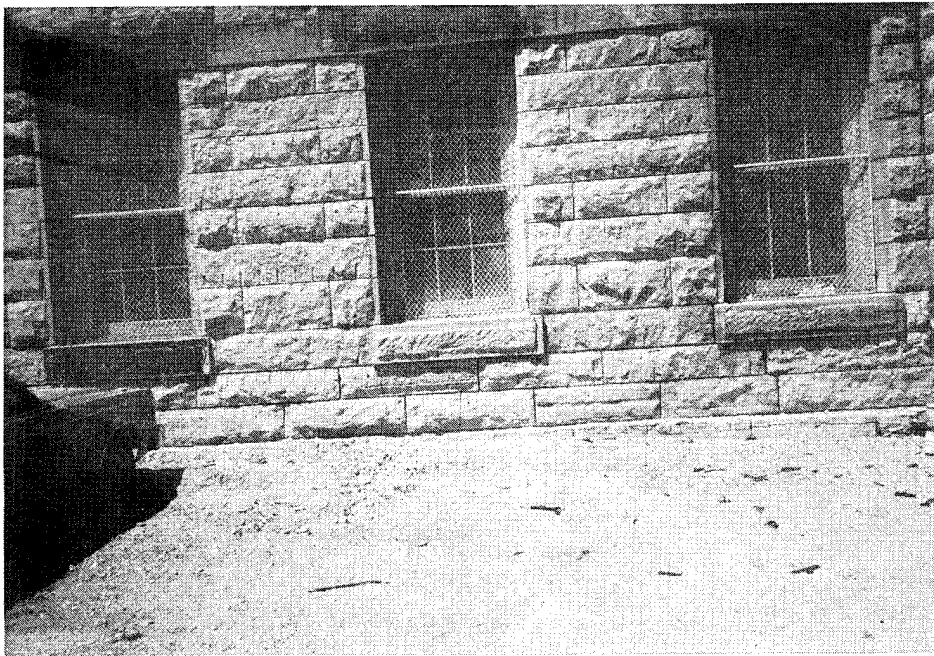
(Photo courtesy of USAED, Rock Island)

Figure 18. Sandstone sills during cleaning

(Photo courtesy, Mr. James Melchor, USAED, Norfolk (Melchor 1992))

Figure 19. Aerial view of Fort Norfolk

1820's, Fort Norfolk was unoccupied until around 1850 when the U.S. Navy converted it into an ammunition depot.

During the Civil War, it was captured by the Confederate Army and used for defensive purposes. The Union Army retook the fort and used it as a hospital until 1863 when they returned it to the U.S. Navy who again used it as an ammunition depot until 1870. In 1923 the fort was given to the U.S. Army Engineer District, Norfolk, for use as its district offices. It is still in their care today.

Structural modifications to the fort were made during the time it was in the care of the U.S. Navy. They added a magazine building in 1855 and a smaller brick workshop later. They also made modifications to several brick buildings to turn them into ordinance assembly and storage buildings during their tenure.

Climatic conditions in the Norfolk area vary from year to year. Generally speaking, winter and spring are the wet seasons and summer and fall are dry. Winter extends from December through March with lows generally in the 40's, however temperatures as low as 18 °F are possible. The season is essentially rainy but the humidity is considered low. Spring runs from March through May with temperatures generally in the 60's. The humidity begins to rise in the spring and it is sometimes a wet season. Summer conditions are moderately hot and humid. The temperatures generally reach 80's and 90's but can get as high as 100 °F. The humidity in the summer generally hovers around 90 percent R.H. The fall climate is dry as is the summer with temperature highs in the 70's and 80's and lows in the 60's. The relative humidity drops in the fall to levels around 50 to 60 percent R.H.

The Norfolk area is on the ocean so there are some droplets of salt water in the air. The salinity in the river is measured at approximately 20 parts per thousand. The amount of salt water in the air depends on the direction of the wind.

In 1991, the Norfolk District entered into an agreement with the Norfolk Historical Society to manage Fort Norfolk and open it to the public. In return the society was allowed to renovate an old brick storehouse on the grounds for use as its headquarters. This case history is developed on the renovations and restoration of the storehouse and will concentrate on the repairs to the brick and stone masonry.

The storehouse was built around 1810 and used by the Army until 1821 (Melchor 1992). The Navy used it between 1850 and 1880. In the early 1920's, the U.S. Army Corps of Engineers made electrical, plumbing, and heating changes to the building, and in 1947 made extensive changes to the exterior and interior of the building. In 1991, the Norfolk Historical Society initiated renovations to the building to restore its exterior to its 1810 appearance.

The changes made by the Navy during its occupancy were predominantly interior modifications or modifications to the roof or wood structure. Minor changes to the masonry were made to install shutter hinges that were used during the period.

Brick or stone masonry modifications made by the Corps of Engineers in the 1920's included addition of an interior chimney and placement of a concrete floor over an earlier brick floor. The Corps modifications made in 1947 were extensive, most of which involved changes to the woodwork. During this time, a porch was added to the storehouse, exterior stairs to the second floor were constructed, and as a result of these modifications, a window on the west facade of the second floor was converted to a door for access to the building from the exterior stairway. Figure 20 shows the storehouse with the porch, stairway, and door. The Corps also placed concrete window sills on four first floor windows, removed the brick chimney previously installed, and modified some interior brick walls to accommodate heating pipe.

(Photo courtesy, Mr. James Melchor, USAED, Norfolk)

Figure 20. Storehouse showing porch during restoration

The modifications to the building done by the Norfolk Historical Society were largely interior and mostly consisted of restoration of the wooden structure. However, they did restore the second floor window that was converted to a door to its condition during the Navy period, closed in a masonry wall opening that had been opened for heat pipes, and pressure washed the exterior of the building to remove numerous coats of flaking paint and whitewash.

Description of the problems

Restoration in this case history was not as much a case of attending to a problem as it was of restoring a brick structure to its original condition. There was deterioration that was discovered as the restoration unfolded, but it was minor and repaired in appropriate fashion.

The major problem addressed in this restoration was to restore the building to its original condition. The first concern was to remove the porch installed by the Corps in the 1947 renovations. This structure was made entirely of wood so removal was simple. However, with the porch removed, the door on the second floor west facade was inappropriate and it was decided to change it back to a window to match the remaining windows on the second floor. These windows were of a construction that existed in 1850 when the U.S. Navy occupied the fort.

The exterior brick walls of the building were in need of protection since the paint and whitewash was peeling and flaking from the bricks. Removal of the paint and whitewash revealed that there was some deterioration of the mortar joints between the bricks. The bricks themselves were in relatively good condition. Those joints that were deteriorated were repointed before the walls were repainted. The last task was the application of the masonry whitewash.

Solutions to the problems

With respect to masonry repair, the first task that was accomplished was the modification of the door opening on the second floor to return it to a window. All door framing material was removed from the masonry opening with care being taken not to damage the bricks in the process. The building was of solid brick construction, built with stretcher bond brickwork, and when the framing material was removed, it left a condition where there were half brick pieces at every other course on both sides of the opening. Before the wall could be repaired, all the half bricks below the window opening had to be removed. All mortar remaining on the existing bricks where half bricks were removed was cleaned out to allow for fresh mortar to replace it.

So that brick work could be built up to the level of the window sill, a number of bricks were needed to match the old brick in material, color, and texture. There were not enough old bricks that could be taken from inconspicuous places in the structure to use old brick for the rehabilitation, so reproduction brick that matched the old had to be found. It is less desirable to use reproduction bricks since they are not of the same material as the original, but there are times when that is the only solution. There are a number of different approaches to this condition which have been documented in the brick repair section of the Tallmadge and Boyer Block case history described elsewhere in this report.

The bricks used to build the storehouse in 1810 were molded clay bricks. They were somewhat larger than new bricks being 8-1/4 in. long by 2-1/4 in. high, by 4-1/4 in. deep, and their color was a pinkish red. The mortar joints in the old construction ranged from 1/2 to 5/8 in. thick. The restoration team went to a local supplier to find brick that matched those from the 1810 period and was successful in finding a reproduction pressed shale brick that matched in size and color for the restoration. The texture of the new brick was a bit smoother than the molded bricks made 180 years earlier.

A compatible mortar mixture was formulated for the new construction. It consisted of 1 part white portland cement, 2 parts lime, and 4 to 5 parts sand. The use of the white portland cement and the lime made a very light-colored, soft mortar which matched the existing mortar very well. The original mortar also had crushed oyster shell in it. The oyster shell was the source of the lime used in the mortar in the original construction. When they made mortar, they crushed shells into tiny pieces and then burned them. This would drive off the carbon dioxide in the shells making the remaining material quicklime or calcium oxide. The process was an incomplete burn of the shell and this left small unburned shell particles in the lime mortar. This technique, though historically interesting, was not used in the repair mortar.

The strength of mortars is an important consideration in restoration work. The composition should be tailored to the project being undertaken. There are a number of trade offs that need to be considered. The use of greater amounts of portland cement in the mortar will increase the strength, density, and impermeability of the mortar (Sodden 1990). This makes for more durable mortar which will have improved bond with the brick, but it also increases shrinkage which will put stresses on the brick. It is desirable to make the strength of the mortar weaker than the brick being used to prevent the bricks from being damaged when there is movement in the structure. If the mortar is strong and the bricks weak, cracking and crushing of the brick will occur under movement of the structure rather than the more desirable crushing of the mortar.

Mortars that use smaller amounts of portland cement are weaker and more ductile. There is also less shrinkage and the hardening rate is slower. These traits reduce the likelihood that the brick will be damaged on structural movement, but at the expense of the durability of the mortar and its protection to the structure. Higher percentages of lime in the mortar also provide for more plasticity as well as aid in retaining the water used in mixing the mortar. Porous brick can draw off water from the mortar and thus reduce the water content of the mixture below what is needed for hydration to continue.

For large areas of self-contained structural repair, the stronger portland-cement mortars can be used with the advantage of obtaining higher durability and moisture protection. For small areas where the replacement mortars will have to interact with older mortars already in place, the use of high-strength mortars will produce hard spots which can cause structural problems (Sodden

1990). In this particular case, the use of soft, lime mortars in an area of small structural repair is the proper approach.

The flaking paint and whitewash was removed after the brickwork had been completed. The restoration team decided to remove the paint and white-wash by using moderate to high-pressure water washing of the exterior of the building. They decided to use no abrasives and no chemicals in the process since they felt that the pressure would be sufficient to remove all the paint and whitewash. This decision would also limit any damage that would be done to the brick from the impact of sand or the absorption of any chemicals into the brick and mortar structure. The washing was done from the top of the struc-ture down to keep the cleaned areas from being overly wetted and to keep paint chip debris from contaminating the cleaned surface.

The use of moderately high water pressure was sufficient to remove all the paint and whitewash from the brick surface. However, they began to realize that the pressure from the washing wand was scoring the surface of the brick and causing damage just from the pressure of the water. They decided that they needed to cut down on the pressure so as not to damage the brick any further. As a result, they reduced the pressure to the point that they were no longer scoring the brick. This left some of the tightly adhered paint and whitewash on the surface of the bricks, but the pressure was still sufficient to remove all the loose paint and whitewash.

The cleaning of the walls revealed that the mortar in the joints was in relatively good condition. Only about 10 percent of the joints were deterio-rated. The deterioration was mainly loose or missing mortar, or mortar that was washed out during the cleaning. The rest of the mortar was in good enough condition that it did not need repair. The deteriorated joints were spread over the entire building and not concentrated in any one location so there was no suspicion that there was any trouble in a particular spot. It was decided that the 10 percent of the joints that were deteriorated would be re-pointed.

Most of the mortar that needed to be removed was washed out during the pressure washing. Wherever cracked mortar was found or mortar that had be-come detached from the brick, it was removed with hand tools. The mortar was removed down to a depth of approximately 1 in. and replaced with the same mortar that was used to convert the second story door back to a window.

The other area of brickwork that had to be renovated was a 1- by 2-ft opening in the end wall of the storehouse that had been cut to allow steam pipes to enter the building (Figure 20.) During the restoration, the steam pipes were removed and the openings closed using the restoration brick and mortar described above.

After the masonry repair was completed, the building was treated with a water-repellent coating. This product is a portland-cement-based material that

helps control water seepage into porous masonry such as brick. It is white in color so it has the added advantage of serving as a whitewash which is the effect that the restorers wanted. The requirements for surface preparation to use this material were a clean masonry surface that has had all grease and other foreign deposits removed. Since the original surface was painted and a water spray was used to remove the old paint, most of the surface preparation was already done.

The coating was applied in two coats to ensure good coverage. The first coat was brushed on to the clean masonry and worked into the pores of the brick to fill small holes. This coat was allowed to dry for at least 6 hr, and the second coat was applied directly over the first.

The coating used in this repair was water based. However, other versions of this material contain mineral spirits as the vehicle and, as such, have the drawback of being combustible and requiring good ventilation for application.

Performance to date

The completed renovation is shown in Figure 21. All renovations are performing well as of this writing. There are no signs of deterioration of the mortar in the joints and the whitewash coat is holding up well. The restoration has returned the building to its appearance in the early 1800's.

The Tallmadge Boyer Building

The Tallmadge and Boyer Block is a masonry and wood-frame building located at 2926 - 2942 Zuni Street, Denver, CO. The building is owned by Tower Development Group, Ltd., and is listed on the National Register of Historic Places. It was designed by Wentzel J. Janisch and J. Edwin Miller in 1891 at the request of its future owners, Charles E. Tallmadge and John C. Boyer.

Tallmadge and Boyer were real estate developers in the Denver area in the late 1880's and, along with other investors, built the Tallmadge and Boyer Block in Highland County, then a suburb of Denver and soon to become a part of North Denver in 1892. The building is a three-story building from the west facade with a basement level that makes it look like a four-story building from the east. It occupies approximately half a block on Zuni Street.

When it was built, the building was a much-heralded focal point of the architecture in the Denver area. In its early days, the building housed a variety of business enterprises. These included a large dry goods store, a popular saloon, a drug store, a bakery, a barber shop, and a jewelry store. The upper floors of the building were used for residences. From 1897 to 1920, the building was the home of the Highland Chief, a local Denver newspaper. From the turn of the century to 1940, the building was owned by a
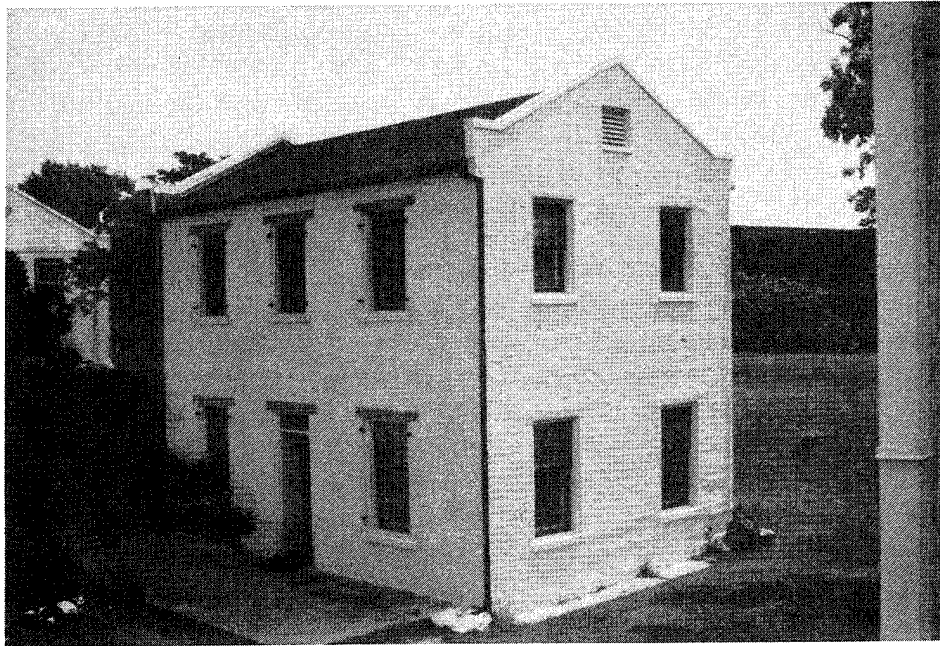
(Photo courtesy, Mr. James Melchor, USAED, Norfolk)

Figure 21. Completed restoration of the storehouse

well-known Denver family, and in the middle years of the 20th century it was claimed by a number of different owners. Over the years the building began to deteriorate from lack of care and was eventually closed in 1981. In 1991, the hundredth anniversary of the year of its construction, the Del Norte Neighborhood Development group, along with several investors and the Denver Housing Authority, financed the renovation of this historic structure.

The climatic conditions in the Denver area are warm summers and cold, dry winters. Summer temperatures extend from June through September with the high temperatures ranging between 80 °F and 90 °F but with occasional temperatures up to 100 °F. July and August are generally the hottest months. There is some humidity in the summer but it is relatively low. Winter conditions are generally present from late October through late March. Winter temperatures are generally in the 30's and 40's during the day and dropping to the teens during the night. Low temperatures can be as cold as -10 °F. Fall and spring are moderate seasons with average temperatures in the 60's and 70's. The rainy seasons in this part of Colorado are generally the spring and early summer with between 10 and 20 in. annual rainfall.

Description of the problems

Before the restoration of the building began, a structural consultant was hired to determine the structural condition of the masonry, steel, and wood.

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Their report indicated a number of problems to the exterior facades as well as the condition of the wood and masonry on the interior of the building.

The west facade of the building, which is the front, is shown in Figure 22. This figure also shows the building in its restored condition. The brick used in this facade is hard pressed red brick. The first floor is dominated by six individual store fronts and an entrance flanked by eight brick columns. Six of these columns extend up to a subcornice between the second and third floors. The columns support steel header beams over the store fronts which in turn support the weight of the brick facade above the first level. At the first level, the brick columns are supported on sandstone pedestals which are supported on stone foundations below ground.

The second and third stories of this facade, Figure 23, are multiwythe, nonbearing brick walls. They are punctuated by 22 window openings on each floor. The brick in the facade of the second and third floors is complemented with sandstone window sills, transom sills, columns, arches, and ornamental stone work beneath the cornice topping the third floor. Figure 24 shows some of the deterioration to these stone features in a photo taken before the 1991 restoration.

The brick columns were generally in good condition. There were some vertical cracks in the brick in some of the columns, and there was distress in the brick at the column-steel beam interconnection over the store fronts. At the second- and third-story levels, the brick appeared to be in good condition. The wall itself has bowed out approximately 3 in. at the center of the wall. The sandstone features of the wall were damaged from freezing and thawing. Observation of Figure 24 shows the sandstone transom sills above the windows on the second and third floor to have been completely weathered through. This occurs on the six windows at the north and south ends of the building. The ornamental sandstone above the third-floor window is also severely damaged. The brick arches over the second- and third-floor windows appear to be in good condition.

The south elevation is the side elevation in Figure 22 that has the soft drink sign painted on it. This elevation and those on the east and north are composed of common red brick as opposed to the hard pressed red brick of the west facade. The wall is a multiwythe wall constructed of softer brick than that of the west wall, presumably because it is not a major architectural facade. The brick was in generally good condition with some minor cracks and no pattern of structural cracking. There were some signs of deterioration of the mortar. This wall also bowed out approximately 3 in. at the center of the wall above the first-floor level. The parapet above the third floor of this wall also showed signs of deterioration due to freezing and thawing and there was some separation of the bricks and sandstone units at the intersection of the south and west walls.

The east wall is a nonbearing, multiwythe wall that is four stories tall due to the exposed basement portion of the wall. The first-story wall is a quartzite

(Photo courtesy, Mr. Michael Bray, Lantz-Boggio Architects, Englewood, CO)

Figure 22. West facade of the Tallmadge Boyer Block

(Photo courtesy, Mr. Michael Bray, Lantz-Boggio Architects, Englewood, CO)

Figure 23. Elevation of the west facade showing architectural details

(Photo courtesy, Mr. Michael Bray, Lantz-Boggio Architects, Englewood, CO)

Figure 24. Deteriorated condition of windows and sills

stone masonry wall that is covered with stucco to the springline of the brick-arch doors at this level. There are 19 doors in this story opening. The stone and stucco at this story were in generally good condition. There was only one location where the stone had softened and the mortar was damaged.

Above the first-story level the wall is brick. There was considerable damage on this facade at the upper levels. There was some brick loss in the area of an incinerator near the center of the wall, and there were crack systems in the wall that indicated structural movement. There is a steel fire escape on this wall that appears to have replaced a wooden stairwell at some time in the past. Mortar loss between the bricks on this wall was extensive. There are some areas of the wall where the mortar was not visible at all and the worst damage was in the area of the incinerator. The wall shows waviness and bowing indicating that there is some wythe separation.

The north wall abuts another building on the block and is separated from that wall by only 6 in. This made inspection of the wall difficult. However, inspection of the wall showed the brick and mortar to be in good condition and not needing repairs.

The exterior foundation walls are quartzite supported on stone footings. These walls appeared to be in good condition. The interior basement walls are brick and had some cracks in them that indicated that there has been foundation settlement over the years. The floor framing of the building is wood planks on 2- by 12-in. wood joists. The joists appeared to be in good condition, and the flooring was rotted in a number of places. On the top floor there was some fire damage to the wood planks.

Description of the solutions

Brick repair. The repairs to the brick of the building included brick replacement and some repointing of the mortar. In instances where the bricks

were cracked, such as the columns of the west facade, they were replaced. These bricks were removed from the wall and replaced with bricks taken from other parts of the building or purchased from local supply. The bricks used for construction of the building in 1892 were somewhat larger than the bricks used today, so to have correct replacement bricks they were taken from areas of the building that are not visible to the public. Several areas of interior walls had to be repaired by replacing the wall with concrete block. In these areas, the brick that was removed was saved and used to repair areas of the facades that were damaged.

The areas to be repaired were first prepared by cutting out the cracked brick and cleaning the remaining bricks of any mortar and broken pieces of brick. Replaced bricks were set in place in a portland cement-lime mortar that matched the existing mortar in color and strength. There were two formulations. On the west facade or the front of the building, the mortar consisted of 1 part portland cement to 2 parts lime. There was very little sand in the mixture and pigments were added to match the color of the existing mortar. On the other facades of the building, white portland cement and lime were used in the same proportions and a buff pigment was used to match the mortar on those facades. The bricks were set in place with their faces flush with the existing masonry and the newly placed mortar joints finished to match existing joints.

In this restoration, the brick was similar to the standard-size brick currently available. However, the texture of the new brick was not similar to that of brick that had weathered for 100 years. Therefore, a decision was made to take replacement bricks from the building itself.

There are a number of standard sources for replacement brick when repairing a masonry surface (Ashurst and Ashurst 1988). Second-hand bricks can sometimes be found to match the original brick in size, texture, and color. This is a preferable method of replacing brick than taking brick from other places in the structure. When selecting second-hand brick, it must be kept in mind that the texture of the brick should match as well as its size and color. If the brick in the building should have a weathered appearance, it is important to try to find a replacement that will have such an appearance.

Reversing bricks is another method of improving the appearance of a facade. If the bricks in the structure are weathered to a point that they may need replacing, it is possible to cut them out and reverse them so that the formerly hidden surface of the brick is now exposed and the deteriorated exposed surface now bedded in mortar. This is particularly useful if the brick is not cracked through or the surface is only deteriorated on one face. It is important to realize that the source of the deterioration to the brick should be identified and stopped before resorting to this type of repair. If the deteriorating condition is allowed to continue then the good surface of the brick will begin to deteriorate as well.

With both second-hand brick and reversing brick, the supply of material may be scarce. A method of extending the quantity of bricks that match those existing in size, color, and texture is to bed slips or facings of the matching brick. This amounts to cutting the existing bricks into thin sections that when set into mortar appear to be an entire brick. This should only be done if the repair is to a small area of brick and to areas where single bricks are to be repaired. This is not a structural replacement since the bedded slip of the brick is much weaker than the entire brick. Large expanses of replacement using this technique could cause serious structural problems.

Making new bricks to match the existing brick is another source of material for brick repair. This technique requires that there be local sources that are qualified to make brick. Since the brick to be matched often is of nonstandard size, most of the bricks will be made by hand and will be an expensive alternative to finding suitable existing brick for the repair.

Using the building itself as the source of brick is the least attractive alternative and should be used only when other methods are not available or out of the economic range. By scavenging other areas of a building to obtain brick for a given area, the building is potentially further damaged. Appropriate sources of brick from this category could come from building areas that had to be demolished in the restoration, or from nonstructural areas that are not visible. For example, in the Tallmadge Boyer Building bricks were taken from a portion of parapet wall that was being taken down as part of the restoration. Structural brick should not be taken without proper consideration for the effect of such an action.

There were cracked and deteriorated bull-nose bricks in all of the columns on the west facade that had to be replaced. These bricks were not available from local supply and there were no rounded bricks from elsewhere in the building to use as substitutes. These bricks had to be hand fashioned by grinding the appropriate edges of existing bricks to produce a 1-in. radius bull-nose brick.

Concrete-block wall repairs. A number of the existing brick walls were strengthened by backing them with concrete-block walls. Particularly those walls that were bowing and were in danger of moving farther out of their original plane. The brick walls were attached to the new block walls by drilling holes in the back side of the brick and securing masonry anchors into these holes with epoxy as seen in the sketch in Figure 25. The masonry anchors were then tied into the bed courses of the block wall as the wall was built. No attempt was made to try to pull the brick walls back into plane because this would likely cause more stress to be put on the brick. The purpose of this procedure was to strengthen the brick wall and keep it from getting further out of plane.

Sandstone repair. The sandstone in the building was largely ornamental and located on the west facade. It consisted of window sills, transom beams, column pedestals, and intermittent column bands, as well as ornamental frieze
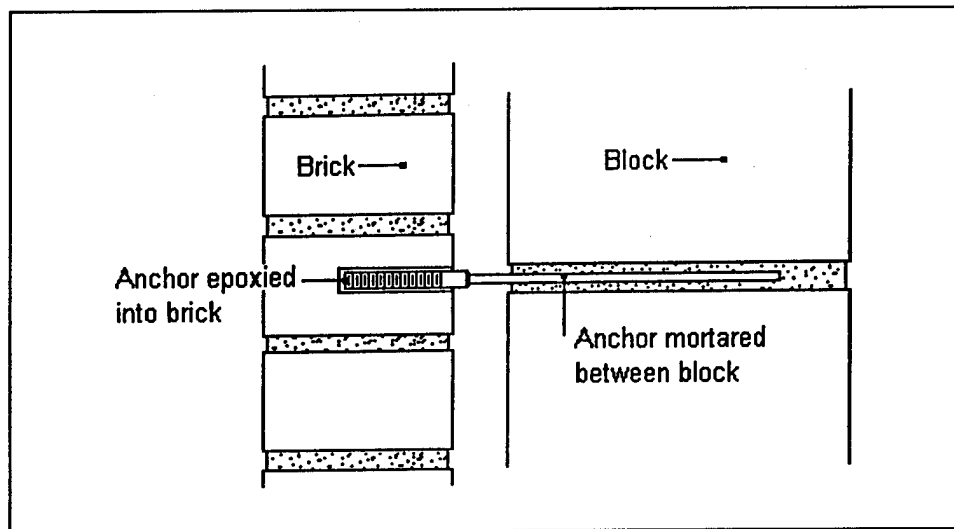
Figure 25. Sketch of anchor detail used to strengthen brick walls

and arch decoration. The scope of the restoration did not allow the complete restoration of the sandstone used in the building. Rather, the level of effort was confined to preventing further damage to all the sandstone and replacing those elements that were damaged beyond repair and essential to the building's renovated use as moderate income housing. As seen in Figure 24, the damage to the sandstone was extensive in some cases. In this figure, three of the sandstone transom sills above the windows on the second and third floors are completely missing, and the carved sandstone ornamental arch over the third-floor window brick arch is badly damaged.

The sandstone in extreme need of repair was replaced with concrete that was formulated to look like the sandstone. To achieve this effect, the remains of the transom sills were cut out of the brick masonry and a concrete transom sill the same dimensions as the original sandstone sill was fabricated. When it had cured, the replacement sill was inserted in place of the removed sandstone. The concrete was a conventional design that used both grey and white portland cement as well as orange and red pigments to match the color of the original sandstone.

The sandstone elements that did not need to be replaced were first shaped so that they would shed water. Over the years, some of the sandstone had deteriorated such that pools of water collected in horizontal depressions in the stone. The stone was chiseled so that it would drain the water, Figure 26, or the depressed area was built up so that water would not collect in it. A method of building up stone surfaces that was developed by the New York Landmark Conservancy was used in repairing these surfaces. The New York Landmark Conservancy recognized in the 1970's that many sandstone structures were in a bad state of repair and there was no suitable available source of new sandstone. They undertook a study of sandstone repair techniques and produced a technical brief condensing the study's findings. The technical

brief (Lynch and Higgins 1982) identifies the composition of sandstone, looks at the decay process, provides techniques for maintenance and preservation of the material, and gives techniques for repairing damaged stone.

The technique used in this repair program was composite patching. Composite patching is a method of building up the surface of a stone through multiple coats of a sand and cement mixture. The purpose of most of the repair was to build up the surface so that the finished pieces of sandstone would shed water. That meant that the repairs would be no deeper than about 2 in. in most places. This technique was an ideal solution for the job. Lynch and Higgins (1982) describe the technique as follows.

(Photo courtesy, Michael Bray, Lantz-Boggio Architects, Englewood, CO)

Figure 26. Sandstone sill chiseled to drain water

"Three types of stone deterioration warrant composite patching: weathering, exfoliation, and blistering. Composite patching may also be used with mechanical repair techniques. When executing a composite patch, care must be exercised in matching the appearance of the old stone, and in mixing, applying and finishing the repair material.

The proper repair mixture consists of a cement-like binder, crushed stone-sand aggregate, and small amounts of dry oxide pigments as necessary. These ingredients are combined dry and then mixed with water containing a small amount of an acrylic latex admixture. Correct mixing and measuring is essential, and proportions are by volume."

Composite patching procedure.

a. Cut away all loose and crumbling stone with a tooth chisel, leaving a rough surface.

b. Undercut the edges of repair areas to a slight dovetail. Drill 1/2-in. diameter holes 1/2 in. deep, at varied angles, spaced 2 to 3 in. apart in staggered rows.

c. Wash area thoroughly with water and bristle brushes to remove all dust and stone fragments.

d. Apply a thin slurry coat followed by several scratch coats to form a base for the colored finish coat. Press scratch coat into the slurry while still moist, and wet each scratch coat before applying the next one. Allow 2 to 4 hr for each scratch coat to cure before applying next coat. No scratch coat should exceed 3/8 in. in thickness. Use wood screeds set in adjacent mortar joints to prevent repairs from extending continuously between separate blocks of stone. Continuous patches can crack and fail if the individual stones behind them move.

e. Apply finish coat, mixed as described in the figure.

f. Finish repair surface to match stone.

Applying the repair stone is not the only consideration. Matching the color and the surface texture of the patch are also important considerations. If a patch doesn't match the color of the original stone, it will look like a poor patch. The color of the patch should be formulated using sands, cements, and pigments that when mixed will harden and dry to look like the original sandstone. If the stone is to be cleaned before the patch is to be installed, then the patch should be formulated to match the cleaned stone. If cleaning is not a part of the process, then the surface is likely to be mottled and it will be difficult to choose the color of the patch. The patch should be colored to blend in with the most dominant hue in the original stone. This color determination should be made by viewing the original stone at a distance of at least 5 ft from the surface and in indirect, natural light.

A test patch should be made before any patch is put on the sandstone. Mix the appropriate amounts of cement, lime, sand, and pigments keeping in mind the color that is desired. Make a sample patch in a 3-in.-diam pie pan. Allow the test patch to cure for at least 48 hr. If the sandstone and patched area will be treated after the patch hardens, treat one-half of the test patch with the material that will be used to treat the stone. And when this has dried, compare the treated and untreated test patch to the original material.

A further consideration for matching patch to original stone is the surface texture of the patch. Even with good color matching the patch will look different from the original stone if its texture is not the same as that of the stone. Since sandstone consists of grains of sand cemented together with natural cements, the best way to get the texture of the patch to mimic the natural stone is to expose the sand grains in the patch. This is accomplished by removing a thin layer of cement from the surface of the patch. Acid etching of the surface is the best method of doing this. It eats away some of the cement in the surface of the patch and does not harm the sand. After the patch material has set for 48 hr, the surface of the patch is brushed with a 1 part acid to 5 parts water dilution of reagent-grade hydrochloric acid. This

solution is allowed to dwell on the surface for 3 to 5 min and then washed with sufficient tap water to neutralize any remaining acid.

There are several areas of concern when using acid to etch the cement from the surface. First, one should not let the acid etch the surface too long because this will take out too much cement and will expose larger particles of sand and aggregate. The surface will then lose the exposed sand grain look and become pebbly. Further, use of acid will darken the etched surface if the acid is left on for an extended period of time. Also repeated treatments of acid will also darken the surface. Careless use of the hydrochloric acid can cause damage to surrounding materials, especially mortar, limestone, and lime containing sandstone. Streaking is sometimes caused by acid draining away from the area being treated when it is not diluted sufficiently.

Other methods of surface finishing that can be used to make the patch look more like the parent sandstone include abrading the surface of the patch with coarse and fine-grade rubbing stones (No. 60 through No. 120 grits). These abrade the cement thus exposing the sand grains. Stippling with a damp sponge or dry troweling with a wooden float when the repair patch has cured to the hardness of leather will also provide a textured surface similar to the original sandstone. Additionally, tool marks can be put into the patch to make the patch look like the original stone. This can be done by scoring a partially cured patch to simulate the stone marks or by actually chiseling the surface of a hardened repair with stone tools.

On the Tallmadge Boyer Building, when the sandstone patches and the replacement concrete had been prepared and put into place, the stone surfaces were treated with a siloxane to retard the entrance moisture that could further allow damage to the stone by freezing and thawing. Details of this type of restoration preparation can be found in the case study of the Mississippi River Commission Building elsewhere in this text.

Foundation stone repair. The foundation stone was in good shape for the most part. The most significant repair that was needed was repointing of the mortar in several locations on the east facade. The masonry contractor used a standard portland cement-lime mortar to do the repointing to this stone. It consisted of 2 parts portland cement to 1 part lime and a 1:3 cement to sand ratio. The use of a relatively strong portland-cement mortar here was acceptable because of the high strength of the stone. The joints were raked to a 3/4-in. depth before the mortar was replaced in the joints. The mortar was tamped into the joints in two layers and tooled to match the old mortar markings.

Performance to date

At the publication of this report, the restoration and repair to the Tallmadge Boyer Block is performing as planned. The bricks that replaced cracked bricks are showing no signs of cracking themselves. The walls that

were reinforced by being attached to block walls built behind the brick walls have stopped their out-of-plane movement. The concrete sills that replaced sandstone continue to match the sandstone materials in color and are showing no signs of weathering. The patches to the sandstone are holding up well, and there are no more depressions to collect water. The repointed mortar joints appear to be performing well.

Berkshire Place

Berkshire Place is a 7-year old eight-story office complex and multifloor parking garage located in the northern section of Dallas, TX, at the intersection of Pearson Road and Northwest Highway. The building is a steel frame structure with an exterior skin consisting of a combination plaster board and precast-concrete cladding panels. The cladding panels are further covered with two types of decorative coatings. A smooth, white, exterior paint was used for the cladding panels which cover the steel columns, and stucco was used to cover the cladding panels between the columns. The building is shown in Figure 27.

The climatic conditions in the Dallas area are hot humid summers and moderately cold wet winters. Summer temperatures extend from June through September with the average high temperatures ranging between 85 °F and 100 °F. Higher temperatures, up to 105 °F, are occasionally observed. July and August are generally the hottest months. Due to its open terrain, Dallas is often subjected to windy conditions with low humidity during this period. Winter conditions are generally present from late November through mid-February. Winter temperatures are generally in the 40's but can get as cold as 10 to 15 °F. Fall and spring are moderate seasons with average temperatures in the 60's and 70's. The rainy seasons in this part of Texas are generally the spring and fall with between 20 and 50 in. of rain a typical annual amount.

Statement of the problems

Within months of completion of the building, two cracking problems became evident in the cladding panels of the building. The more serious of the two conditions was a structural cracking of the panels. This problem manifested itself in the form of cracks that extended vertically through the cladding panels and aligned themselves from floor to floor to indicate a structural problem. Figures 28 and 29 show several of the cracks in the panels. As shown in the figures, some of the cracks lined up from floor to floor of the building and others originated at reentrant corners in the panels. The movement of the building frame was suspected as the cause of this cracking problem.

Figure 27. Site view of Berkshire Place

The other type of cracking that was observed is shown in Figure 30. This form of cracking was more random, did not always extend across the entire width of the panels and manifest crack widths that were generally small. It was diagnosed as shrinkage cracking of the stucco coating on the cladding panels. The cracks formed when the cement paste in the stucco coating shrank as moisture was lost by evaporation. The shrinkage caused tensile strains in the paste which were greater than the tensile strain capacity of the paste. Even though these cracks were small, they were highly visible and presented a maintenance problem in the building. The cracks shown in Figure 30 are not as wide as the photo makes them look. These cracks have been prepared for repair and are now wider than they were naturally.

Solution to the problems

The Berkshire Place building is comprised of retail shops on the ground floor, a five-story parking garage above ground, and is topped with expensive executive suites on the top three floors. The tenants complained that the cracks in the building were unsightly and they needed to be fixed even though they caused no structural problems.

The engineering firm that was hired to evaluate the structure and provide a solution noted that much of the cracking was a function of problems with building expansion. There were expansion cracks and movement cracks on panels on all sides of the building. They found that the building had been built without planning for expansion joints between panels. Therefore, when
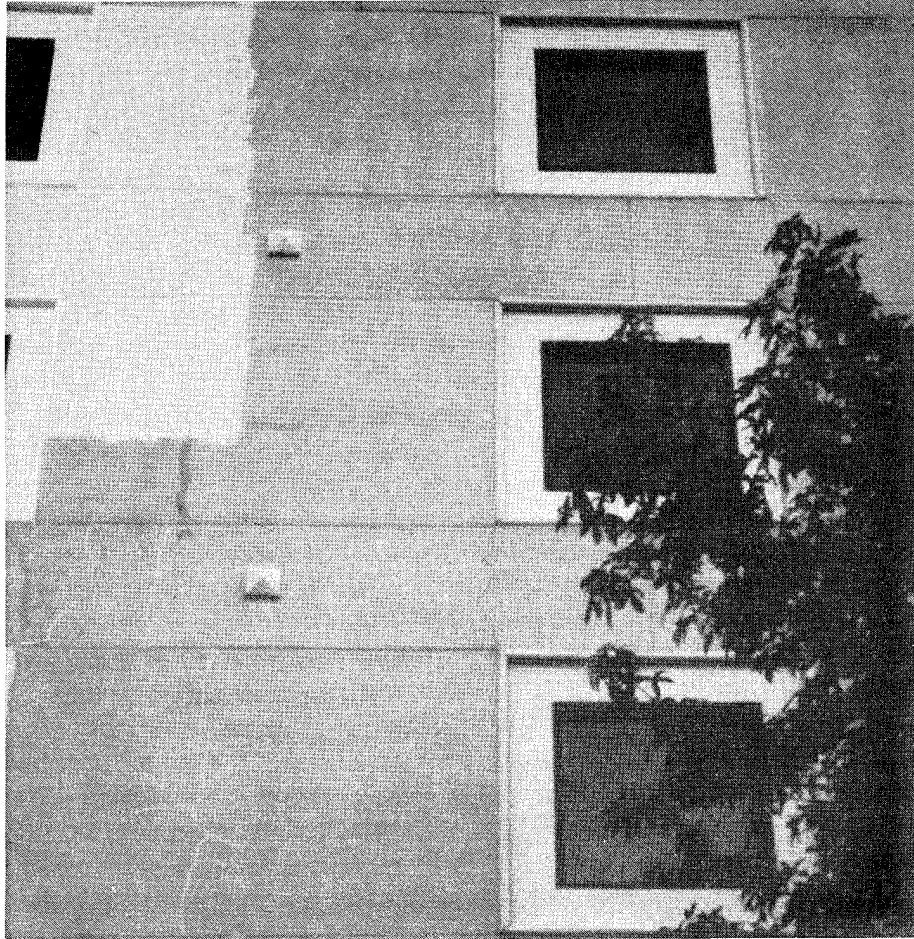
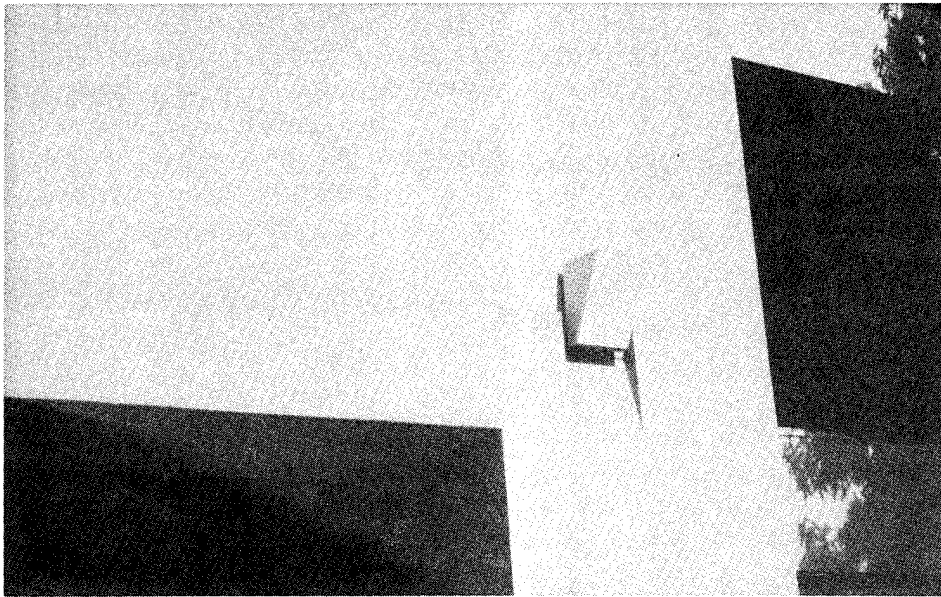Figure 28. Vertical cracks in panels at left of window
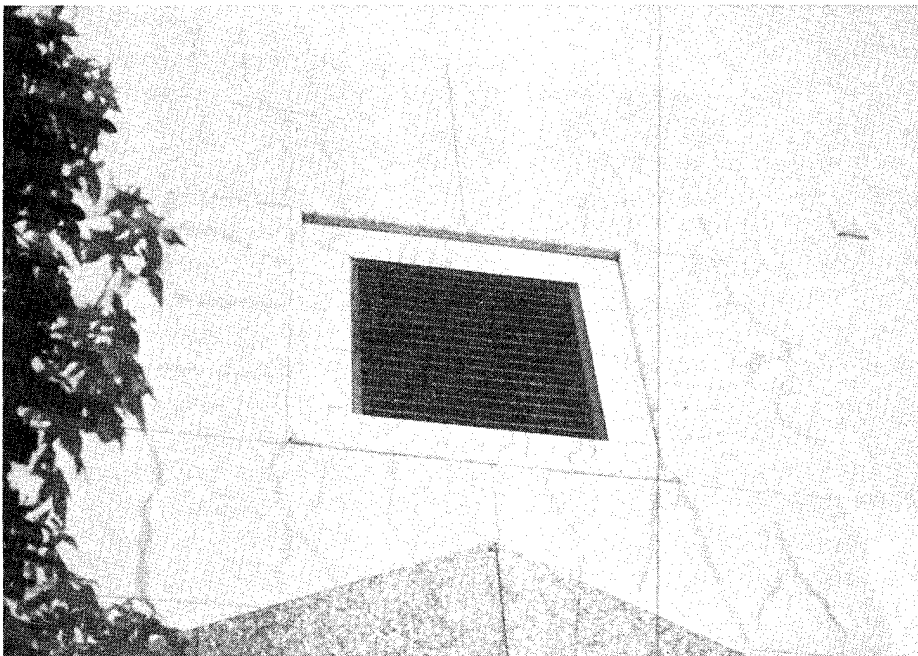
Figure 29. Cracking in panel at a corner

Figure 30. Shrinkage cracking in panels

the building experienced differential temperature change, the panels, which were tightly fixed to the structure, strained more than the steel and cracked.

The engineers decided that two actions were necessary to repair the situation. Firstly, the cladding panels had to have some sort of expansion joint design retrofitted into the walls; second, a method must be provided to cover the cracks in the stucco and paint.

The solution to solving the expansion joint problem was to cut through the panels from the ground floor up to the top floor at approximately 40-ft horizontal intervals. This would allow the panels to move as the building moved without further damaging the concrete. The expansion joints were sawed through each panel in as straight a vertical direction as possible. Whenever the joint would intersect a window, the joint was sawed around the window and then continued up the wall. When the sawing of the joints was completed, they were filled with a two-component polyurethane joint sealant.

The existing cracks in the panels had to be sealed and then covered in some fashion. Patching these cracks and then applying a new coat of stucco would hide the cracks until the panels expanded under thermal load. Additionally, there was no certain way of knowing that the added expansion joints would prevent all of the cracks from opening again. If the cracks opened, they would propagate through the new stucco coating and again be visible on the panel surface.

The engineers decided they needed a coating that would be flexible enough to stretch without cracking or breaking if there was any additional movement of the cracks. They chose an elastomeric acrylic coating that could be applied to be as smooth as paint or mixed with sand to give the appearance of stucco. The coating used depended upon the size of the crack being covered and the location of the crack in the building. All the exterior columns of the building had been painted with a smooth paint and did not require a stucco-like appearance. Figure 31 shows one of the columns with the smooth coat of paint and numerous cracks in the cladding panel. These surfaces were coated with the smooth elastomeric coating tinted to match the original color of the column. All the precast panels between the columns that were originally coated with the stucco were coated with the elastomeric acrylic coating that contained sand particles to simulate a stucco surface.

Repairs to the precast panels

Before any repair work was initiated, the building was washed with high pressure water. The water washing cleaned the surface of any dirt or oil based materials that had accumulated over the 7 years since the building had been built. This was necessary because the elastomeric coating would not properly adhere to dirty and oily surfaces. The power washing also stripped any loose paint from the surface of the panels and columns. The water was
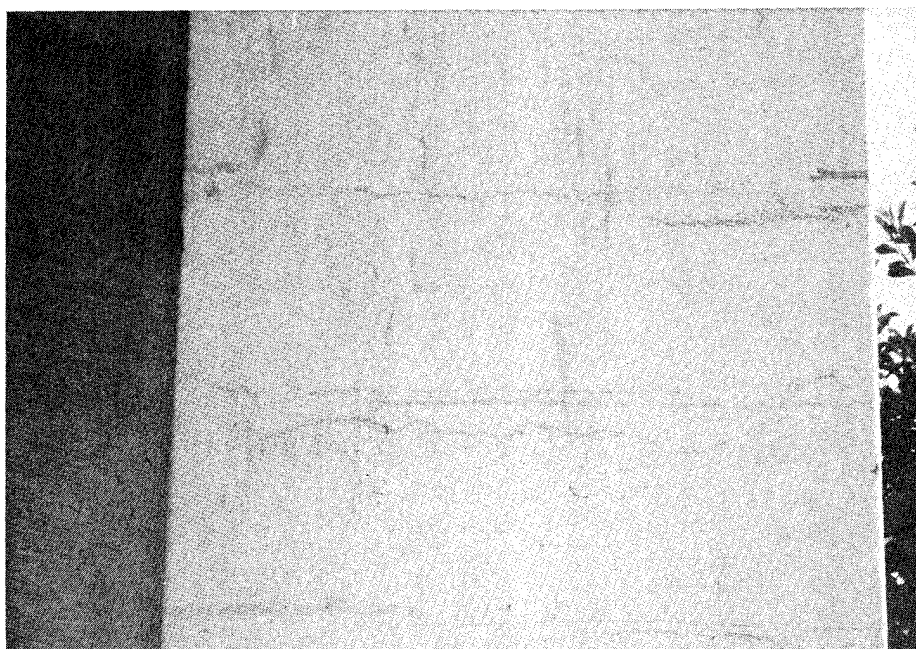
Figure 31. Cracked column panel showing smooth panel coating

delivered at approximately 1,100 psi from a wand with a fan nozzle. With the building cleaned and the loose paint removed, it was ready to be repaired.

The cracks in the panels had to be prepared before the surface could be coated. The material used to fill the cracks depended upon the size of the crack. For hairline cracks less than 1/8 in., the opening was filled with a flexible, nonsag, acrylic-dispersion-based crack filler. Cracks that were 1/8 to 1/4 in. were filled with a waterproof, modified-acrylic-emulsion filler. Those cracks that were greater than 1/4 in. were routed out to a depth of 1/8 in., cleaned of any debris left in the cracks, and filled with a polymer modified, cement-based crack filler. The fillers were allowed to dry for 3 hr before any further work was done on the repair (Figure 30).

The method of applying the different elastomeric acrylic coatings depended upon the type of surface texture that was desired. In those areas where the coating was to be smooth and to be applied over an old smooth surface, the coating used was a high-flexibility, acrylic-polymer coating that was tinted to match the color of the building. The old smooth surface had been cleaned and all loose paint removed by the power washing. The smooth coating was then rolled on with conventional paint rollers and supplemented in difficult-to-reach areas by brush application. The first coat was allowed to dry for a period ranging from between 1 to 4 hr, depending upon ambient drying conditions. The first coat was followed by a second coat once the first had dried. Figure 32 shows this type of coating on one of the column panels. This provided a water-resistant, vapor permeable elastomeric coating.
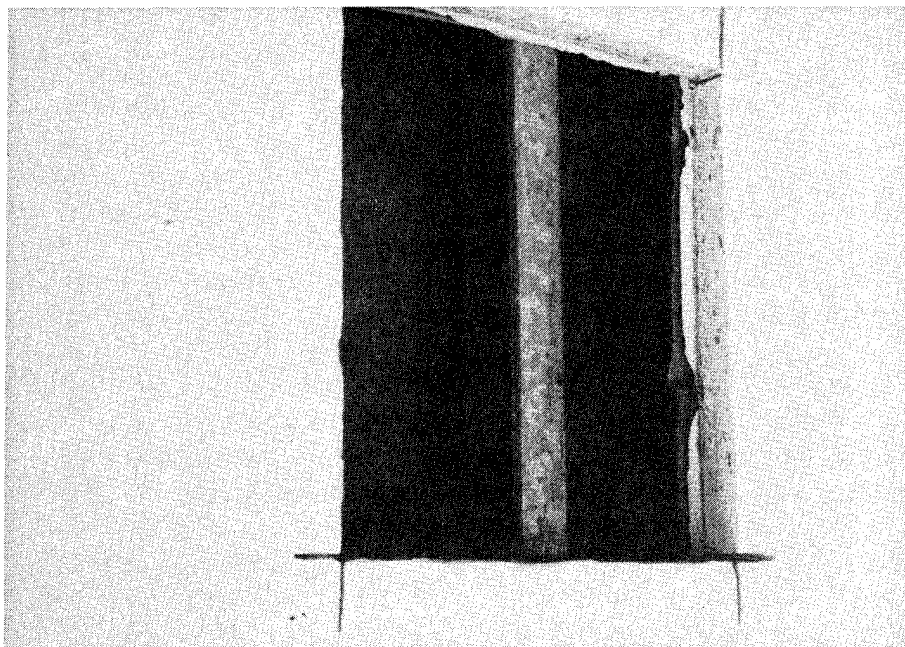
Figure 32. Smooth elastomeric coating applied on column panel

The stucco-like elastomeric coating was applied in a three-step process. After all cracks in the panel were patched, the first coating was trowelled over the surface of the panel. This coating consisted of a flexible acrylic dispersion-based coat that was trowelled on in a thickness of approximately 1/32 in. Figure 33 shows a worker applying this coating to the old stucco surface of the building. This coating has a working time of approximately 30 min before it sets. Within this 30-min period, the next step must be accomplished. The second step consists of embedding a flexible polyester mesh into the still wet dispersion-based coat. The mesh is thinner than the 1/32 in. of the dispersion coat so when it is trowelled into place it will embed completely in the base coat. The openings in the mesh are approximately 1/16 by 1/16 in. The mesh is cut to the appropriate size, laid over the base coat, and then trowelled into the wet material. Figure 34 shows this mesh being trowelled into place. The base coat with mesh is then allowed to cure for 24 hr. Because these coatings are acrylic, they dissolve in water. If it is expected that the coating will be exposed to rain within the 3 hr after it is placed, it is recommended by the manufacturer that the placement be delayed until the threat of rain has passed.

The final coating is the stucco-like coat. This coating is the same as the high-flexibility acrylic polymer coating with the addition of sand particles to the mixture. When trowelled onto the surface, this material simulates the cement stucco finish of the original building. It is also trowelled on in a 1/32-in.-thick coating. Figure 35 shows a corner detail in which the finished top coat is at the top of the figure and the base coat with the mesh is shown at the bottom.
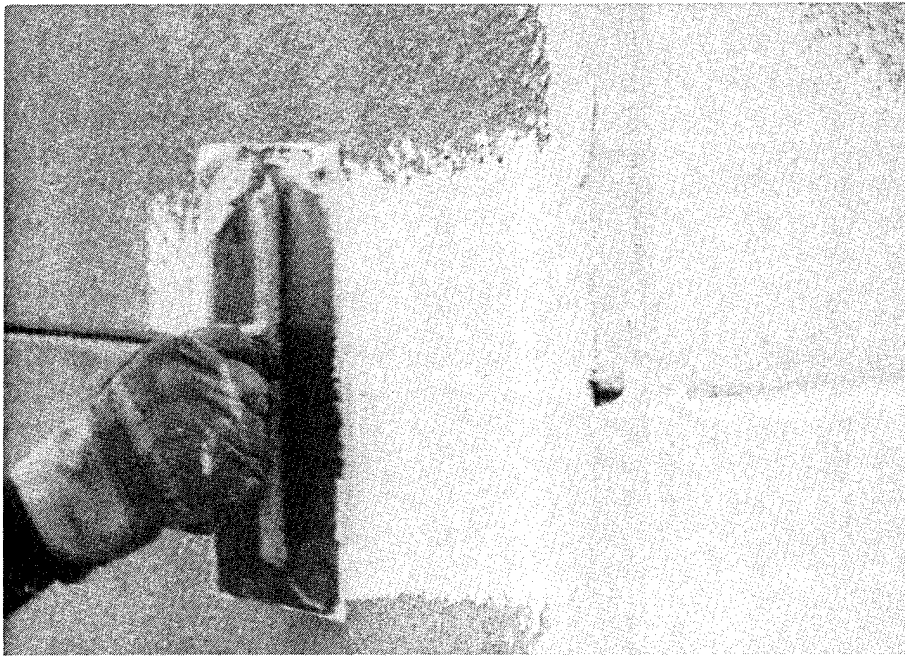
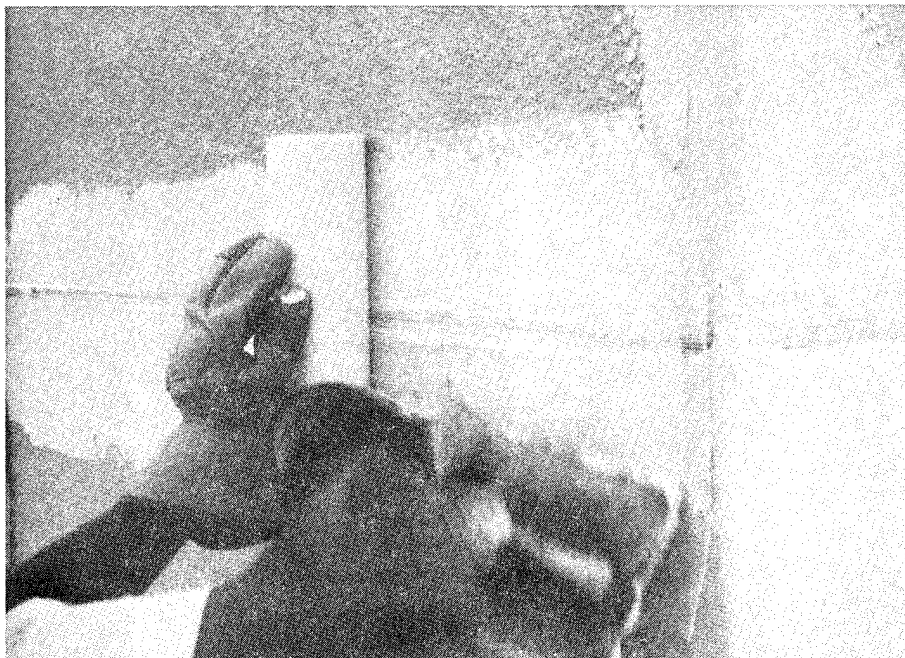Figure 33. Application of the elastomeric base coat

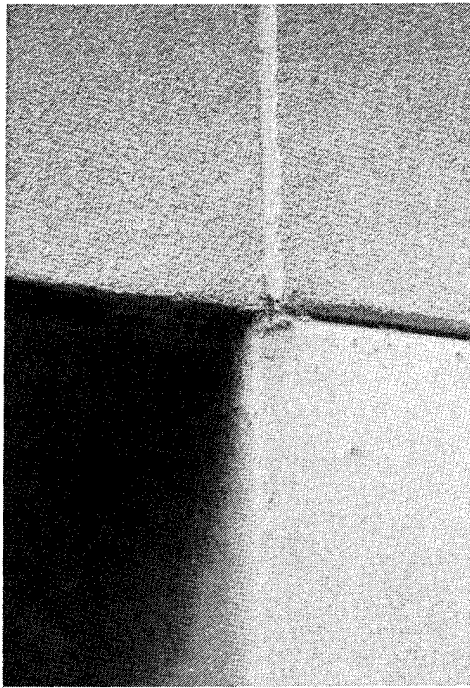Figure 34. Trowelling of the mesh into place

Repairs to the window frames

The cracked precast window frames in this project required a special repair. The frames sometimes had cracks of significant depth. After the cracks were filled the smooth elastomeric coating was rolled over the concrete surface, there was fear that the cracks would still show when a shadow fell across the crack. For aesthetic reasons, it was decided to repair the window frames with the flexible acrylic dispersion-based coat and the polyester mesh and then cover over that with the smooth high-flexibility acrylic polymer coating.

This procedure was very similar to the application of the base coat and mesh used on the precast panels. The surfaces of the window panels were first cleaned and filled. The flexible polyester mesh was then trowelled into the wet base coat and allowed to dry. The drying time was 1 to 3 hr to set and 24 hr before finish coat application. The acrylic coating could be applied to the base coat with a roller and in tight spaces by brush. This coating provided a highly elastic coating that would bridge the cracks as well as resist penetration of water. The application time was approximately 45 min and because this coating was applied over the base in a smooth coating, the drying time was short, from 1 to 4 hr. This provided a smooth level surface which would avoid any shadows. Figure 30 shows a cracked window frame prepared for the mesh and coating, while Figure 36 shows the final condition of the windows after repair.

Figure 35. Contrast between base coat and finish coat

Performance to date

Work on the Berkshire Place Complex was completed in the summer of 1992. The elastomeric coatings over the existing cracks have performed well. One exception to this condition was demonstrated during the Winter when a large temperature drop was experienced and vertical cracks opened up where a control joint should have been cut. When control joints were originally cut, economics played a part in the number of joints that were made. The extreme drop in temperature showed the engineers where the precast panels had cracked and where additional control joints needed to be placed. These additional joints were made and a new layer of elastomeric coating material placed over the joints. Since that time the overall appearance of the building has been without flaw and as a result of the coating, there has been no water leakage into the building.

One potential drawback with using an elastomeric coating to hide cracking is that the coating will not only hide old cracks but will also hide new cracks

that could indicate further problems. In this case history, the concrete that was being coated was not structural concrete. However, if a flexible coating is used to cover cracks in a structural member, any new cracks that form will also be hidden which will hide warning signs of further structural damage.

Fort Sam Houston - Gift Chapel

Fort Sam Houston, located in the center of San Antonio, TX, is the headquarters of the Fifth U.S. Army and, for many years, has been the home to Brooke Army Medical Center. The army first conducted operations in the San Antonio area in 1845 only 9 years after the siege

Figure 36. Repaired window frames

of the Alamo. Among its first missions was the task of quartermaster for the army in the area. Construction of the fort began in 1870 with 92 acres of land donated by the city of San Antonio. Additional land has been added to the facility over the years, and the post was designated Fort Sam Houston in 1890.

The fort contains many of the historic landmarks in the San Antonio area. It claims the largest number of historically significant buildings in the United States, nine times more historic structures than Colonial Williamsburg. Among these buildings are the Quadrangle building built in 1876 as a quartermaster supply depot to house Army materiel then being stored in the Alamo; the Staff Post buildings, built in 1881 to house the general officer staff of the post; and the Gift Chapel, built in 1909 to serve the religious needs of the soldiers assigned to the post.

The climate in the San Antonio area is typical of South Texas with hot, dry summers and mild winters. The mean annual temperature is near 70 °F. Summer temperatures extend from June through September. July and August are generally the hottest months with the high temperatures ranging up to 105 °F. Winter conditions are mild and generally present from late November through mid-February. Winter temperatures are generally in the 50's but can get down into the 30's. Fall and spring are moderate seasons with average temperatures in the 60's and 70's. The rainy seasons in this part of Texas are generally the winter and spring with between 30 and 40 in. of rain a typical amount of annual rainfall.

Description of the building

This case history concerns the Gift Chapel. The Gift Chapel is an interdenominational church constructed on land donated to the Army by the City of San Antonio. As its name implies, it was constructed with funds donated by local inhabitants and military personnel from the fort. It was the first permanent religious institution built expressly for servicemen and their families at Fort Sam Houston. It was completed during the summer of 1909 and dedicated by president William Howard Taft on October 17, 1909.

The building faces south on Wilson Street within the confines of the fort. It is a brick and concrete structure built in the Beaux Arts Classical style that was popular in the area during the early 1900's. Its south facing facade is shown in Figure 37. The soils beneath the building were sampled from boring and are dense, tan, sandy gavels with clay fines to depths of up to 16 ft. Beneath this layer is a massive layer of very dense to very stiff, tan, silty clay to depths of 58 ft. The deepest layer explored is a very dense, gray, clay shale beginning at a depth of 73 ft and extending down to at least 80 ft.
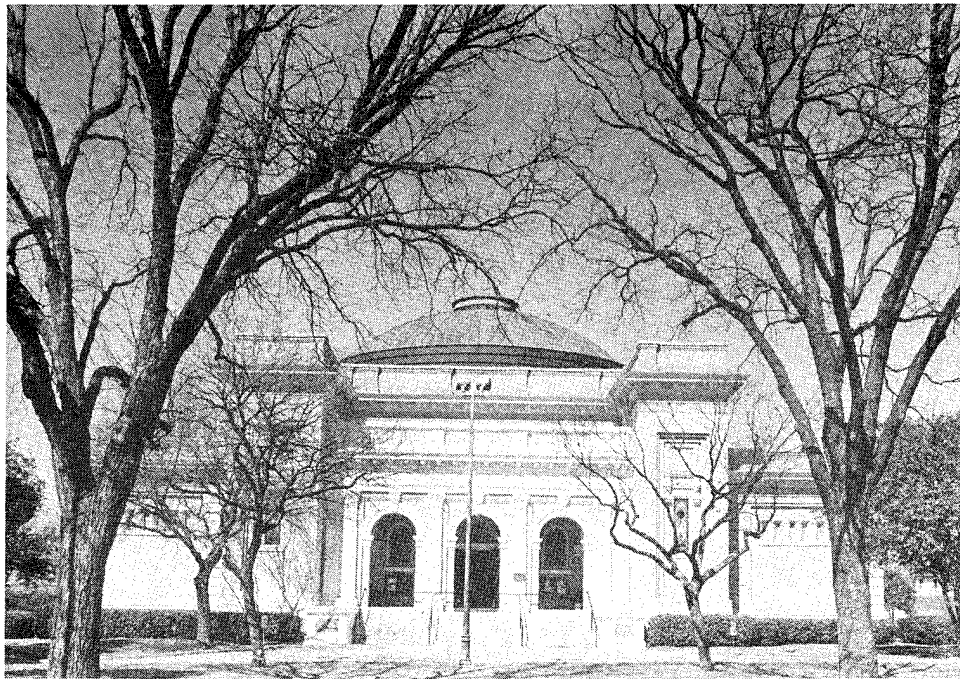
(Photo courtesy, Library of Congress)

Figure 37. South facade of Gift Chapel

The building is founded on a brick and concrete foundation with limestone blocks at the basement wall level. The central portion of the building is square in plan with load-bearing brick walls extending up two stories. This is the Protestant chapel. Flanking the Protestant chapel on its east and west

sides are single-story rectangular chapels also of load-bearing brick. The east chapel is a Jewish chapel, and the west chapel is Catholic.

The foundation footings beneath the walls are strip footings extending down 5 ft below basement level. Within the central Protestant chapel there are four massive columns which are the main supports for the trusses that support the central dome of the chapel. These columns bear on their own spread footings and extend up to the top of the second-story walls of the central portion of the chapel. The circular dome covers the entire central portion of the building and is supported on the four columns as well as at 12 additional points on the load-bearing walls of the central chapel.

The facades of the building are constructed of a buff-colored brick set in stretcher bond and, in some places, common bond. The south facade contains the main entrance to the chapel. It consists of three arched entrances with decorative keystones in the arches and separated by Corinthian pilasters. A renaissance balustrade defines the balcony above the entrance and the remainder of the south facade is brick with carved terra-cotta panels. The south facing walls of the east and west wings are solid with decorative brickwork as well. The east and west facades have six stained glass windows and the remainder of the walls at the first-floor level are brick (Figure 38). These wings are one story, have flat roofs, and are bordered by brick parapets. The east and west walls of the central chapel above the flat roof of the east and west wings each contain three arch windows. The north face originally had windows in its facade, however they were bricked up when a mechanical room was added to the building in 1961. The mechanical room housed heating and cooling equipment and the room was constructed directly against the original north wall.

Description of the problems

This case study is not only a restoration study, but also a structural study. The original reason for the restoration was to alleviate a problem of cracking in the east and west walls of the central chapel. Cracks in ceiling plaster over one of the wing chapels was the first reason to conduct a survey of the entire building. The building survey showed up a number of other cracks in the walls and the brickwork on the outside of the building. The major cracks were apparent in the east and west walls of the central chapel over the center of the most northern arch windows (Figure 39). The cracks were narrow at their base and became wider as they progressed up the wall. Some of the widest cracks could not be seen from within the chapel itself and had to be viewed from above the inside ceiling of the central dome. These cracks were on the order of inches wide and penetrated completely through the thickness of the wall. This led engineers to suspect that there was differential settlement of the building and that the front and back portions of the building were settling in different directions. A survey of elevations of the building was conducted and it was determined that the south face of the building had settled over 4 in. in relation to the north face.
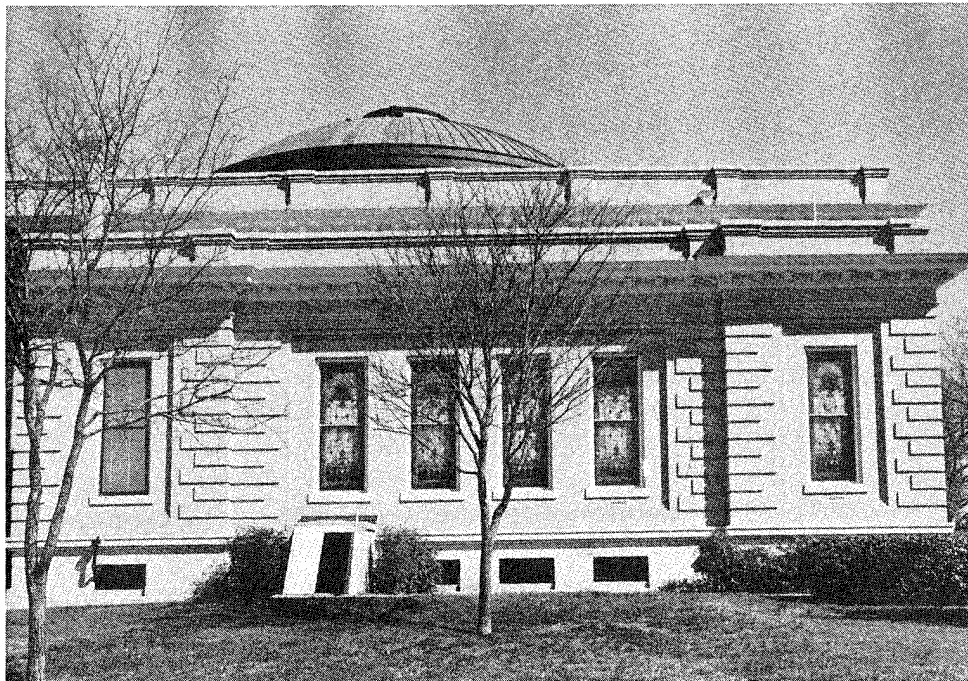
(Photo courtesy, Library of Congress)

Figure 38. Elevation of the west facade

Figure 39. Cracks over arch window in west facade

Apparently settlement had been a problem with the Gift Chapel since it was first constructed. In studying the building to determine what could be done to arrest the further growth of the cracks in the building, a series of tension rods were discovered running east and west along the north face of the chapel. Some of these rods were round in cross section, but two of them (found in the basement) were square in cross section. The engineers theorized that these were the oldest rods and perhaps had been put there soon after the building was constructed or they were part of the original construction. These tension rods were placed there to tie the building together.

Further examination of the structure of the chapel revealed a design error as well as some structural deterioration that was the result of building movement. The engineers found that the trusses which support the dome over the central chapel did not sit squarely on the center of the main cruciform columns that transferred these loads to the foundation. The truss-bearing plates sat on the outside portion of the columns such that the load was transferred eccentrically to the column. This happened at all four columns which prompted the engineers to speculate that there was a design error in placing the columns in the central chapel. Because the bearing points were not in the center of the column, the weight of the truss and dome was supported on two of the arms of the column and the weight was distributed over a smaller, less massive area. Partly as a result of this error, as well as the subsequent movement of the foundation, the arms of the column beneath the bearing pads of the trusses were cracked in the inspection of the building. The cracks were found at the root of the arms where they meet the central portion of the column, and extended down the column for a distance of 3 ft.

In addition to the structural repairs that were needed, the cracks in the east and west facades of the central chapel required that the brickwork be restored, particularly over the arch windows at the north ends of these walls. In the process of restoring these areas, the engineering team decided to remove other areas of brickwork that had been improperly repaired from previous efforts and restore them as well. Notably some closed openings in the east and west walls of the central chapel had been closed with materials that poorly matched the color and texture of the original brick. It was also decided that all the limestone and brick of the building should be cleaned. The paint on the limestone was removed as part of the cleaning.

Solutions to the problems

Structural restoration. It was recognized early on that the best solution to the problem of settlement was to strengthen the foundation enough to stop the settlement. Preliminary plans were aimed at doing that. The architect-engineer recommended that the mechanical building attached to the north face of the chapel be demolished and a new building be constructed away from the existing building. They had determined that the mechanical building was founded on 18-in. drilled underreamed piers to a depth of 38 ft below grade. They further recommended that the foundation for the north wall of the chapel be excavated and needle beams be placed under the north wall strip footing to prevent further settlement. They felt that the piers of the mechanical building could be used to support the north wall of the chapel.

This solution to the problem was not followed because it would have required that the entire footing along the north wall be excavated to install the needle beams and the engineers felt that such a procedure would be detrimental to the stability and soil structure interaction of the building. The continuous strip footing beneath this wall is unreinforced. The needle beams would only provide support at intermittent intervals, thereby potentially causing negative bending moment in the strip footing and new cracking in the footing and brick walls above.

It was also suggested by the engineers that the mechanical building be left in place rather than demolished, since it was not known if the building provided lateral support to the north wall of the chapel and what would happen if the building was removed. They recommended that should the building be removed, all new tie rods be put in place before it was demolished. A further survey of the building revealed that the north wall was at nearly the same elevation as it was when the mechanical building was constructed in the 1950's and that the south wall of the building had settled between 3 and 4 in. below that elevation. Because of this, it was felt that the mechanical building could be removed without adverse effect to the chapel.

The decision not to modify the foundation prompted the engineers to stop further separation of the walls by tying them together with additional tie rods. There were already a number of tie rods in the central chapel running in the

east-west direction (Figure 40). These had been in place from previous repairs. The tie rods that were to be installed during this renovation were to run north and south to address the separation of the building in this direction.
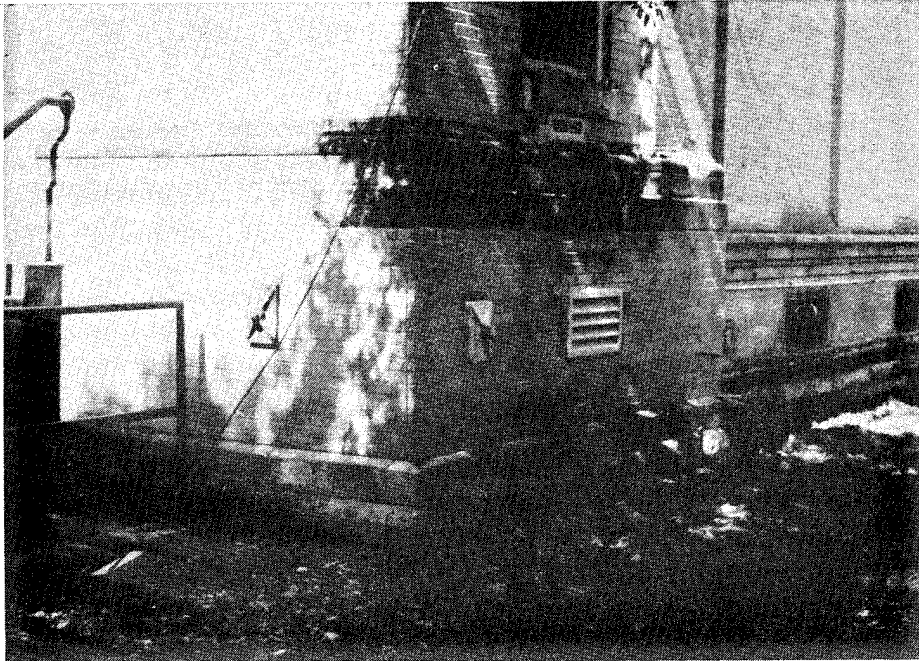

Figure 40. Existing tie-rod anchor in east facade at northeast corner

Figure 41 shows the location of the tie rods in the chapel. Dashed lines indicate rods from previous repair and solid lines indicate rods added recently. One tie rod from previous repairs had been installed from the inside wall of the room at the northeast corner of the chapel through to the inside wall of the room at the northwest corner of the chapel. The engineers felt that this tie rod was causing shearing stresses in its present configuration, and they decided to add extensions to each end of the rod to extend it to the outside walls of those rooms.

The addition of new tie rods to the building was not intended to posttension the cracks shut. Indeed, it was realized that trying to close the gaps would only put bending loads on the north and south walls which would potentially fail the masonry. Instead, the effort was intended to help make the building again function as a single structure.

The design of the tie rods was based on trying to compensate for an overturning moment on the wall due to a 2-in. out-of-plumb condition of the north wall. The overturning moments due to the weight of the brick wall, the dead load of the roof bearing on the wall, and the live load of the roof bearing on the wall were summed and equated against a righting moment (one tie rod) at a height of 34 ft above the base of the wall. The tie rod and bearing plate were designed from the resulting force in the tie rod. Six such tie rods were
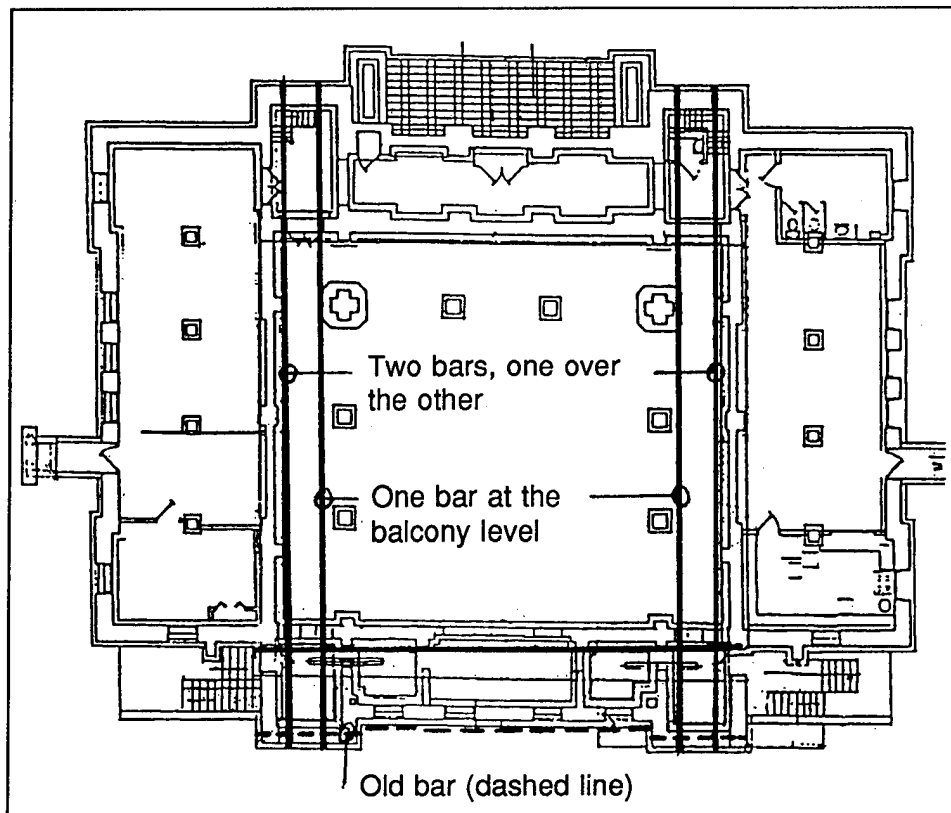
Figure 41. Plan of gift chapel showing location of tie rods

installed between the north and south faces of the chapel giving the tie rod design a healthy factor of safety (Figure 42).

The new tie rods were 1-1/4-in.-diam, A-36 steel tie rods. Three rods were installed in each side of the central chapel running in the north-south direction and one rod was installed in the attic space running in the east-west direction just outside of the columns in the north wall of the central chapel. In each side, two tie rods were installed just below the ceiling in the balcony on the second floor of the central chapel, and a third rod was installed at balcony floor level running along the wall beneath the windows. After the rods were installed, the nuts were tightened down on the bearing plate and hand tightened. The nuts were then tightened one additional turn by the use of wrenches. There was no attempt to tighten them more than that.

In choosing the location of the rods, the engineering team gave much consideration to visibility, safety, and proper location. Consideration was given to routing the rods within the walls and inside the woodwork that runs around the balcony of the central chapel. However, the effort to accomplish such a feat was not economically feasible, and the rods were run adjacent to walls. Their final location was chosen so that their visibility would be limited. They were run near the floor, behind pews, and in corners between
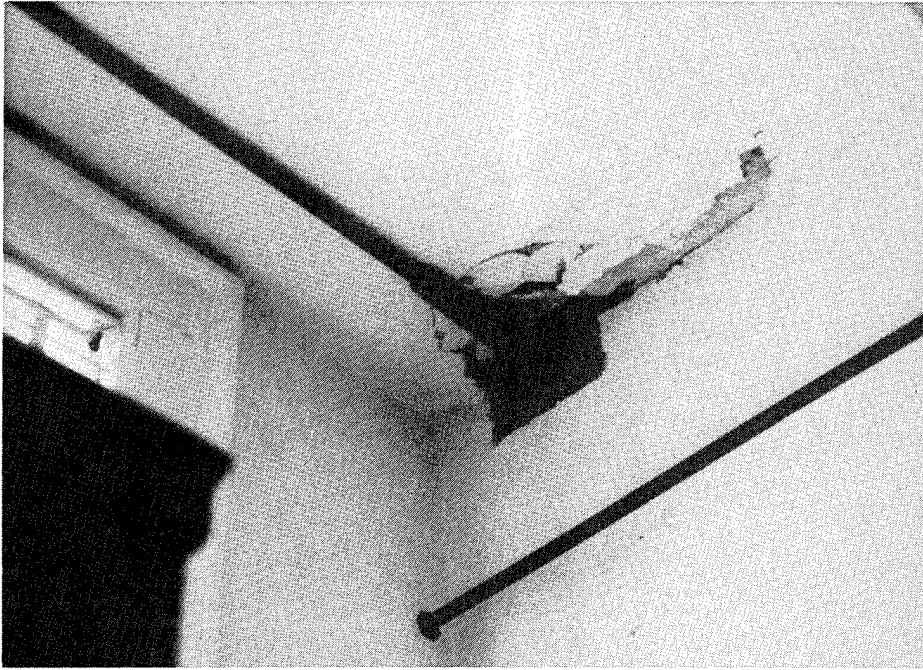
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Figure 42. Two tie rods in the northeast corner of the chapel

walls and ceilings. They were painted the same color as the walls to further conceal their location.

Performance to date. At the writing of this case history, the anchors have performed well, accomplishing the task for which they were designed. There have been no signs of any additional movement in the building since the tie rods were installed. The rods have held their tension, and there have been no signs of distress around the anchor plates indicating further movement of the walls. The repairs to the column capitals appear to be functioning as intended, since there has been no additional cracking of the brick beneath the level of the grouped steel collar.

Masonry related restoration

There were several masonry related areas of the restoration that bear discussion. The repair of the columns carrying the load of the dome truss and the brickwork repairing the cracked arch windows in the upper east and west walls of the central chapel are the ones that are structural in nature and discussed first. However, the chapel brick was cleaned and repointed, and this will also be discussed.

Column repairs. The columns in the main chapel are cruciform in shape. There are four columns in the chapel, two that are free standing and two that are part of the wall surrounding the main altar area as can be seen in Figure 41. The cracks in the columns were confined to the two arms of the cross

on which the dome truss rested. There were cracks in three of the four columns (none were found in the northeast column) extending down from the top of the column at the intersection of the arms of the cruciform shape where the arms meet downward and outward in a diagonal fashion for a vertical distance of 3 to 4 ft. The width of the cracks ranged from hairline to no greater than 1/16 in.

It was first anticipated that the free standing columns could be repaired by banding the broken portions. It was determined that even though the bricks were cracked, the column would retain its load-carrying capacity if the broken portion was restrained from separating any further. The plan was to surround the column with three 1-in. steel bands that would secure the broken brick to the rest of the column. When the engineers began to band the columns, they discovered that the columns had deformed at some of the corners and that the bands would only bear on the corners of the brick. Because of these conditions, they decided to use another method of stabilizing the columns.

As an alternate means of repairing the columns, the engineers decided to surround the entire column cap with welded steel plate for a length of 3 ft from the top of the column (Figure 43). The plates had to be cut and taken up to the top of the column where they were welded in place around the column. Because the shape of the columns was somewhat irregular, after the steel was welded in place there was space between the steel and the brick. This volume was filled with a portland-cement grout to help solidify the repair. The free-standing columns were considered repaired with the application of the steel collars. The columns that were contained in the main altar wall were repaired along with the brick repair that took place on those walls. They could not be contained in the same manner as the free-standing columns.

Arch window restoration. The large cracks in the east and west upper walls of the central chapel were repaired by removing the brick on either side of the crack opening and relaying them as shown in Figure 44. These cracks occurred over arch windows and, since the cracking had opened the top of the brick arch, the arch was not working as an arch while it was cracked. The loads were being distributed to other parts of the building. Since there was no load on the brick arch, it was dismantled brick by brick, retaining the bricks that were not damaged. These bricks were cleaned of all mortar and stored for reuse in rebuilding the arch. The arch was dismantled from the top of the crack (which extended to the roof eave) down to within two or three courses of brick up from the bottom of the arch.

An arch-shaped form was built to use as a guide in replacing the bricks in the new arch. The masons reused any bricks that were not damaged during the dismantling of the wall. In instances where there was need for more bricks, they drew from a supply of bricks which they reclaimed when dismantling a brick chimney from the north facade of the chapel.
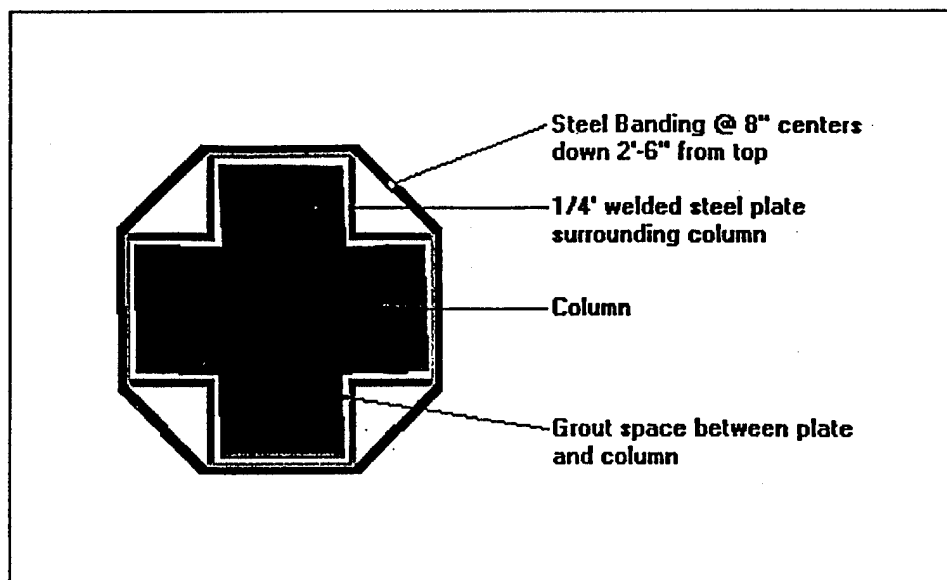
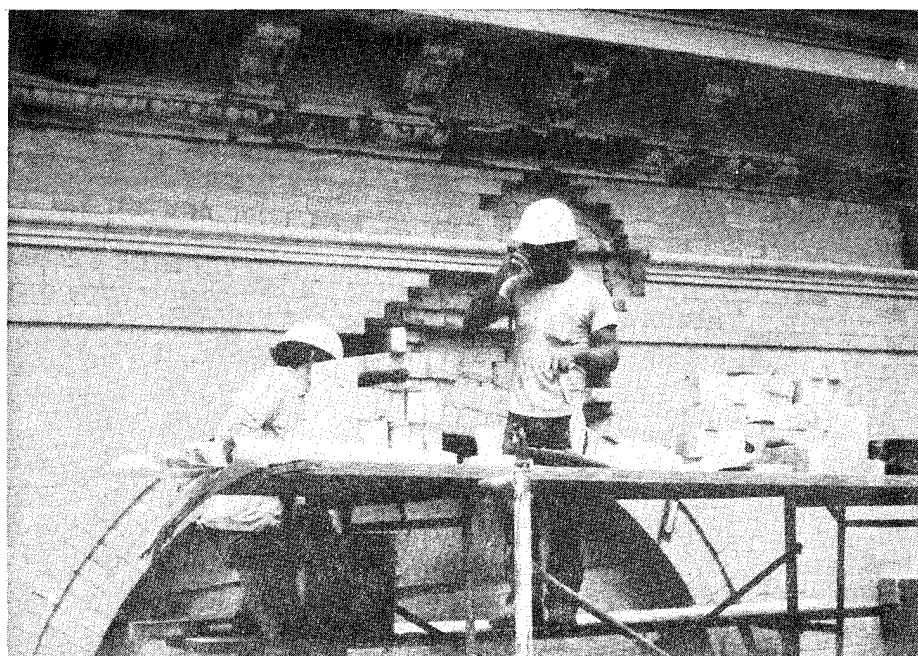Figure 43. Sketch of repairs to the damaged columns

Figure 44. Rebuilding of arch window at northeast corner of central chapel

Since the front and back of the chapel were moving away from each other, the masons had to contend with what to do to make up for the width of the crack that had formed in the wall over the arch. Rather than trying to rebuild using a different number of bricks, the masons decided to widen the head joints between the bricks to make up for the additional space. The higher up on the arch they went, the wider that gap became and the wider each head joint had to be. The objective here was to keep the correct number of bricks and minimize the width of each of the joints in the repaired area.

The mortar used to repair the windows was a type N mortar consisting of 3 parts sand to 1 part type N masonry cement. This mortar is designed to be weaker than the brick, not a difficult requirement to meet, because the bricks were very strong.

Brick repointing. Originally, the funding for the chapel restoration did not include money for repointing the brickwork. However, a small amount was designated for repointing only the mortar that needed the attention. This was limited to obvious places where the mortar had been damaged or washed out by the high-pressure washing, where the mortar was cracked from the structural damage, and a small contingency for repointing additional mortar at the discretion of the engineer.

When the contractor began to remove mortar for the repointing, he only removed approximately 1/4 in. of mortar from the joints. This depth is insufficient for proper repointing. Adequate depth is required so that the new mortar has sufficient surface of brick to develop a good bond to the brick and to help seal moisture from the repaired joint. Proper joint preparation calls for removal of the deteriorated mortar to a minimum depth of two and one-half times the thickness of the mortar joint (Mack, Tiller, and Askins 1980). This will usually result in removal of 1/2 to 1 in. of mortar. If the mortar is still deteriorated at this depth, it should be removed to a depth where sound mortar is found. The depth to the bottom of the cleaned joint should be uniform across the width of the joint to ensure that the new mortar forms a strong base and will not break with movement. The contractor's misconception was corrected and the joints were prepared to a depth of 3/4 in.

The cement used for repointing was the same type N white masonry cement used to repair the arch windows. The white cement was used to provide a buff color mortar which best matched the color of the original mortar. The mortar was again mixed using 1 part masonry cement to 3 parts sand.

The mortar was placed in the raked joints in layers. The first layer was approximately 1/4 in. thick and was packed into the bottom of the joint. It was allowed to harden to where the mortar would deform under the pressure of the thumb, and then the remainder of the joint was filled. The two-layer approach and the time between application of layers allows for each layer to begin to harden. The mortar shrinks most during this early hardening period, and applying the mortar in layers minimizes the overall shrinkage of the mortar in the joint, thereby putting less stress on the joint. When the final

layer of mortar was sufficiently hardened, the joint was tooled to match the old joints.

Since the Gift Chapel had been repaired several times during its life and since at other times the mortar used to repoint and repair was not chosen to match the original color or texture, the building often had different color mortars in different areas. The contractor made every effort to match the mortar to the color and texture of the original mortar.

Masonry cleaning. While the masonry repair was going on, the chapel was being washed of the many years of dirt and grime it had collected. The contractor decided that the washing could be accomplished without using chemicals since the dirt on the bricks was only soil and some light coating of pollution. The decision to use no chemicals allowed him to wash before some of the repointing. He proceeded to wash with water at a medium pressure. Figure 45 shows a workman spraying the parapet walls on the roof of the east wing of the chapel. The water was sprayed on the bricks at a pressure of approximately 400 psi. This was considered strong enough to remove the grime and any loose mortar in the joints without damaging mortar that was strong. The entire chapel was washed from the top down to keep newly washed areas from being recontaminated from draining dirty water.
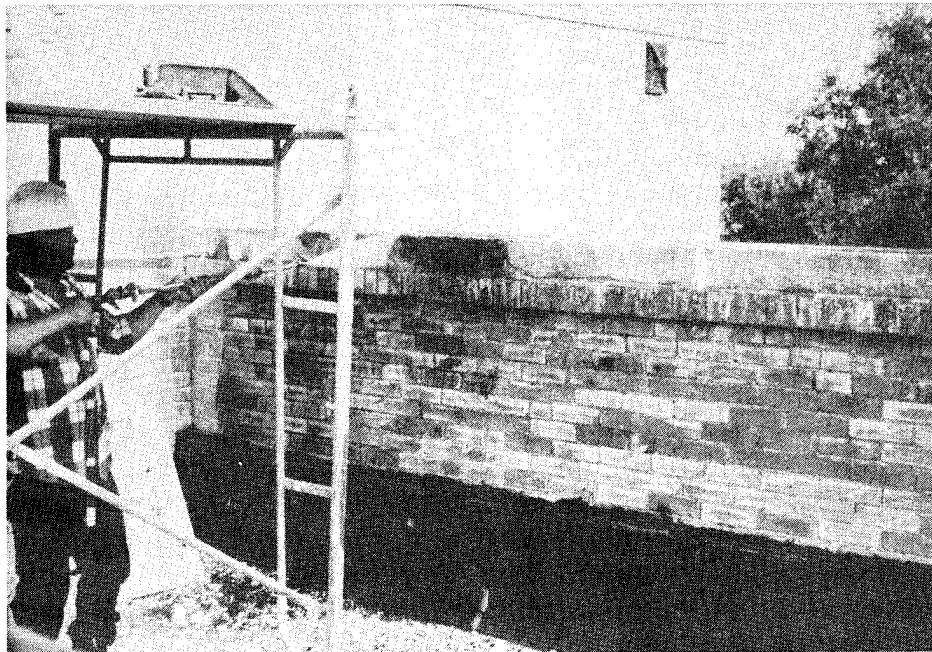

Figure 45. Medium pressure water cleaning of masonry

Performance to date. The performance of the masonry appears to be satisfactory at the time of this writing. The structural repairs halted the further cracking of the east and west walls, and there has been no indication that the masonry repairs have cracked or the bricks have separated. The mortar

joints that were repointed are performing well. They show no signs of deterioration, and there is no moisture leakage in the walls.

Hotel Oakland

Introduction

Rarely are we given the opportunity to examine the rehabilitation of a historical building, study the efforts to seismically strengthen it, adapt it to a new use, and then, 10 years later (due to a major earthquake), have the opportunity to reexamine the same building a second time. This case history is an instance of exactly that. In 1979, the team of The Ratcliff Architects, Emeryville, CA, and their structural consultants, H. J. Degenkolb and Associates, San Francisco, were retained to work on the restoration of Hotel Oakland, a major historic building in downtown Oakland, CA. The work was undertaken, completed, and tenants allowed to move in. As a result of the Loma Prieta earthquake 10 years later, the building was again damaged, and the same team was retained by a different developer to repair earthquake damage and restore the same building to full use.

Description of the building. In September 1906, a burgeoning civic pride in Oakland "reached new heights when the business leaders of the community announced that the building of a 'magnificent modern hotel' was to become a reality (Scott 1959)." The Hotel Oakland, needed to attract and accommodate visitors to the Oakland area, was financed by the Hotel Oakland Company, a consortium of bankers in the area. They initially raised $1,500,000 for the construction through the sale of stock and bonds and later, as construction costs increased, sold additional stock to bring the funding to over $3,000,000. It was intended to be the East Bay equivalent of the Palace Hotel in San Francisco. As a Santa Fe Railroad booklet observed in describing the growth of the city, the block-square hotel was another indication that the city had "thrown off the swaddling clothes of suburbanism and become distinctly urban" (Scott 1959).

The developer originally hired New York architect H. J. Hardenburgh (designers of the New York Plaza Hotel and the Waldorf Astoria) to design the structure. However, due to financial restructuring and travel difficulties, the original architect was replaced by the San Francisco firm of Bliss and Faville (designers of the St. Francis Hotel). Purdy and Henderson of Seattle, Washington, were the structural engineers. The general contractor was P. J. Walker. Actual construction began in August 1910, and the hotel opened its doors on December 19, 1912, with the sixth, seventh, and eighth floors unfinished.

The building consists of a steel frame with a reinforced concrete foundation supported on spread footings on sandy-silty material at the basement level (Wosser 1981). The floor slabs are also constructed of reinforced concrete.

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The columns were originally designed to be built-up sections of angles and plates, but Bethlehem Steel "H" sections were ultimately used. The steel was erected by Milliken Brothers, New York City, a company which was later to become a part of Bethlehem Steel. The exterior walls were constructed of three wythes of brick as a 13-in.-thick nonbearing wall. The face brick was described as Carnegie Pressed Brick of a cream beige color. Brick was used to fireproof the columns, while beams and girders were fireproofed with concrete. All partitions in the building were of hollow clay tile with a plaster finish. The building is topped by two 30-ft-high bell towers above the roof.

The December 19th opening was celebrated with a dinner and grand ball for 1,150 guests. It featured acorn shaped menus and a "Hotel Oakland March" composed by the director of the hotel's orchestra.

During the next decade, the hotel became a prominent social center, hosting important political events and conventions. The largest ball, attended by 4,000 people, was held in 1919. Presidents Wilson, Coolidge, and Hoover were guests at the facility, as were other celebrities, including Amelia Earhardt, Sarah Bernhardt, Jean Harlow, and Mary Pickford (Scott 1959). A view of the hotel is given in Figure 46.
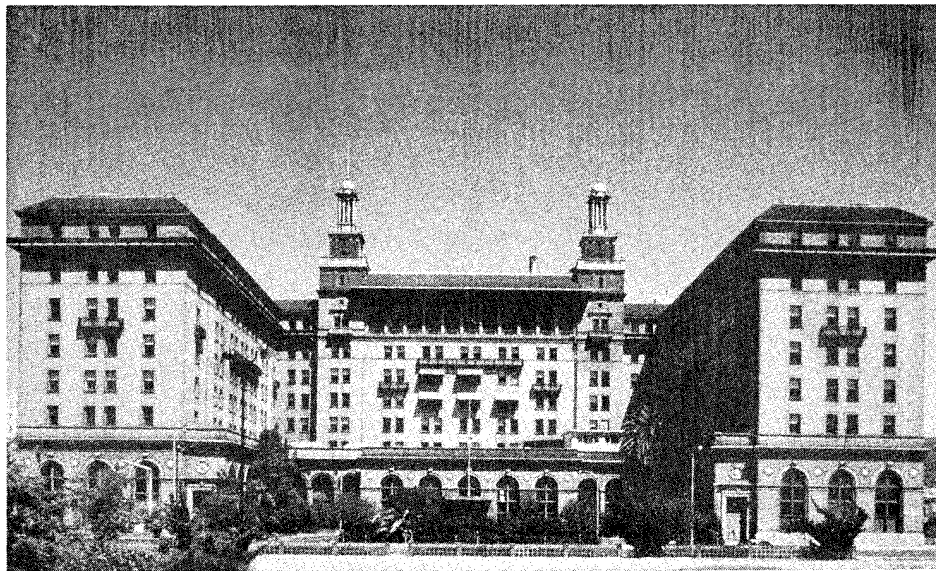
(Photo courtesy, Mr. James E. Roberts, Obayashi Corp., Danville, CA)

Figure 46. View of Hotel Oakland

During the hotel's heyday, a men's entrance off Harrison Street led to a barber shop, and a men's bar and clubroom next to the 13th Street courtyard. The ladies' entrance, on the opposite side of the hotel on Alice Street, led to a foyer near the ballroom. A full kitchen and bakery served the cafe and dining room. The hotel's stores and supplies, including high-pressure-steam boilers that furnished heating and domestic hot water, were located in the basement.

The depression of the 30's as well as management difficulties caused the hotel to go bankrupt several times during its early life until, in 1943, the U.S. Army condemned it and took possession of it for use as a hospital. All furnishings were auctioned off, including irreplaceable chandeliers of which only photographs remain. Following World War II, several unsuccessful attempts were made to reopen the hotel for public use. The Veterans' Administration eventually gained control, occupying and operating the facility as a VA hospital until August of 1963. From then it stood vacant until 1978 when Housing Innovations, Inc. (HII), a Boston based developer obtained possession and remodeled it into a housing project for the elderly. It remains in this use today.

Currently, the exterior of the building and the two-story spaces on the main floor are on the National Register of Historic Spaces. These grand, ornately decorated, two-story-high rooms include the main entrance Lounging Room off the 13th Street courtyard; a Corinthian-columned, 5,000 ft² ballroom and a dining room, both off the 14th Street entrance; and the cafe, located at the corner of Harrison and 14th Street with its 30-ft-high, dark paneled, oak walls and finely detailed ornamental plaster ceiling.

Oakland weather

While the restoration of the Hotel Oakland is not driven by weather dominated deterioration of the brickwork, the climate in the area will be described, for the sake of consistency.

The climate in the Oakland area is relatively dry with mild, dry summers and cool, winters. Summer temperatures extend from June through early September with temperatures ranging from the high 60's to the low 80's. July and August are generally the hottest months. Winter conditions are mild and generally present from late November through mid-February. Winter temperatures are generally in the 50's but can get as down into the low 40's. Fall and spring are moderate seasons with average temperatures in the 60's and 70's. The rainy season in this part of California is generally in November and December. Average annual rainfall is between 14 and 18 in.

Description of the problem

1979 restoration. When HII began renovations in 1979, they found much deterioration to the building. They undertook a number of structural studies which revealed two major deficiencies. The building's structural steel frame and concrete foundations were in good shape. Although steel buildings do not usually collapse in an earthquake, unreinforced masonry walls do. The first major deficiency related to brick-wall collapse in earthquake situations, so the hotel's three-wythe brick walls had to be tied to the steel frame to guard against collapse and pulling away from the steel framework. To do this, a unique basketing system was devised.

There are many considerations in building reconstruction, but of prime importance in the rehabilitation of the Hotel Oakland was the need to develop a system of earthquake bracing that would effectively reduce the life safety hazard at a cost that was compatible with the feasibility of development.

The building was designed originally to resist wind forces, but it fell far short of complying with current seismic code requirements. The exterior walls were of unreinforced brick, a brittle material subject to failure in an earthquake. However, the walls were nonbearing walls and not dependent upon for the vertical support of the building. All gravity loads were designed to be carried by the structural steel frame, which normally performs well in response to earthquake forces, even when not designed specifically for them.

It should be noted here that the Hotel Oakland lies approximately 20 miles east of the San Andreas Fault and 5 miles west of the Hayward Fault which is also capable of being the locus of major earthquakes.

The exterior brick was part of the charm of the building, and furthermore, to attempt to replace the brick with another cladding would have been prohibitively expensive. Therefore, one of the givens in the repair solution was that the brick would remain.

The second major deficiency that the structural survey indicated was that major vertical shear walls were required throughout the building to strengthen it.

In addition to the major structural deficiencies, there were other challenges encountered.

> It was discovered during the demolition that portions of the concrete floor surfaces were at different elevations depending on the location within each floor. This was due to raised ceramic tile floors in the bathrooms and lowered floors in the corridors.

> Sixteen years of accumulated pigeon droppings, in every interior area accessible to the birds (through broken windows or other openings), made cleanup a unique problem.

> Clay roof tiles on the sloping mansard roofs were loose and presented a falling hazard.

> Large, 4-ft-wide and 2-ft-high ornate sheet metal cornices located at the seventh floor were leaking, and much of the metal work was rusted and needed replacement.

> Interior rainwater drainage pipes had been arbitrarily cut off and, in many cases, abandoned.

The decorative bell towers that rose 30 ft above the roof at either end of the main building were seriously deteriorated.

These and other unknowns increased the original contract of $10.2 million by 15 percent to $11.8 million.

While these aspects of the design were of primary importance, there were a number of other elements of the project that were of interest.

The single wythe brick walls of the two 30-ft-high bell towers above the roof were supported on decayed wood sheathing. After the State Historic Office rejected the proposal to replace the brick with sheet metal, a new system was devised to tie the brick into a new metal stud system, removing the decayed wood.

The retention of some of the decorative walls at the ground level called for some creative design. Historic, interior surfaces were carefully removed for installation of new structural elements. The removed material was marked and cataloged for later replacement.

Unreinforced brick parapets at the second floor level presented a hazard of falling brick at the main entrance and courtyard.

Where new floor areas were added at existing floor openings, they were filled in with steel decking and concrete.

Description of the solutions

Because of the National Historic Register and an Oakland Landmark classification of the building, a decision was made initially to conform to the Department of Interior guidelines, and those of the California Historic Preservation Office and the City of Oakland Landmarks Preservation Advisory Board. The historic elements of the building included the exterior and the five interior historic spaces. Beyond that, the goal of the renovation and restoration was to develop a maximum number of one-bedroom and efficiency apartments for housing of the elderly.

In the initial efforts to renovate the building, many schemes were tried to remodel the existing rooms and corridors for apartment use. It soon became apparent that the existing scheme of rooms would not provide the number of units necessary to financially carry the project. This, coupled with the fact that the interior walls were constructed of hollow clay tile, led to an early decision to demolish all interiors walls from the underside of the roof to the basement. Exceptions to this decision were the concrete floors, the exterior walls and the historical rooms. Removal of the hollow clay tile partitions eliminated substantial earthquake hazard, since they will shatter in an

earthquake. Figure 47 shows these tiles during the 1979 renovations. This also reduced the total mass of the building thus lowering the effective earthquake inertia forces.

(Photo courtesy, Mr. James E. Roberts, Obayashi Corp., Danville, CA)

Figure 47. Clay tile partition rubble from 1979 renovations

During preparation of the construction budget by the general contractor, three decisions were made that greatly expedited demolition and construction.

The building would be fully scaffolded.

Debris from the wall demolition would be removed from each floor by means of a chute constructed in an exhaust duct opening that ran from the roof down to the basement. Floor by floor demolition was accomplished by small bobcats lifted onto the various floors by crane and inserted through a demolished window opening.

A cut would be made through the courtyard to form an earthen truck ramp down to the basement level. Further, a hole would be cut in the foundation wall so that debris could be removed from the building site easily.

While the architectural planning was going on, a structural analysis of the building was being prepared. Because of the increased knowledge and code requirements of buildings in earthquake zones, the major structural concern was to provide for life safety from collapse or sections of falling walls or parapets.

Building codes in California required older buildings to be brought into conformity with current seismic code requirements when there is a change of occupancy to a higher or more hazardous level or when the total new work exceeds a certain value of the building. In the case of the Hotel Oakland, the occupancy was not being changed to a higher exposure, and the City of Oakland agreed that there were no other circumstances that would require bringing the building up to current seismic code. However, the Department of Housing and Urban Development had a policy which stated:

> "*Earthquake Hazard Evaluation.* In Zone 3, as shown on Seismic Risk Maps in References (1) and (2) of the foreword, a building's structural components and condition shall be evaluated by a registered engineer familiar with lateral force design. The evaluation shall include an examination of the structure for continuity, ductility, and resistance to lateral forces. Structural elements and connections between elements shall be strengthened and new elements provided as required. The degree of resistance provided shall be such as to prevent major collapse or loss of life due to earthquake forces."

It was the opinion of Degenkolb Associates that this building could be reinforced to reduce the life-hazard exposure to a minimum and that, while a major earthquake would cause significant damage, there would be no collapse or major life safety exposure. In working with these criteria, the structure was evaluated to provide resistance to 60 percent of the forces required by the 1973 Uniform Building Code. The limitation to 60 percent was controlled by the overturning forces, but, in many respects, the structure had the capacity to resist much higher forces. The presence of the existing structural steel frame added significantly to seismic resisting capability of the building, in addition to providing a complete independent framing system for the support of gravity loads. While no attempt was made to assign any numerical value to its seismic participation, it was understood that the frame would act as a backup system, providing additional ductility, continuity, and redundancy to the structure. No building with a complete structural steel frame has ever been known to collapse in an earthquake. Significant experience with the type of structure similar to the Hotel Oakland was gained during the 1906 San Francisco earthquake where numerous steel-frame buildings over 10 stories in height survived with reportedly little earthquake-induced damage.

Strengthening of the brick walls

It was recognized that the existing brick walls, because of their great length, would provide stiffness to the building to resist minor and moderate earthquakes. It was also clear that major earthquakes would cause severe damage to the brick, creating a problem which needed to be solved.

In resisting lateral forces, whether from wind or earthquake, the brick walls had to resist forces normal to their surface as well as those produced in the plane of the wall. That is, they have to be able to resist floor-to-floor, normal forces and act as shear walls for in-plane forces. At low force levels, brick walls have the capacity to do this. However, major earthquakes create stresses that will exceed the brick strength, particularly for out-of-plane bending. The shear wall response is complicated by the number of openings in the walls (i.e. window openings), causing the piers and spandrels to be subjected to flexural as well as shear stresses.

To determine the shear strength of the existing masonry, 6-in.-diam cores were removed from the exterior walls and bed-joint shear tests were performed on the cores. Fifteen samples were tested showing an average shear strength of 50 psi.

The testing proved that the walls were simply not designed for resistance to the high force levels experienced in an earthquake. However, if the brick wall could be held in place, it could be effective even after suffering major cracking because it will absorb a great deal of energy in crushing of the brick along fracture surfaces during earthquake movement.

To effect this type of performance, the decision was made to provide a basketing system to stabilize the brick walls after cracking occurred. The system devised was incorporated into the new wall furring which was applied to the interior of the steel frames of the exterior walls. Figures 48 and 49 show some of the system details. Heavier structural studs were mixed in with the basic stud furring system. These heavy structural studs were spaced to allow wall anchors to be secured at approximately 3 ft on center in both vertical and horizontal directions. The wall anchors were 1/2-in.-diam bolts long enough to extend from the structural studs through the two interior wythes of the exterior wall and into the face brick. The bolts were inserted into the wall through holes drilled into the brick to a depth including partial penetration in the face brick. They were then anchored to the brick with polyester-resin epoxy cartridges.

Tests were conducted to determine the strength of the epoxied bolts in the brick. Prior to the actual use of this system, three anchors were epoxied into brick test panels and were loaded to failure. One failed at 7,500 lbf, and the other two at 9,000 lbf, with all failures occurring in the anchor, not in the brick or in bond between the brick and the anchor. There were 4,900 bolts used in the wall renovation, and 520 of these bolts were subjected to pullout
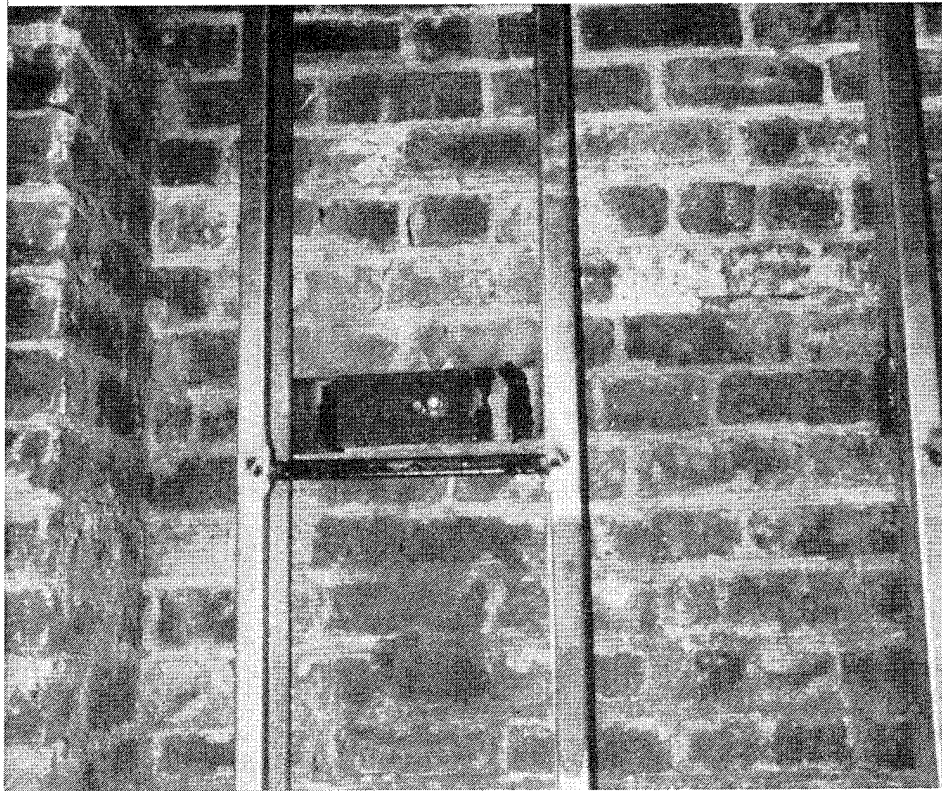
(Photo courtesy, Mr. James E. Roberts, Obayashi Corp., Danville, CA)

Figure 48. Overall view of structural studs and wall anchor
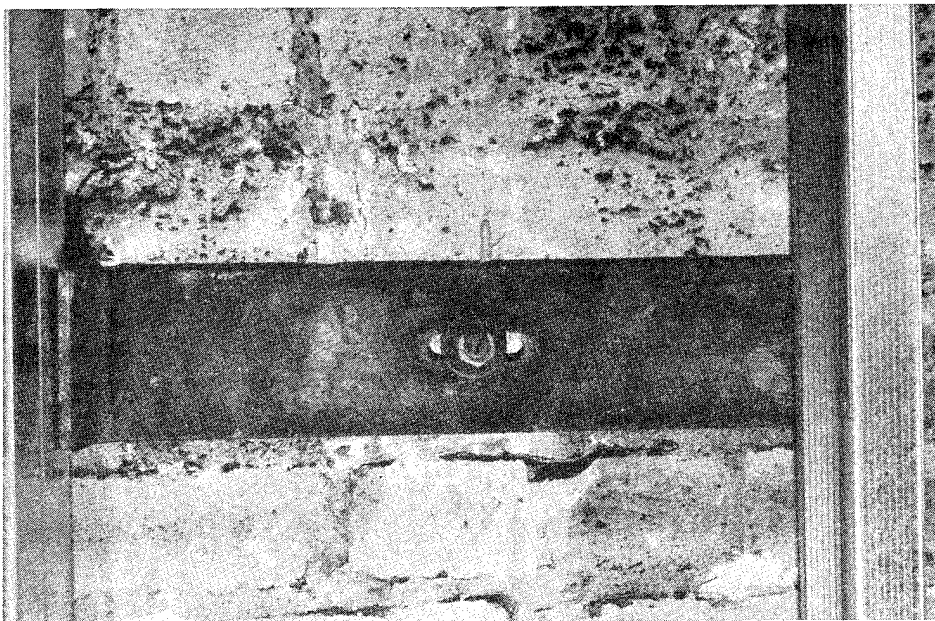
(Photo courtesy, Mr. James E. Roberts, Obayashi Corp., Danville, CA)

Figure 49. Detail of basketing anchor

testing. The anchors were loaded to a magnitude of 1,000 lbf and held at that level for 1 min. Only 34 anchors failed the proof loading.

To complete the anchorage of the wall, the bolts were then attached to plates which spanned between adjacent structural studs. The stud system then provided a positive anchorage detail to the floor framing above and below. Thus, the exterior wall system was reinforced with steel studs having the capacity to brace the walls against out-of-plane forces after failure of the brick. The system was intended to hold the brick in place, reduce the potential falling hazard, and use the crushing of the brick (during an earthquake) for its energy absorbing value.

Shear wall strengthening

Reinforcement of the exterior brick walls was important to the performance of the building in an earthquake, but it was only part of the story. To provide additional strength and ductility to resist major earthquakes, a new system of reinforced concrete shear walls was designed to be added around the stair and elevator shafts (Figure 50). This system, well distributed around the building in the upper stories, was supplemented by additional shear walls from the second floor down to the foundations.

Several functions are served by this system: the needed seismic shear resistance was provided by the new walls, the shafts (stairwell, elevator, etc.) would remain accessible and operable (free of debris that would result from use of a more brittle material), and a 4-hr fire-resistive environment in the shafts was provided.

The new shear wall systems also worked well within the confines of the existing structural framing system. The walls were tied into steel floor beams which served as collectors to deliver diaphragm forces, and into the steel columns, which acted as chord members to resist the tension and compression due to the cantilever action of the wall. Nelson studs were required to be added to the existing structural steel members to develop the forces. The new walls were reinforced for the shear stresses as well as to resist net tension forces at the steel columns to supplement the capacity of the column splices. The most critical aspect of the design of the new shear walls was the overturning effect. Although the interior stresses within a shear wall were readily accommodated, it was necessary to mobilize enough gravity load in the walls to enable them to resist overturning. To accomplish this, the
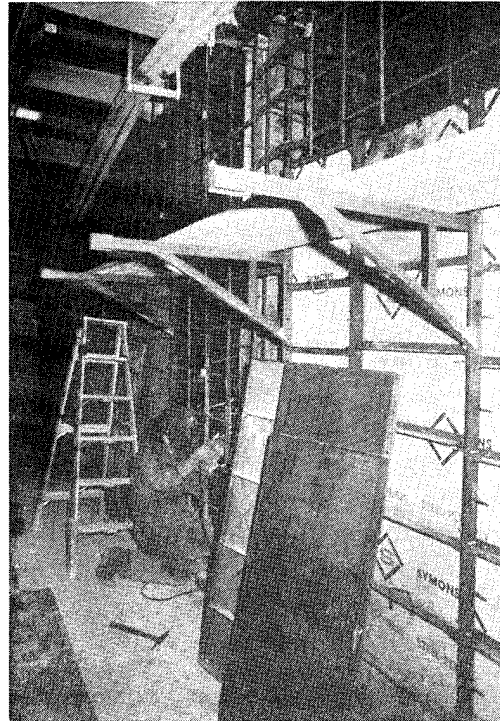
(Photo courtesy, Mr. James E. Roberts, Obayashi Corp., Danville, CA)

Figure 50. Forming for interior shear walls

walls were tied into the load-carrying columns in the upper stories. In the lower stories it became necessary to extend the walls so that they could embrace adjacent columns to create a bigger base and provide stability for each shear wall system to resist overturning effects. In areas where the existing steel columns could not transfer all the uplift into the foundations, additional reinforcing steel was provided, and the new foundations were interconnected with the existing footings to provide a new composite system.

1989 Loma Prieta earthquake

On October 17, 1989, a major earthquake, measuring 6.9 on the Richter scale, hit northern California. The quake occurred along the San Andreas Fault which cuts through the San Francisco peninsula. Oakland lies 20 miles east of the fault, across the bay from San Francisco. The intensity of the quake in downtown Oakland was severe and many structures were badly damaged.

Although major structural damage was done to many unreinforced masonry buildings in the Oakland area, the Hotel Oakland survived with architectural damage to the exterior brick walls, some cracking, and damage to some of the apartments interiors. The minimal damage sustained was a result of the 1979 strengthening and rehabilitation.

The structure performed as the engineers anticipated it would. Its sound performance was a vote of confidence for practical measures taken to strengthen existing buildings. While these measures would not bring the buildings up to current codes or structural standards, they did provide a life safety performance level which prevented collapse and protected human life.

Description of the problem

Shortly before the earthquake, the hotel had been acquired by the A. F. Evans Company, a local real estate development firm with a long history of successful rehabilitation development.

Two days after the quake, the new owners contacted the architects and engineers who immediately started examining the damage, coordinating with state and local agencies to obtain the necessary clearances and approvals and starting the design work necessary to put the structure back together again.

In assessing the damage and estimating the costs of repair, the owner and design team enlisted the assistance of Roberts-Obayashi, an experienced general contractor, who was completing a new building across the street from the hotel and who had previously worked with Evans. The architects, engineers, and general contractor worked as a team from the initial investigation until completion.

Although the 1989 Loma Prieta earthquake did no damage to the integrity of the structure, there was considerable architectural damage to the exterior brick masonry walls and to a number of apartments. Substantial amounts of brick had fallen to the street from the southwest corner of the building, exposing some of the apartments and the steel framing (Figure 51). With the engineers working to determine the extent of the damage, it was soon learned that the damage was not structural and that except for 30 apartments, the remaining 185 units could continue to be occupied while the repairs to the remaining units were conducted.
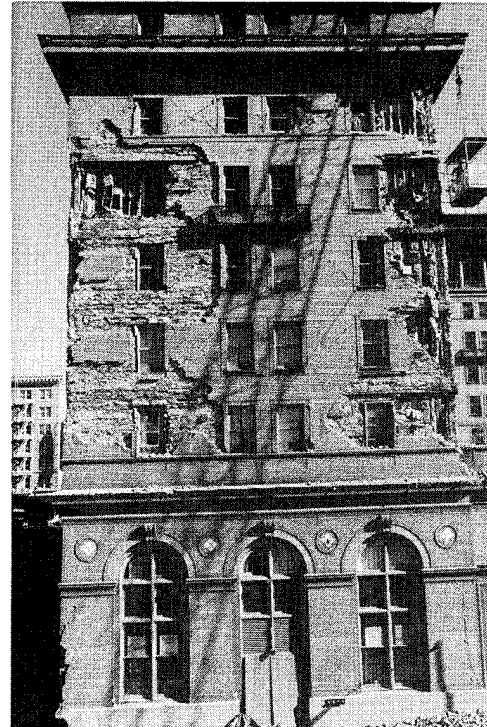
Additionally, because of the building was on the National Historical Register, all aspects of the repair that affected the exterior of the building or the historical rooms were reviewed and approved by the State Office of Historic Preservation. U. S. Department of the Interior procedures were enforced and a historic easement was created and filed with the County Recorder with the nonprofit Oakland Heritage Alliance being retained to assume oversight responsibility for maintaining the easement requirements.

Because of the destruction or significant cracking of much of the exterior brick walls, the patching, making of new brick, and cleaning of the walls were monitored by the State and City Historic Departments.

Structural damage

The most evident and significant damage sustained by the hotel was the cracking of the exterior brick walls. Although they are not load-bearing walls, the brick walls are the stiffest elements in the building and resisted the main thrust of the earthquake force. The walls are infill brick supported on the structural steel frame, and therefore the damage did not affect the vertical load-carrying capacity of the building. The damage to the brick was manifested as diagonal (X) cracks in the wall piers with virtually no cracking in the horizontal spandrels. Reference to Figure 51 shows this X cracking between bays of windows.

(Photo courtesy, Mr. James E. Roberts, Obayashi Corp., Danville, CA)

Figure 51. Damage to southwest facade after removal of loose brick

The most severe brick damage took place on the Thirteenth Street end of the Harrison Street wing of the building. There were cracks over 1/2 in. wide, with complex fracturing through the entire thickness of this wall. There were also areas where the face brick had fallen and other areas where it was loose.

Much of the brick on this wall was damaged enough to create a potential life safety hazard which could not be ignored. An aftershock could have dislodged portions of the wall which could fall on people below. Further, it appeared that it would not be possible to adequately repair the brick and that it would have to be removed and replaced during the reconstruction.

Only very minor damage (hairline cracks) occurred in the reinforced concrete interior walls which were constructed in 1979. Additional cracks were reported in the concrete floor slabs and may have been a result of the earthquake.

It is interesting to note that during the 1979 renovations reinforced concrete stair towers were built into both the east and west wings of the building. In the east wing, the stair tower was built with its longitudinal axis perpendicular to the longitudinal axis of the wing itself or parallel to the facade of the end wall of the wing. In the west wing, where the major brick damage from the 1989 earthquake occurred, the stair tower had been built with its longitudinal axis parallel to the longitudinal axis of the wing due to space considerations. The east wing experienced significantly less damage to the brick facade as a result of this additional stiffening.

The City of Oakland required that the building be seismically upgraded to meet the requirements of their postearthquake ordinance. After the earthquake, the city established provisions requiring all buildings which lost 10 percent or more of their total lateral force-resisting system's strength to be strengthened to meet the 1988 Uniform Building Code force level for the design of new buildings. Although the brick walls were not intended to be part of the lateral force-resisting system of the Hotel Oakland, they acted as shear walls because of their stiffness, and they lost much more than 10 percent of their strength. The concrete shear walls added in 1979 had only sustained minor cracking.

The reentrant corner areas of the building where the wings meet the main body of the building were damaged during the earthquake, especially in the upper floors (Figure 46). The concrete floor slabs exhibited some cracking starting at the corner and extending into the main floor area. The steel floor framing in these areas does not line up directly with the walls allowing for a direct load path between the floor diaphragms and the walls. The floor slab strengthening consists of the addition of new steel drag elements interconnecting the below-slab existing steel framing to relieve stress concentrations in the slabs and help collect and deliver the tributary loads to the new shear walls.

Solutions to the 1989 Earthquake damage

In consultation with building department officials, it was decided that the building's new strengthening elements would be designed to meet 75 percent of the current Uniform Building Code design force level for the design of new buildings. The new elements are also designed to meet the full detailing

provisions of the Code. In this respect, the owners were interested in meeting the requirements of the local building officials and in providing further assurance of life safety to the occupants, as well.

The additional strengthening measures were developed to be sensitive to the historic character of the building. The structural strengthening system was designed to provide all the seismic resistance in a system of reinforced-concrete walls arranged in a relatively uniform manner to minimize diaphragm stress and earthquake forces on the brick walls. In areas where the concrete walls were damaged, new reinforced-concrete walls are being added to the interior face of the exterior brick walls so the total required resistance will be provided by the new and existing reinforced concrete.

In the first-story historic spaces, the strengthening walls are being located behind the existing historically sensitive wall surfaces to keep the architecture of the space clean (Figure 52). In the upper stories, Figure 53, the additional wall thickness will encroach into the living spaces and the units will be remodeled. Because of the tight spaces in which to work in pouring the new concrete shear walls against the existing brick and the limited amount of work space, the contractor devised and ingenious forming system. Stay-in-place formwork was used and held in place by metal studs that were in turn supported by steel dowels which were carefully placed and epoxied into the facia brick. The studs not only supported the forms but became the method of anchoring the brick to the new concrete walls. The studs were stiffened by wood blocking at each stud and laterally supported by whalers. This method allowed for observation of the pour through the formwork and greatly simplified and accelerated the process. The metal studs that remained in place were used as furring for the interior finishes so there were no forms to remove, only the wood blocking and whalers.

Because of the hotel's landmark status, the new shear walls, which are cast against the interior face of the exterior brick walls, must incorporate the existing window and door openings. Historic preservation considerations did not allow for filling the door and window openings so a solution was needed that could meet these constraints.

The wall openings and the effect on the predicted performance of the new walls presented another challenge. The concrete shear wall detailing provisions of the Uniform Building Code require the use of tightly tied reinforced boundary elements in the walls and diagonal shear reinforcing in some of the spandrel beams between the window openings. To reduce some of the reinforcing requirements and to minimize construction costs, higher strength concrete was specified in these shear walls.

Where the brick wall was removed, a new reinforced concrete wall was constructed and finished with brick veneer to match the existing brick work. Major new foundation work is required to carry the additional weight of the new concrete walls, and, more importantly, to resist the overturning effects of earthquake forces.
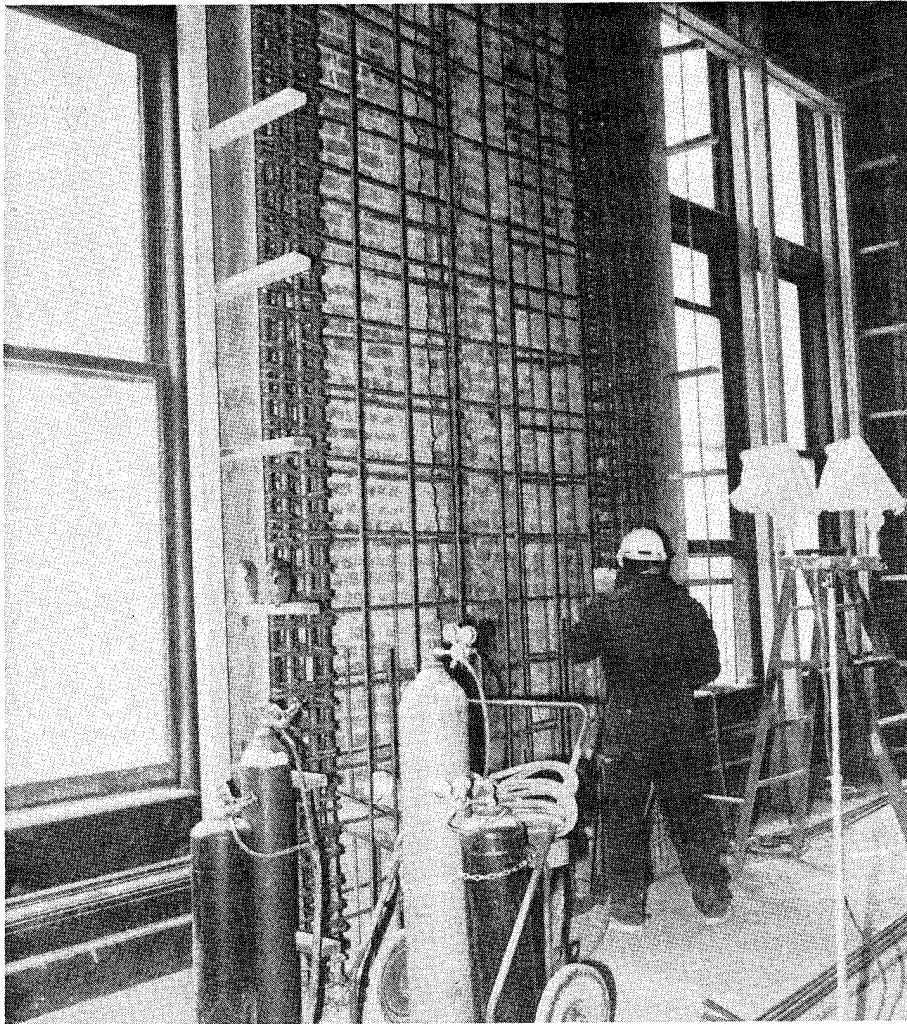
(Photo courtesy, Mr. James E. Roberts, Obayashi Corp., Danville, CA)

Figure 52. Strengthening of walls behind historical facades
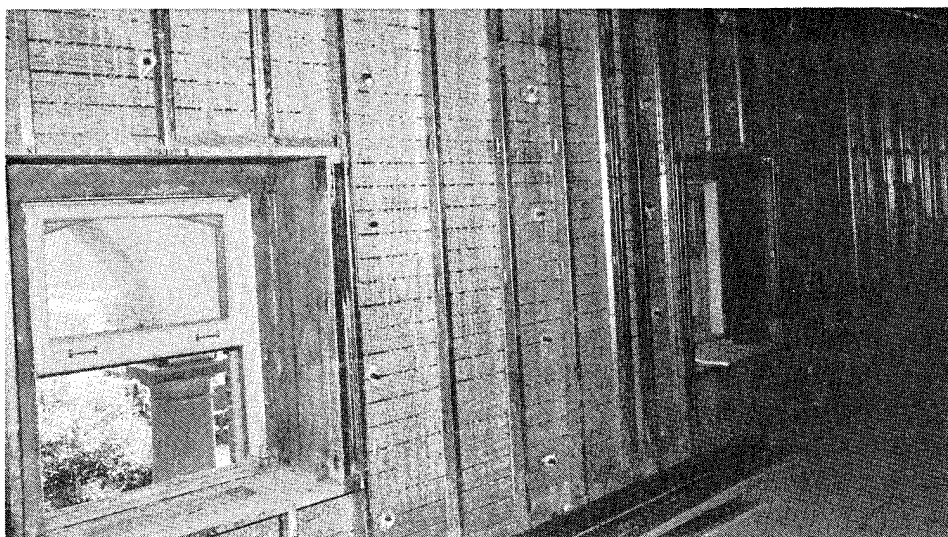
(Photo courtesy, Mr. James E. Roberts, Obayashi Corp., Danville, CA)

Figure 53. Strengthening of typical upper floor walls

The exterior brick walls required significant work to repair the cracks caused by the earthquake. The cracks were injected with epoxy to restore original strength, and the finish was then patched to match the adjacent surfaces as closely as possible. The restoration process was complicated by the effects of cleaning on the existing material and how that affects the color of new face brick and mortar.

The seismic strengthening system selected for the Hotel Oakland was done so only after considering several alternative systems, including steel bracing, interior wall locations, and shotcreting the entire exterior wall system. The final choice was based on a combination of structural effectiveness, minimal disturbance to the building's residents, preservation of historic significance, and relative cost, including cost of displacement.

Performance to date

This project has afforded a unique opportunity, by the design architect-engineer, of actual observation of the performance of a seismically strengthened historic building in an earthquake and seeing that the criteria used in the earlier work performed as projected. It also presented the challenge of revisiting the damaged building and, working within the constraints of current codes, modifying it for current structural code compliance, for life safety and within an affordable budget.

A total of 315 apartments were developed, including a portion of the ground floor and the mezzanine floor. At completion, 272,000 sq ft of residential floor area had been remodeled at a cost of $11.8 million which

averaged $44 per square foot. Three hundred fifteen efficiency and one bed-room apartments have been created. Fifty thousand square feet of first-floor public space has been developed, part of it for tenant use and part to be historically restored for leasing as commercial space.

This effort demonstrates the importance of consistent and cooperative effort between a developer with development and financing expertise, a contractor that can successfully work with the unknowns and complexities of an old building in constructing new concrete shear walls in almost inaccessible locations, and an architect-engineer team with the knowledge and technical ability to creatively solve the attendant problems.

The architectural and engineering work and the construction documents were completed in mid-1991; financing was in place and the construction loan closed in early 1992, with construction starting shortly thereafter. Construction was completed in August 1993.

3 Discussion

The case histories of repair and restoration to brick and stone masonry structures presented here are intended to highlight some of the techniques that are being used to restore and repair old structures. The Corps of Engineers is responsible for the maintenance of many old structures in its building inventory, some because of their historical significance and others to allow the structure to continue to be useful with proper maintenance and repair. Because of their historical significance or location in historical districts, some of these structures must incorporate restoration technology into their repair strategies while others can receive customary proper maintenance and repair techniques to keep them in proper service. Regardless of the reasons for repair, proper and high quality restoration techniques will always serve well for long-term care of brick and stone masonry structures.

Throughout the text of this report, certain repair and restoration procedures and techniques have been described which are considered to be beneficial in preserving the state of older masonry structures. Table 5 is a summary of the case histories presented in this report. It gives the structure information and the solutions for repair together for ease in further studying the case histories. While each structure will have unique conditions which dictate the level of effort to be used in the repair or restoration, the procedures and techniques that are discussed here will help to further understand the reasons why these techniques are used. There are many more techniques than can be discussed in one text. This discussion is only intended to recap the techniques used in the reported case histories.

Surface Cleaning

Generally speaking, surface cleaning will be one of the most common repair and restoration techniques used. It will be discussed first, but it should be pointed out that it is not necessarily the first operation that should be undertaken. Chemicals are often used in surface cleaning and their movement into the pores of a structure can be detrimental to the health of the structure and to further restoration efforts. Wherever possible, surfaces should be sealed or repaired before working with chemicals when chemical penetration would be detrimental. A case in point is tuckpointing. Surface-cleaning

Table 5
Summary Table of Case Histories

Structure	Type of Construction	Cause of Repair	Repair Materials and Procedures
U.S. Capital	Stone masonry	Exposure deterioration	**Paint removers.** Spray applications of turpentine based solvents, chloride and alkaline-based paint removers. **Stone strengtheners.** Spray applications of silicic ethyl esters. **Stone replacement.** Masonry replacement of deteriorated sandstone with limestone. **Water-repellent coating.** Rolled application of silicone-based emulsion and binder.
Mississippi River Commission Building	Brick and stone masonry	Damage to brick surfaces; water damage	**Slate roof.** Removal and replacement because it had been installed incorrectly. **Brick repair.** Repointing and cleaning using a spray application of a mild acidic cleaner. **Sandstone.** Spray applications of paint remover for paint and limestone restorer to remove mortar. **Water-repellent coating.** Spray applications of a silicone-based water repellent
Rock Island Arsenal	Stone masonry	Structures needed cleaning	**Mortar replacement.** Repointing of mortar joints using a type N mortar **Stone Cleaning.** The majority of the limestone was cleaned using a strong alkali cleaner. A heavy-duty restoration cleaner was used on sandstone sills because alkali cleaners would cause damage.
Fort Norfolk	Brick masonry	Building restoration	**Building restoration.** Removal of a wooden porch and replacement of a second-story doorway to its original condition as a window was first accomplished. **Brick repair.** Repointing of brickwork was accomplished next with use of restoration brick. **Cleaning and whitewashing.** Cleaning of old paint and whitewash was done using a spray application of moderate-pressure water.
Tallmadge Boyer Block Building	Brick masonry	Building rehabilitation	**Brick repair.** Brickwork was replaced using replacement bricks or reuse of existing brick. Repointing of the mortar was also accomplished. **Repair using block.** Strengthening of existing walls was accomplished by backing them and attaching them to block walls behind the brick. **Sandstone repair.** Badly eroded sandstone sills were repaired by building them up with concrete designed to look like sandstone in a composite patching procedure.
Berkshire Place	Steel frame, concrete cladding panels	Cracking of Panels from structural movement	**Expansion joint design.** The concrete cladding panels were retrofitted so that they had expansion joints at needed intervals. **Crack repair.** Existing cracks in the panels were covered using an elastomeric patching material that expanded with movement of the cracks in the panels without causing crack damage to the patch itself.
Fort Sam Houston Gift Chapel	Brick masonry	Structural movement	**Structural repairs.** Tie-rod anchors were installed through the building to add support to the moving walls. **Masonry related repairs.** Openings in the walls were repaired by removing bricks and replacing them to fill the crack opening. Portions of the walls were repointed and the exterior was cleaned with a moderate-pressure water wash.
Hotel Oakland	Steel frame, brick masonry facade	Earthquake damage	**Brick stabilization.** Damaged walls were strengthened by tying them to the steel building frame using a specialized basketing system of attachment. **Core building strengthening.** Shear walls were added to the structure at the core stairwells and elevator shafts. Special shear walls were designed to hide behind the historic areas of the lobbies.

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chemicals can get into areas of structures through damaged joints. If the tuckpointing is done first before the cleaning, these areas will be protected.

Surface cleaning will be done for many reasons, among which are: removal of dirt, discoloration, and unwanted surface coverings. These will require different solvents and various levels of solvent. Wherever possible, the gentlest-means-possible philosophy of work must be used to protect the material beneath the layers to be removed. Start with water, if reasonable, and determine if that will suffice. If not, then progress through mild detergents and, as a last resort, to strong specialized chemicals to find a level of cleaning that will both accomplish the task and do the least damage to the substrate.

Quite frequently it will be necessary to use chemicals to accomplish the cleaning. The chemicals which are used should be chosen so that they are compatible with the substrate material. For example, strong acids are not recommended when the substrate will be attacked by the acid. Hydrofluoric acid is particularly aggressive to limestone, terracotta, and highly polished masonry surfaces. Demonstration of chemical compatibility on test panels should be a requirement in many restoration programs and is highly recommended. Use of these panels will help establish the proper chemical and the right strength of that chemical before it is applied to the main body of restoration.

Sandblasting is one of the methods that is currently used to clean surfaces. This method is discouraged because of the damage that the sand does to the substrate. In the MRC Building case history, the scars to the brick surface from sandblasting during a previous restoration were still visible after 35 years. The impact of the sand eats away at the brick's natural skin and exposes more porous material to the environment. In the Rock Island Arsenal case history, the use of sandblasting was prohibited because it would erode the distinctive hand tooling work on the stone that is part of the building's heritage. There are many gentler methods to use for surface cleaning than sandblasting.

The method of application of chemicals should always be in accordance with the manufacturer's recommendations unless they are detrimental to the structure being restored. When applying chemicals to and removing them from a surface, common sense should dictate the proper order of operations. It is generally acceptable in applying chemicals to work from the top of the structure down toward the bottom. This ensures that any chemicals that fall from the surface being treated do not come in contact with surfaces that have already been cleaned and which may be more vulnerable to the effects of the chemical due to their exposed nature.

Chemicals should be allowed to dwell on the surface for the amount of time recommended by the manufacturer, however they should be neutralized as soon as possible after that time and then washed from the surface. Strong acids are generally neutralized with bases and bases with acids to produce

neutral salts. The strength of chemicals used should not deviate from the manufacturer's recommendations, and the chemicals that have been applied should not be allowed to dry out during the dwell time. Drying concentrates the chemicals and in effect makes them stronger than they were when they were first applied.

Often a single application of the chemical will not completely remove all of the material to be removed. When this happens, a second application at the same strength or a weaker strength will be needed to complete the job. This process should be done according to manufacturer's recommendations for reapplication of the chemicals.

When rinsing chemicals from a surface, it is generally more appropriate to work from the bottom of the treated area toward the top. This technique floods the surface with a nonaggressive liquid, most often water, and dilutes the aggressive chemical already on the surface. It further ensures that the chemicals being washed from the surface will fall on a surface that is already wetted with the nonaggressive liquid, further diluting the waste. All these procedures are designed to minimize any additional damage to the substrate material being cleaned.

It is also important to remember to protect materials below and in the vicinity of the areas being treated to prevent them from being contaminated by wind driven spray or chemicals falling from the treated areas. Plants, building materials, personal property, and people are all considerations in this respect.

Test Panels

Test panels are used whenever the results of any treatment are uncertain. They are useful for choosing color of brick, approving tuckpointing techniques and skills, testing chemicals on masonry, determining dwell time, strength of chemicals, magnitudes of pressure rinses, and many other applications where it is prudent to try the process before approving its wholesale use. In cases of repair and restoration to older masonry buildings, test panels will generally be a portion of the actual structure. The choice of location of a test panel should be from some area of the building that is hidden or unobtrusive. Choosing a test panel area will minimize the aesthetic damage to the structure should a test turn out negatively. Test panels should be at least 4 ft by 4 ft in size to be able to judge the results of the test adequately.

All procedures applied to test panels should be executed by the contractor or technician who will eventually execute the work and the techniques used should represent those which will be used on the remainder of the structure. If environmental conditions such as humidity or bright sunlight are a factor on the majority of the structure, these conditions should be a part of any test panel demonstration. Coatings to surfaces should be applied and allowed to

dry for a minimum of 3 days to allow for curing or to see if there will be any color changes during that time.

The results of test panel work should be approved by the architect or engineer in charge of the work.

Condition Surveys

Condition surveys will help determine the condition of a structure and the level of effort necessary to bring it back to restored and repaired condition. Surveys can be as simple as visual inspection of the surface that needs repair or they can be extremely comprehensive such as the detailed surveys conducted by National Bureau of Standards (now the National Institute of Standards and Technology) in finding the damage to the stonework of the U.S. Capitol. The level of effort will depend on the type and severity of damage.

Visual surveys are most useful when the restoration involves cleaning and the damage has not gone beyond the surface. Structural surveys are necessary when the structure has experienced damage such as deteriorated brick, stone, or mortar, structural cracking, or other structural movement of the building. Stowe and Thornton (1984) wrote a guide to condition surveys of concrete structures as part of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) program which is a good guide to the different types of surveys that are available. These same techniques can be applied to brick and masonry structures. A more general text on condition surveys has been published by the American Concrete Institute (1993).

Brick Repair and Replacement

Due to the wide use of brick in construction during the 18th and 19th centuries, there are many brick structures that now are in need of restoration. Five of the eight case histories described in this report had restoration involving brick. Because of the advanced age of many of these structures, the availability of matching brick for repair or replacement may be poor to nonexistent. As a result, much of the brick that is used in restoration work involves reuse of existing brick or use of reproduction brick.

New brick can be used in the repair of older structures if the new brick matches the old in size, color, and surface texture. Repair will not look correct if any one of these items is ignored. It is important to consider the strength of the brick being used in connection with the strength of the brick that is not being replaced. If the new replacement brick is significantly stronger than the old brick, there can be problems of damage to the old, softer brick should the repaired structure experience structural movement or expansion due to thermal changes. It is desirable to keep the strength of the new and old materials the same.

Finding suitable, new, replacement bricks will be difficult, particularly if the structure is very old. There are a number of choices to consider when finding brick for repair and restoration. Reproduction brick is new brick that has been fashioned to look like old brick. The same caveats that apply to new brick apply here. Additionally, many reproduction bricks will not have the weathered look that the original bricks have and consequently will look different when used in large areas for replacement of damaged brick. Test panels should be constructed before committing to reproduction brick.

Bricks reclaimed during any brick removal associated with the restoration is one of the best sources of appropriate replacement brick. These bricks could come from any portions of the building that were being torn down during the restoration or as a stock of bricks that were salvaged during the repairs. The bricks reused in repairing the arch windows of the Gift Chapel in that case history were both bricks that came from a chimney that was demolished and not replaced and from bricks taken from the arch windows and cleaned and reused.

Frequently, if brick is damaged on the exterior surface the brick can be reversed and the interior face used as the exterior. This provides an undamaged face using the same brick, but there is the potential problem that the reversed area will not have the same weathered look that undamaged original brick had.

Fashioning bricks from ground brick powder and polymer binder can sometimes be used to provide bricks where no other source exists. The brick powder would come from pieces of damaged brick from the restoration and they would be fashioned into bricks for reuse. These bricks will have a different look due to the polymer binder so they should only be used where it would be difficult to distinguish this difference in appearance.

In some cases, bricks of special shapes may be needed and are not available. For instance, rounded bricks for special corner conditions may be necessary. It is sometimes possible to hand fashion these special shapes from more common old bricks from the project. This is generally a successful process if the bricks are soft and easily worked. If they are hard and brittle, the efforts to shape them may not be successful.

Several brick replacement alternatives exist that should be used only as a last resort effort. Use of slips or facings of old brick can be bedded in mortar to give the appearance of full, old bricks. Depending on the thickness of the slip and the condition of the brick, two or perhaps three slips can be made from one brick. This solution is only a cosmetic one and should never be used in any load-bearing situation, since the slips or facings will no longer be able to provide the bearing capacity of a full brick.

Bricks taken from other parts of the structure and used for restoration should only be used as a last resort. It is best not to damage another part of a building for repair if it can be avoided.

Finally, it should be mentioned that in repairing or replacing brick one should address the problem that first caused the need to repair or replace. If this is not addressed and corrected, then the condition will reoccur and cause need for additional repair later.

Mortar and Mortar Joints

In any type of rehabilitation or restoration to masonry structures there will be a need to determine if the mortar should be replaced. It is always a good practice to evaluate the mortar to see what can be saved and what should to be replaced. If the mortar is weak, crumbly, cracked, separated from the masonry, or missing altogether then it must be replaced. A visual examination of the exterior surface will likely reveal any of these defects. In most cases, strong, tightly bonded mortar will not need to be replaced. Only in cases where it is impossible to match the color of replacement mortar in the vicinity of the strong, old mortar should good quality, existing mortar be removed.

In general, if the mortar is of sound quality or if less than 1/3 in. of depth is deteriorated, there is no need to remove and repoint the masonry. However if the deterioration is more severe, steps should be taken to remove the deteriorated mortar, clean the joint, and prepare it for repointing. Old mortar should generally be removed to a depth 2-1/2 times the width of the joint to provide surface for good bond of the new mortar. This depth usually is between 1/2 in. and 1 in., but it can be more. All loose mortar should be removed regardless of the depth that is required to do so.

It is recommended that the joints be manually raked clean. This will prevent any damage to the brick or stone on either side of the joint. However it is not always possible to clean large jobs in this manner, and power tools are often used to remove the old mortar. Power tools can potentially affect the visual character of the masonry as well as lead to accelerated weathering damage, if not used properly. Their use should not be permitted without the consent of the architect or engineer on the project, and operator proficiency and technique should be demonstrated on a test panel before such permission is granted.

The mortar raked from a joint should be removed uniformly to the required depth. All mortar should be removed from the surface of the brick or stone on either side of the joint to provide a good bond surface for the new mortar.

It is not highly important that the replacement mortar match the historic mortar in physical and chemical properties. What is important is that the new mortar match the old in color, texture, and detailing. The new mortar should also be as soft or softer than the original mortar, and it should be softer than the masonry it is being used with (Mack, Tiller, and Askins 1980). The sand used in the mortar will play a significant part in the color of the mortar and one should pay attention to the color of the sand in the old mortar. Color can

also be adjusted by the use of pigments, but it is preferable to match color through the use of proper sand color.

The strength of the mortar should be weaker than the masonry it surrounds so that the mortar will fail, not the masonry, if the structure is affected by movement. The composition of the mortar will determine its strength as well as its properties for durability. The decision on what mortar to use will depend on the situation. The two binders most often used in mortar are lime and portland cement. Lime mortars are characteristically weaker than portland cement mortars as well as more porous. The lower strength of the high-lime mortars makes it a good material to use in terms of being weaker than the surrounding masonry, however the greater porosity will cause it to absorb more moisture. Portland-cement mortars, on the other hand, will be more durable and less affected by moisture and can be stronger than the surrounding masonry because of their composition. For the most part, the lime mortars are preferable to portland-cement mortars for their good repointing properties.

The techniques used to fill the joints with mortar are also important. Areas that have had mortar removed to a depth greater than 1 in. should be filled first. These areas should be filled in 1/4-in. layers with each layer being tamped for compaction and allowed to set until the mortar will dent when a thumb is pressed into it. Successive 1/4-in. layers are built up in this manner until the joint is filled. The final layer should be tooled when the mortar is at the thumb-indent stage. Tooling should match that of the original masonry. The finish texture on the mortar can help make it match the old masonry as well. The look of the mortar can be weathered somewhat by bristle brushing it after tooling to give it a rough texture.

Surface Treatments and Strengthening

Several of the case histories discussed in this text described surface treatments and methods to strengthen stone and masonry. Perhaps the most important point associated with these subjects is that any coating or surface treatment applied to stone and masonry should cause no damage to the material it is treating. That may sound very simplistic, but it is easily possible to put a coating on a masonry surface and thereby seal that surface so that internal moisture can not move in or out. This condition can cause water vapor to collect on the back side of the sealed surface, condense and, in the presence of cold temperatures, freeze and cause severe damage to the structure.

Surface treatments can serve as water repellents, stone and brick strengtheners, and techniques to repair and rebuild certain stone or masonry carvings. In each case, it is important to study the material being used in the restoration to ensure that the cure will not be worse than the disease. Whatever material is used should penetrate the surface pores of the material being coated but not plug these pores. This calls for using treatment materials that have a very

small molecular size and, in the case of liquid treatments, low viscosities. Materials of this nature will penetrate the pore structure of the masonry and coat the walls of the pores without filling them up with the treatment material. Liquids will be excluded from the pores because of their high surface tension properties but vapors will be allowed to pass through these coatings.

Stone strengtheners achieve their ends by penetrating the weakened materials and reestablishing bonds between the adjacent grains. If a strengthener does not fully penetrate through the damaged layer, the strengthened layer will be founded on a weaker subplane and will just transfer the stresses to that weak plane where any failure will occur. Low-viscosity strengthening materials will penetrate farther into the surface of the damaged structure and potentially reach sound material beneath the damaged areas to form its anchorage base.

The results of stone replacement techniques, like brick and mortar replacements, should match the existing structure in color, texture, and shape. As an example, the sandstone sills replaced in the Tallmadge and Boyer case history were made of concrete that was formulated to look like the sandstone they replaced. The sand that was used in the concrete was specially chosen, buff-colored pigments were mixed into the concrete and the surface of the sills was built up to simulate the stone that was missing. Any material that is used to strengthen stone or masonry should be tested on test panels before being used on a structure. Strengthening materials must cure for a period of time before they can achieve their results. During this cure time, their color can potentially change. The color that appears on the surface of a repair at the time of application may be different after 72 hr of curing. The use of test panels will prevent a color miss-match from happening.

Structural Repairs

Two of the case histories discussed in this report, the Gift Chapel and Hotel Oakland, dealt with structural repairs. Both of these restoration projects involved strengthening an existing structure. In the vast majority of cases where a restoration involves structural repairs, the intent will be to strengthen the structure. Masonry walls can be strengthened against lateral forces by tying the masonry to a stronger backing wall such as a steel column or a block masonry wall. Ties are used for this purpose and are generally placed in the mortar between the additional wall or are tied to it in some manner such as the special basketing systems used on the Hotel Oakland.

Strengthening procedures generally change the original structure by adding additional structural materials. For purposes of keeping the structure looking as it originally did, it is important to hide any structural additions to the greatest extent possible. Hiding new structure can sometimes be accomplished without compromising the project. In the case of the Hotel Oakland, shear walls were used to strengthen the structure. These did not compromise the exterior of the building. The tie rods used in the Gift Chapel restoration had

to be routed through the main sanctuary to beneficial. However, engineers chose locations for the rods so that they ran behind pews, and through ceiling areas for the most part. Where they couldn't hide the rods, they painted them the same color as their surroundings to make them as unobtrusive as possible.

4 Conclusions and Recommendations

This report has presented a number of case histories of repair and restoration to brick and stone masonry structures. Within the Corps of Engineers there are a significant number of such structures, many of which are old and historic because of their age and the history. It is important to understand the advantages of repairing and restoring these structures as opposed to razing them to build new ones. The advantages of renovating and restoring structures for their historic value is obvious. Less well understood and accepted however, is the value of restoring a structure for the preservation of its architectural style. Too often, excellent examples of an architectural style are destroyed in the name of modernization, and a part of our architectural history is removed forever.

From an economic point of view, repair and restoration are generally more economical than razing. The cost of labor and materials involved with demolition and new construction is often significantly higher than restoration, and the volume of materials that are reused in a restoration can drastically reduce the cost of procuring new materials.

In all forms of repair and restoration of brick and stone masonry structures, one key technique surfaces as the best course to follow in accomplishing the goals of the project. Whether it is the intention to repair, rehabilitate, restore, or clean, it is always best to try and accomplish those goals through the least harmful means possible. It is wise to consider the consequences of any repair or restoration technique to evaluate whether using such a technique will in some way cause more damage to the structure than is necessary. An example of following this approach would be to consider whether or not sealing a surface to keep moisture out would have the detrimental side effect of sealing moisture in as well and thereby creating a new and serious associated with the solution of the original problem. A further example would be using strong chemicals in a cleaning situation where mild detergent or plain water may accomplish the same end. The harsh chemicals will accomplish the task, but at a price of damage to the structure that is not warranted. In the long run, the gentlest-means-possible philosophy is the most prudent in care of any structure.

Cleaning brick and masonry facades is perhaps the most common technique employed in repair and restoration. It is also one of the least costly, providing one of the greatest visual improvements for the money. Conducting cleaning in a proper manner by using the proper techniques and taking the appropriate amount of time will pay off well in the ultimate judgment of the task.

Authenticity of repair materials is not a necessity in conducting quality restorations. Quite often it is impossible to find a material that is of the same color and physical composition as one that was produced perhaps hundreds of years earlier. In these cases, the best effort that one can make is to provide a material that will accomplish the same task at the same time as looking like the original material. The most important properties that a repair material should have are good color and texture match and compatible strength characteristics with the original materials.

There is no one proper way to repair or restore any structure or to work with any one material. Proper guidance can come from many sources. The extensive work that the National Park Service had done on repair and restoration provides an excellent source of information on proper repair and restoration techniques. The series of Preservation Briefs compiled by the National Park Service and published by the Department of the Interior is recommended as an excellent basic guide for members of the Corps of Engineers team involved in brick and stone masonry restoration projects.

The structural repairs described in this text make use of one of the most important aspects of repair and restoration to brick and stone masonry structures. In all cases, it is most beneficial to hide any structural repairs that are not a part of the original structure to preserve the original look of the building. As was the case in the restoration to the Gift Chapel at Fort Sam Houston, it is not always possible to completely hide structural repairs. In those cases, minimization of the structural intrusion is advised.

Much has been done to provide for structural repair and strengthening of old buildings. However, this area of restoration is still in need of more advanced techniques and more innovative materials to accomplish these tasks. Research in this area of restoration is greatly needed, particularly in the areas of providing better techniques for transfer of brick and masonry wall loads to other supporting structural supports and for improved methods of strengthening old masonry structures to resist earthquake loadings.

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13. ABSTRACT *(Maximum 200 words)*

The purpose of this study was to develop, review, and report case histories of repair and restoration to damaged brick and stone masonry structures for the purpose of presenting many acceptable repair and restoration techniques in use today. It is designed to familiarize the reader with some solutions to masonry restoration as well as provide further reference material for more detailed study.

The study is organized to give a background of each structure, the general climatological data for the area in which the structure is built, a description of the problems the structure was experiencing or the reason for the rehabilitation, a review of the solutions and techniques used to accomplish the restoration, and the performance to date of the repairs that were made. In several cases, additional research information on repair techniques and repair goals have been provided to supplement the data on the repair. The case histories have been chosen to give a broad review of different types of deterioration to brick and stone masonry construction and the chosen solutions. The cases reviewed cosmetic restorative work as well as structural restoration and structural upgrading to earthquake resistance standards.

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