Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Roofing as an Essential Element of Structural Integrity

Samuel Y. Harris
S. Harris & Co., Philadelphia, PA USA

ABSTRACT: Eastern State Penitentiary was and is a monument to the Quaker notion of one's "inner light". The idea of rehabilitation during incarceration had no western architectural manifestation prior to this, the first use of the term penitentiary. Today it has proved to be a veritable experimental station of temporary stabilization techniques, particularly as it has related to roofing, specifically, and water management, generally. Intervention in the deterioration processes began in earnest in the early 1990's; however, the rate of intervention was less than the rate of disintegration until quite recently. Since the closing as a prison in 1973, the engineering challenge has been critical stabilization of the exterior walls, waterproofing and restoration of roofs and skylights and selective conservation of interior masonry, plasterwork and furnishings, more importantly to gain a positive balance in this equation with sporadic, unreliable, and generally abstemious funding. The efforts are further intended towards its successful preservation and interpretation of its history. This paper will provide the case study of the stabilization and rehabilitation of roofs of this building in which analytical methodology, inspections and testing, intervention techniques and innovative materials are examined for over seventeen years of efforts.

1 INTRODUCTION

Eastern State Penitentiary occupies a site of over eleven acres (approximately 4.5 hectares) in what at the time of its initial construction was farmland and orchards approximately a mile and a half (2.5 km) from the center square of the then rapidly growing city of Philadelphia. Designed by John Haviland, the plan for the facility was inspired by notions expounded and articulated within the community of the Society of Friends, as known as Quakers.

The initial construction phase began in 1822, and John Haviland's original scheme was completed in 1836. Inside the forty foot (12 m.) perimeter walls, several cell blocks and auxiliary buildings were added, and some buildings were demolished over the course of operation which ceased effectively in 1969. Ultimately, the facility was sold to the City of Philadelphia, and ceased all operations involving inmates in 1973, see Fig. 1.

Through the efforts of concerned citizens coming together from a number of different interests and positions, an Ad Hoc Committee was formed and studies were commissioned through grants from various foundations.

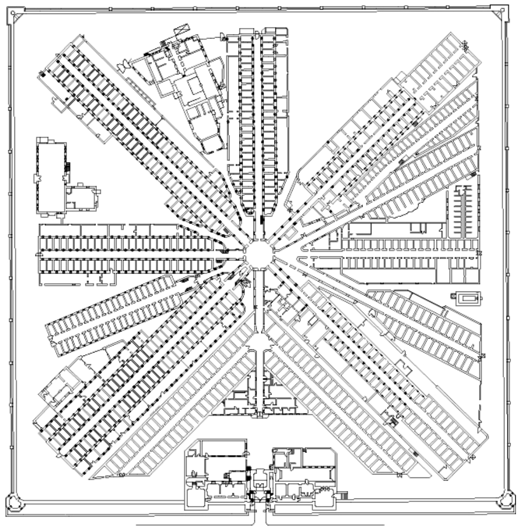


Figure 1 : Eastern State Penitentiary Site Plan

1.1 Roofing Campaigns and Decay Patterns

There were several roofing-substrate combinations covering the 56,000 m^2 of original roofing surface. The most common were coincident with the respective eras of construction. The earliest roofs were wood shingle attached to plank sheathing and timber substructure. This basic type accounted for the roofs of the original seven cell blocks, the administrative building and the central rotunda. All of these roofs were subsequently re-roofed with slate shingles and even later with asphalt shingles.

The second roofing campaign was standing-seam, painted sheet steel on wood sheathing and substructure. This type was applied to Cell Blocks Eight through Eleven, as well as the administrative building and the central rotunda in the late nineteenth century. Many of the exercise yards were also covered with relatively flat timber decks and hot asphalt in the later part of the nineteenth century. The third primary roofing campaign applied hot asphalt to concrete decks. This was used at Cell Blocks Twelve through Fifteen plus the covers of approximately half of the former exercise yards which were systematically being converted to specialty uses and works rooms in early twentieth century. This was one of the more questionable design decisions in the facility's history, but it was rivaled in it short-sightedness by the use of hot asphalt to repair and in some cases completely cover sheet metal roofing. The free sulphur radicals in the petroleum product converted to sulphuric acid and aggressively attacked the residual metal roofing. During the same era of the third primary roofing campaign, ca.1910, two new buildings were constructed with heavy timber trussed roofs, plank sheathing and Pennsylvania slate shingles.

By 1970, several of the roofing schemes were nearing the end of their respective useful lives. There was probably not a square meter that was less than fifteen years old. Because younger roofs were generally asphalt, even those were showing advanced deterioration from ultra-violet and ozone attack. The deterioration mechanisms were well established and in some cases accelerating quite rapidly at precisely the moment that all intervention in these processes ceased.

From 1970 until 1988, the site was in a state of neglect. In 1988 a comprehensive assessment was commissioned. The timber-covered exercise yard roofs had typically collapsed or were in an imminent state of collapse. Several structures were admitting water in gross quantities and every single roof was deficient in some manner or other. The immediate problem was one of hemorrhage control. For the next eighteen years, right up to 2006, the stabilization and preservation of this site has been dominated by efforts to cost effectively staunch the structure-threatening consequences of roof decay and failure. Beginning in 1988, the priority has been to save the major cellblocks, the perimeter wall, and the larger ancillary structures from physical collapse. The primary threat to these structures was related to water penetration, hence, diminishment of cross-section area of structural members. Following are three case studies of stabilization and rehabilitation of significant portions of the site which demonstrate the methodology and implementation of their respective invention solutions.

2 CELL BLOCK ONE AND ADMINISTRATIVE BUILDING TYPE AREA

Cell Block One was determined to be the single most historically significant resource on the site and the fabric of the roof, albeit compromised by decay, was deemed important to save in situ. This particular area was encapsulated with an entirely new redundant roof which covers the cell block's original roof. The design of encapsulation of the existing structure into a "tent-like" structure around it was like putting the structure into a time capsule. This rendered minimum disturbance to the historic fabric, while waiting for a later date and funds for more comprehensive repairs with an adhered EPDM (ethylene propylene diene modified) protective cover. The Administrative Building was also an early candidate for intervention. In this case the existing asphalt shingles were removed, the sheathing repaired, and a replacement adhered EPDM membrane was installed. EPDM was a preferred choice as it is a single ply synthetic rubber which was developed specifically to resist ultra violet radiation damage. The polymers are artificially cross-linked and the chains re-formulated such that subsequent UV energy does not rupture the polymeric chains. It is available in 40mm, 60mm, and 90mm thickness; it may be adhered, mechanically fastened, or loose-lain and ballasted; and it comes in black or white exclusively. Seaming is achieved with adhesive which means that installation is compatible in and around flammable and irreplaceable historic fabric. Installations in the late 1970s and early 1980s displayed premature adhesive failures; however, membranes installed in the last fifteen to twenty years are performing with little if any measurable deterioration. The single greatest vulnerability is installation workmanship. The long-term deterioration mechanism has yet to be established; however, there will be one, whether it is manifest or not at this point, see Figs. 2.

(a) (b)

Figure 2 : (a) Cell Block Two, during renovations, 2002; (b) Cell Block One, after renovations, 2002

2.1 Cell Block One Link, Central Rotunda and Other Links

The roofing exercises at Cell Block One and the Administration Building were followed by a modestly sized but extremely important intervention in the link between Cell Block One and the Central Rotunda. This particular link was critical to the safe passage through Cell Block One inasmuch as it provided a second means of egress; however, one of the skylights had collapsed into the corridor, rendering the link impassable, hence unsafe.

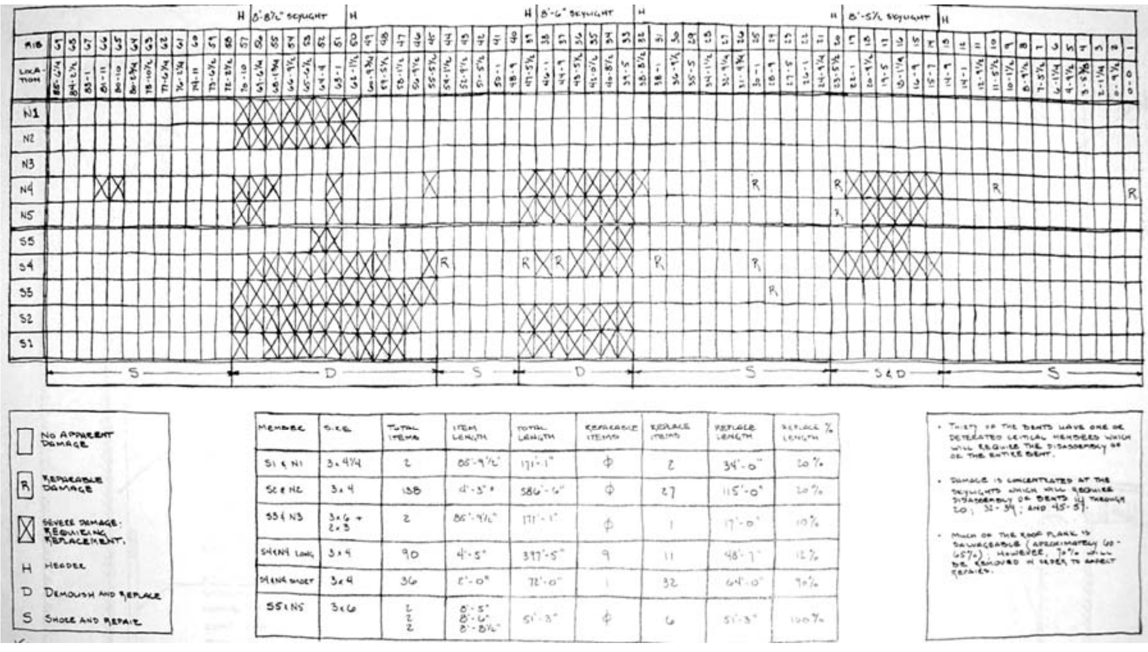
The project entailed documenting the each and every piece of the structure, evaluating each historic wooden roofing element, removing the old metal roofing, repairing deteriorated members or replacing those beyond reparability, installing a new standing seam lead-coated copper roof, and conserving the historic plasters. This approach was consistent with the long-range goal of managing the site as a "stabilized ruin", as was concluded as the operating principle identified in an exhaustive reuse study conducted in 1992.

The design of the replacement roofing raised an interesting and mildly frustrating issue of authenticity. The original roof structure and cover consisted of timber ribs surmounted with tongue and groove plank and a standing seam, steel sheet roof painted with red lead paint. The roof provided useful service for approximately sixty years with the primary maintenance requirement that the roof be repainted every five to ten years. At the end of its useful life there was considerable compromise of the sheathing ad structure as well as the loss of the sheet metal. Our charge was to provide a roof which would last longer and with lower maintenance and less collateral damage at the end stages of its useful life. In other words, replace the original system with a system which approximated the original roof in character and form but which need not match the materials or connections of the original. Normally, we face compromises of authenticity because of high costs of matching original materials or installations workmanship. In this case, authenticity was attenuated by exceeding the material quality and installation of the original construction.

2.1.1 Methodology

The project began at Link One, with a partial demolition to expose the form of the construction and the sizes of the elements. From this a matrix was prepared for each structural rib and each element within the rib. We assessed the restoration requirements of each specific piece of wood in the roof. From this rather precise assessment, the builder was able to submit a more precise bid, and we were also able to learn the exact costs of any modifications which may arise during construction. The merit of this approach, namely the inventory of every single element within the structure, has proven to be an invaluable management tool. As the demolition proceeded and more elements were exposed, we compared our assessment with the exposed conditions. Some elements proved to be in better condition than expected; others, worse. The matrix allowed us to control the adds and credits in an expeditious and accurate manner. We found that the areas of maximum damage from water intrusion were in the vicinity of skylight penetrations. This allowed in future investigations of even roughly comparable conditions to allow for greater replacement cost in comparable areas. This technique has allowed the institution to maximize retention of original fabric and to optimize cost control at the same time, see Table 1 and Fig. 3.

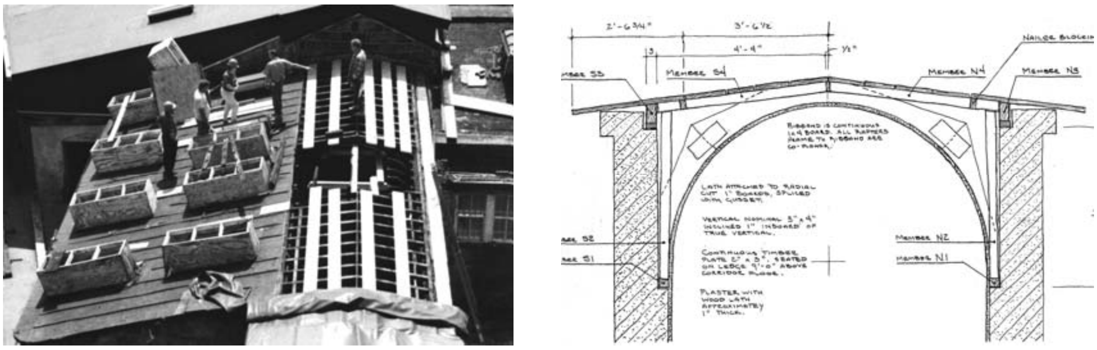
Table 1 : Matrix for Condition Survey of Structural Members



MEMBER	SIZE	TOTAL ITEMS	ITEM LENGTH	TOTAL LENGTH	REPAIRABLE ITEMS	REPLACE ITEMS	REPLACE LENGTH	REPLACE % LENGTH
S1 & N1	3x4¾	2	85'-9½"	171'-1"	ϕ	2	34'-0"	20%
S2 & N2	3x4	138	4'-3"	586'-6"	ϕ	27	115'-0"	20%
S3 & N3	3x6 + 2x3	2	85'-9½"	171'-1"	ϕ	1	17'-0"	10%
S4&N4 LONG	3x4	90	4'-5"	397'-5"	9	11	48'-7"	12%
S4&N4 SHORT	3x4	36	2'-0"	72'-0"	1	32	64'-0"	90%
S5&N5	3x6	2 2 2	8'-5" 8'-6" 8'-8½"	51'-3"	ϕ	6	51'-3"	100%

The detailed pathology of the sheet metal failure mechanism was studied at the test case of

Link One. Initially, the sheet metal failed because it admitted water in two distinct and regular modes. The first was at the flat seams of one pan connecting to the next; the second was at the eaves where the standing seam was inundated by occasional heavy rains, and the joint was actually submerged. When combined with modest pressure differential across the fine line pathway, water siphoned to the sheathing below. The water that entered through the flat seam lateral joints tended to penetrate further into the structure as it rolled across intersecting tongue and groove joints. Water that entered at the standing seams tended to collect at and to attack the fasteners of the standing seam attachment details.



(a) (b)

Figure 3 : (a) Section of the existing structure for Link 1, S. Harris, 2000; (b) Structural reconstruction and roofing campaign for Link 1, 2001

Ti Based on this and subsequent investigations of the metal roofing at Eastern State Penitentiary, we have concluded that sheet metal roofing is not a perfect membrane system at all and should more accurately be described as a metal “shingle” system, meaning that the seams and joints provide avenues of pressure differentially driven water to surmount the seams and flood the joints. The metal, however, is an excellent protective cover for a more vulnerable, but improved true membrane below. These properties tend to work against the long-term durability of the system as a whole. Through the experiments at Link One, we have reasonably demonstrated that by switching the classification from a membrane system to a “shingle” system, we can redetail the metal roof for greater integrity and durability at a lower cost. See Fig. 4.

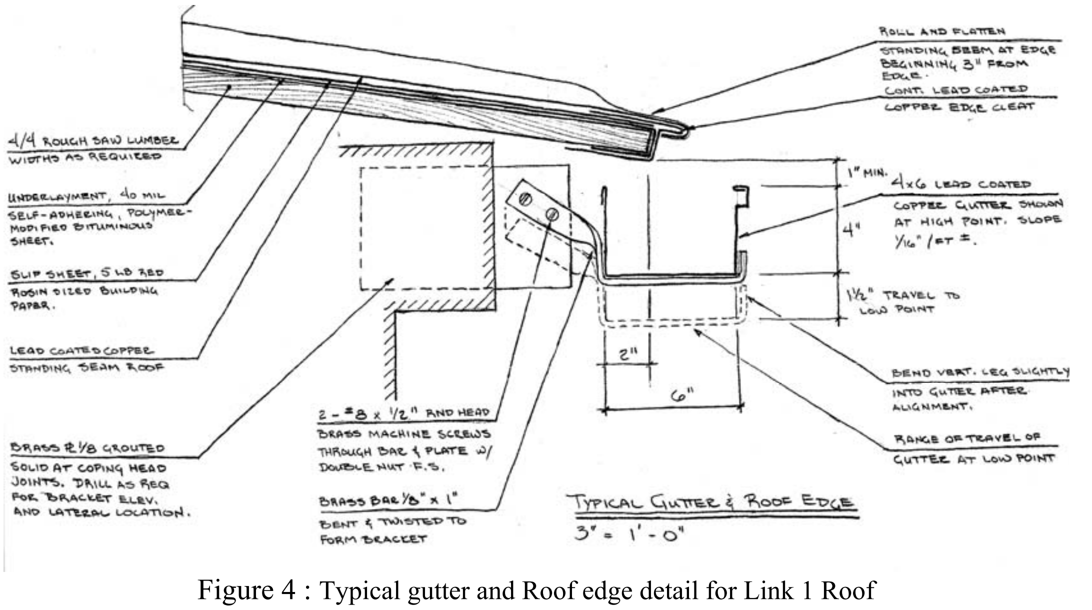


Figure 4 : Typical gutter and Roof edge detail for Link 1 Roof

By revising our attitude toward sheet metal as a roofing system, we now tend to view the metal as a physical cover and protection for the membrane roofing below the metal. In the reinstallation for Link One, we placed a 40 mil adhered EPDM membrane on the reconstituted and restored sheathing. We nailed the ties through the membrane with metal grommets around the nail shank to seal the perforation. When the sheets were seamed we deliberately left the seams open without solder. We have found that this system initially admits more water than a fully soldered system; however, this approach accepts the admission and directs water to the edge collectors without resulting interim damage.

The Central Rotunda and the link structures at Cell Blocks 2, 3, 4, 5, 6, 7, 10 and 11 followed Link One closely in time and for identical reason, namely safe egress and access to the major cell blocks. Once again we were replacing sheet metal over sheathing and ribs in the links and sheet metal over a twentieth century steel structure at the rotunda. Based on the lessons at Link One, we again used a "shingle" approach with a protected membrane below. Instead of the lead-coated copper we used at Link One, we used a more conventional painted, galvanized sheet steel cover.

We have found on other similar projects outside of Eastern State that the approach toward sheet metal as a protective cover and not a true membrane is viable and extremely durable, and have continued to modify the system which we developed at Link One. We have found that the solar gain of metal roofs is sufficiently high to potentially bind the underside of the sheet metal to the EPDM below and shift it with the sheet metal as it contracts and expands. We have not actually observed this condition with sheet metal and EPDM, but we have seen it happen on a failing project where a patented product employing modified bitumen and laminated with polyester film was used as the membrane below the sheet metal, and the temperature of the underside of the sheet metal was high enough to soften the amorphous solid of the bitumen and cause it to adhere to the metal. Consequently, the cooling metal dragged the adhered membrane. With repeated cycles the membrane began to rupture. Even though the EPDM has not shown this tendency; it is an amorphous solid and there is a temperature at which is can soften and potentially adhere to the metal even though that point may well be beyond any realistically achievable level, at least not in Philadelphia. Even so, we now recommend that a layer of rosin sized paper slip sheet be installed between the sheet metal and the membrane. We have also experimented more with the seam joinery techniques. Theoretically, as we are now relying on the EPDM membrane as the roofing and the sheet metal as a protection cover, we could leave the seams open entirely; and we have, indeed, left standing seams open. Flat horizontal seams, however, are more problematic because inundation is absolute and protracted. For flat seams we have, in one case, turned to automobile technology for ideas. The head of an engine block of an internal combustion engines is sealed with a gasket. The gasket is, in turn, sealed to the metal block with adhesives specifically designed to bond to metals and to withstand high temperatures. We have abducted these adhesives and used them with sheet metal roofing with success and cost savings.

3 EXPEDIENT TEMPORARY ROOFING MEASURES AT CELL BLOCKS FIVE AND SIX

As the above projects were underway, the bulk of the site continued to deteriorate at accelerating rates. We had engaged in several fruitless experiments with "temporary" roofing measures. One of the more notable failures involved the use of conventional polyethylene sheet goods, some as thick as 12 mil, both transparent and black. The polymer is simply too brittle at temperatures below 5°C to withstanding buffeting by winds. Although the material is also theoretically vulnerable to ultra-violet degradation, the brittle fracture properties preclude any display of UV vulnerability. The plastic simply shreds in cold winds. We have had similar results from polyester tarpaulins, which do deteriorate rapidly from UV and ozone embrittlement. See Fig. 5.

Figure 5 : Links to cellblock 2, 10 & 11 before repairs, 2003.

The most promising option for temporary roofing which we have identified is a modified, medium-density polyethylene sheet specifically formulated for external, all-temperature installations. The polymeric modification is a process of "pre-fracturing" and cross-linking the polyethylene polymer chains, much as is the case with EPDM. One consequence is that the elongation property of the material is enhanced such that the brittle fracture point is substantially lowered, resulting in increased resistance to fracture at low temperatures. The cross-linking also increases UV and ozone resistance. The distinguishing feature of this class of products, however, occurs as a result of the manufacturing process. As the polyethylene is drawn from and cooled in the mill, it is effectively "prestressed" in tension, resulting in built-in residual stress in the sheet. If the sheet is re-heated to a point where the amorphous solid begins to soften, the residual stress is released and the sheet shrinks in dimension. The initial application of such "shrink wrap" materials was for the protection of items during shipping. In our application we have effectively shrink-wrapped whole buildings, or, at least, the roof portions of whole buildings. See Fig. 6.

Figure 6 : Tuffwrap work on cellblock 5 & 6, 2005.

The material comes in either a transparent form, which is actually the unaltered nature of the polyethylene, or in black, which is achieved by the inclusion of 2.5% concentration of carbon black in the polymer matrix. The carbon black allegedly provides added UV protection. By implication, this means that the transparent film has less UV resistance; however, we have not employed the material long enough to determine whether this is the case or not. Installation requirements include particular attention to avoiding sharp projections or edges which could puncture the sheets and attention to temperature at the time of initial installation.

Although the residual stress release will effectively "shrink" the material, subsequent temperature fluctuations do result in continued material expansion and contraction. If the material is stretched on the building in very hot weather and shrunk to a tight fit, subsequent shrinkage due to cooling can rupture the fabric. Similarly, but not as disastrously, if the material is installed and shrunk in very cold weather, it can and will relax in warmer weather. If the loose or stretched material is subjected to wind buffeting during warmer temperatures, the consequences are not as significant or to the same degree as in depressed temperature conditions.

The material is available in three thicknesses; however, we have found that only the heaviest of the grades, namely the 20mil material, is acceptable. The first installation, at the link of Cell Block 11, employed a 10mil fabric, and it utterly failed during the first winter. The cost of the 20mil system is approximately USD20/m^2 installed, not including any structural preparation of the roof to withstand the weight of the installation crew. Another consideration is that the manufacturer and installers do not warrant the system for more than two years. This is not an inconsiderable limitation on any temporary roofing approach, particularly due to the duration of the impermanence. We have placed “shrink-wrap” on Cell Blocks 5 and 6, the Kitchen, half of the Industrial Building, the link of Cell Block 11, and the skylights of Cell Blocks 4 and 7. The installations did suffer from sporadic installation flaws; however, the system does lend itself to repair. All of the installations are performing quite adequately; although the oldest installation is barely two years old. Those installations, namely Cell Blocks 5 and 6, have endured two complete seasonal cycles; however, this past winter was one of the milder winters on record and prolonged cold temperatures combined with heavy wind were rare or non-existent. In short, the system is not fully tested but very promising.

4 CONCLUSIONS AND FUTURE RESEARCH

The summary of experience with the roofs and roof structures at this large of a site, and with this many systems over this long period, has been a virtual laboratory of causes and effects of roofing failures on structures. The experience has afforded the institution and the respective professionals to consistently and logically compare various approaches and results, and to refine subsequent interventions based on the lessons learned. Rarely has an historic site provided such a wealth of well earned comparative analysis and experimentation, as it relates to the efficacy of temporary versus permanent options, or the continuity of management to not lose heart or to forget the recent past. Probably, the most enduring and graphic lesson of Eastern State is the unassailable importance of maintaining roofing integrity relative to structural conservation. Without viable weather protection, no structure can survive the elements for very long.

The purpose of this paper has been to expose the audience to recent, large scale efforts in the area of roofing as applied to the historically significant site, Eastern State Penitentiary.

We have experimented with encapsulation, metal roof technology, temporary roofing and have discovered many things through the tolerance of the operators of the site to risk experimentation. We have learned that sheet metal roofing, for example, despite a long history as a membrane system, is much better viewed as an outer protective cover of a true membrane. We have learned that the term “temporary” can become rather more “indefinite” and that unmodified polyethylene and polyester cover will not tolerate UV attack even in the relatively moderate latitude of Philadelphia. We have learned that considerable amounts of deteriorated fabric can be salvaged provided that the contract allows for on-going assessment and evaluation of the structure throughout the contract period; but more important that any technical or documentation lessons has been the lesson that an informed client willing to take well-reasoned risks can be the most important ingredient in the stabilization and preservation of a threatened site.

REFERENCES

Johnston, Norman et al. 1994. *Eastern State Penitentiary: Crucible of Good Intentions*, Philadelphia: Philadelphia Museum of Art for the Eastern State Penitentiary Task Force of the Preservation Coalition of Greater Philadelphia

Hardy, Steve, 1998. *Time-Saver Details for Roof Design*, New York, Mc Graw Hill Companies Inc

Harris, Samuel Y, 2001 *Building Pathology: Deterioration, Diagnostics, and Intervention,* New York, J. Wiley, chapter 5

Kieran, Timberlake & Harris, 1992 *Eastern State Penitentiary: Alternate Use Study*, *Volume 1 & 2,* For Eastern State Penitentiary Task Force a committee of the Preservation Coalition of Greater Philadelphia (Unpublished)

Websites

http://www.easternstate.org/stabilize/index.html