

**AN EVALUATION OF MECHANICAL PINNING  
TREATMENTS FOR THE REPAIR OF MARBLE  
AT THE SECOND BANK OF THE UNITED STATES**

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# **1. INTRODUCTION**

## **1.1 THE SECOND BANK OF THE UNITED STATES**

In order to address the deterioration of marble at the Second Bank of the United States, located in Independence National Historical Park (INHP), the Architectural Conservation Laboratory of the University of Pennsylvania in conjunction with INHP developed a conservation plan in 1999, as part of an effort to study the characteristics of the Pennsylvania Blue marble used for construction, document and analyze the conditions of the building's exterior facades, and recommend treatment options. One of the more evident and detrimental conditions of stone decay on the columns of the building's porticoes is incipient spalling, where lens-shaped fragments of marble have begun to crack and eventually detach in a pattern parallel to the column faces. The cause of the spalling is most likely a combination of several processes, including the foliation of the Pennsylvania Blue marble as a major contributing factor. While the poor weatherability of the marble is now known, the fact that many buildings of great historical significance, such as the Second Bank, were constructed with this stone has created a situation that requires an appropriate conservation response. The aim of this present study is to evaluate mechanical pinning repairs as a treatment option for incipient spalling stone with reference to the masonry conditions of the columns at the Second Bank. This evaluation will hopefully aid in conservation decisions necessary for implementation of the treatment.

## **1.2 MECHANICAL PINNING AS A CONSERVATION TREATMENT**

Where conditions of masonry include fractured and detached material, such as spalling or delamination, an ideal remedial treatment is one in which the weakened areas are reinforced by joining deteriorated stone with the substrate. Forming substantial structural integrity between the elements can secure the material in place, slowing or preventing further decay and detachment. Treatment options include the application of adhesives and grouts, as well mechanical pinning repairs. Incipient spalling is a condition of active deterioration in which a discontinuity exists behind the surface of the stone, with only limited accessibility; so that the injection grouting of fractures can offer only limited predictability of success. The insertion of pins through the masonry has the ability to distribute forces between the substrate and the spall in a more controlled manner in order to resist the stresses associated with deterioration. While this might appear simple in concept, the mechanics of how the pinning repair functions and how the treated stone will behave are complex. As with any conservation treatment, serious consideration must be given to the proper design and application of the repair, as well as a thorough understanding of the mechanisms causing stone decay.

## **1.3 CONSERVATION LITERATURE SURVEY**

The addition of pins or rods placed into stone for conservation purposes can be employed with a variety of materials and techniques. The requirements, scale, and application methods are typically determined by the type and characteristics of the deterioration. Pins inserted between two pieces of completely fractured stone can be utilized as a concealed

repair, also known as blind pinning. This method is commonly used to provide internal support in conservation of sculpture (Plenderleith, 1971), as well as architectural applications for elements such as finials, or for tombstones. (Grimmer, 1984; Park and Grimmer, 1989). On a larger scale, rods can be inserted into fractured structural elements such as beams and lintels. The technique involves drilling holes, usually of equal length, into each fragment, injecting an adhesive or grout into the holes, and then inserting rigid pins into each fragment. In addition, the surfaces of the fragments are usually coated with adhesive before they are joined together.

Conservation of wall paintings has also employed the use of small pins, primarily for reinforcing a surface layer to the substrate during detachment procedures such as a *stacco* method. (Mora, 1984; Botticelli, 1992)

In terms of treatment options for deteriorated masonry, mechanical pinning is often discussed with injection grouting as a repair designed to address stabilization of masonry elements. In this type of application the repair is known as a through masonry technique. The basic approach to such a treatment has been explained by several authors. (Wenzel, 1990; Weber, 1991; Mills, 1998; Croci, 1999; Robson, 1999) It can be used to stitch cracks, provide alternative routes for loads, and secure elements together; a key feature of mechanical pinning being that it allows for the retention of significant fabric, as well as providing a less intrusive in situ repair. Supplemental reinforcement from internal connections is employed in cases where tension stresses occur which the masonry cannot withstand, and the repair can be used both as local reinforcement of single elements and as global remedial action for the structure. The tensile resistant bars or rods, usually small diameter stainless steel threaded rods, are

grouted into position using a suitable cementitious or resinous grout, an appropriate coverage of which helps to ensure corrosion resistance of the bars.

Prudon (1979) describes in more details than most the basic function and application of a mechanical pinning repair to reinforce facing and backup masonry, mentioning also that anchors can be placed in individual segments of broken units to secure cracked elements. The technique requires drilling a hole no more than 1/2 inch diameter into a joint or through the face of the masonry, an epoxy adhesive with a gel-like viscosity is injected into the hole, and then an undersized anchor inserted. However, no indication of an anchor length or an effective embedment depth is given. The anchors recommended are stainless steel threaded rods or stainless steel tubes, in to which epoxy is injected directly through the tubing until it reappears on the surface after flowing back along the outside of the tubing. Two anchors are suggested for placement into masonry units and four anchors into joints. A publication by the New York Landmarks Conservancy based on work done by the Sandstone Restoration Study provides some detailed guidelines for the treatment as well, mostly addressing conditions of delamination. (*Sandstone restoration study*, 1982; Lynch and Higgins, 1982) For through surface pinning repairs the authors recommend that the holes be drilled to a width 1/8 inch greater than the diameter of the threaded pin, the maximum size diameter hole being 1/4 inch. The pin materials suggested are stainless steel, bronze, Teflon, nylon, or glass-reinforced Teflon, adhered with an epoxide resin-based system or a cementitious acrylic-based one.

The most commonly used material for pins is stainless steel, and where adhesives are used threaded pins are preferred in order enhance the bond. The adhesive

must be strong enough to hold the pin in place and transfer load between elements, therefore for structural or external situations an epoxy or cementitious system is typically utilized. Applications with other pin materials and adhesives have been used as well. Selection is usually based on factors such as strength, and compatibility with the masonry and environment. Alessandrini et al. (1984), for example, reattached detached fragments from a Roman era portal inside a medieval church with a blind pinning technique using Teflon pins and Paraloid B-72. Titanium threaded rods were embedded in cement mortar for the structural repair of marble elements at the Acropolis monuments in Athens, chosen because of titanium's excellent corrosion resistance and a low value of thermal expansion coefficient similar to the stone. (Zambas et al., 1986).

A case study by Levine and Harris (1991) demonstrates the variety of scale of reinforcement that was used to stabilize a terra cotta cornice. Epoxy anchors were not acceptable because of the high moisture content of the concrete fill, so mechanical anchors with expansion assemblies consisting of stainless steel rods varying in length from 9 inches to 6 feet and 7/16 inch diameter were used, secured in place at the cornice facing with aluminum plates and steel nuts. Anchor placement varied according to the location of cracks.

The benefits of using ceramic pins have been addressed by Fiori (1995). In addition to their good mechanical properties, ceramics are also advantageous because of their excellent stability, a similar thermal expansion coefficient to stone, and their good adhesion to binding mortars. Unfortunately, they also tend to be expensive, especially materials such as silicon nitride.

Kreilick and Matero (1996; Oliver, 1997) experimented with small-scale through

masonry pinning systems that did not require the use of adhesives to secure detached fragments of sandstone at a rock art site in New Mexico. A proprietary system, Helifix wall ties of 8 mm diameter, and stainless steel threaded rods size 6-32 diameter and 4 inches in length inserted into a nylon sleeve were field tested. The advantage of each of these systems is that they provide a degree of retreatability not available with pinning methods employing epoxy and cementitious grouts.

For a repair to fire-shattered church window tracery, Ashurst (1998) used fiberglass pins with an epoxy mortar. The pins were then covered with wire armatures and built up with mortar to recreate the tracery profile. Wood and Burns (2002) also designed a repair at the same church for another section of fractured window tracery and in doing so examined Ashurst's previous work that had been done in the 1970's; and which had now failed. The authors felt that it was unsuccessful because the pins were too large (15 mm diameter), spaced too far apart (45-60 cm), and placed in locations which were under considerable structural stress. Additionally, since plastic pins have a high coefficient of thermal expansion, failure resulted from the difference in thermal movement between the slender detached nosing and the mullion stone substrate. Their treatment was designed to ensure that the repairs were confined to the tracery and that the masonry could continue to accept minor thermal movement in the mortar joints. The pins used were two strands of thin copper wire twisted together and inserted at varying angles across fractures to provide a dovetail. All pins were inserted a minimum of 1 inch beyond the fracture and seated in an epoxy, which was described as having a degree of flexibility.

While Wood and Burns were critical of Ashurst's failed repair, their own pilot

project was undertaken without any preliminary testing. Some indication of how a mechanical pinning repair might function can be determined from examining properties of the pins and adhesives, but pinning treatments are an integrative repair and testing is usually necessary to properly evaluate their strength and behavior. Since pins provide tensile reinforcement, assessing the strength of the repair can be conducted by pullout tests, as well as bending and shear testing. Prudon (1979) conducted field pullout tests of installed anchors and suggested that 600 to 800 pounds of load should be sufficient to hold masonry units into a wall. But, not surprisingly, most other evaluations of treatments involving the introduction of reinforcement have been for structural applications, which can be somewhat limited in correlating to smaller scale pinning repairs.

The concept of inserting rods or pins in stone is not unlike a reinforced concrete material, and a similar evaluation methodology has been employed by Modena and Cecchinato (1985) in studying the structural behavior of limestone lintels strengthened with stainless steel bars. Rods of 11 mm diameter, both smooth and notched, were embedded in stone samples of 220 cm length with cement and a cement-acrylic resin mixture. Conducting bending tests, the crack patterns and failure mechanisms of the samples suggested calculation of strength could be determined with formulas used for reinforced concrete beams. The authors found a good correspondence between calculated and measured values.

Zambas et al. (1986), as mentioned earlier, used tensile reinforcement to reconnect separated parts of architectural elements such as beams, architraves, and lintels during restoration of the Acropolis monuments, and employed reinforced

concrete theory to determine the number and size of the bars. Testing was conducted prior to application using threaded titanium bars of 10 mm and 16 mm diameter inserted at various lengths into marble samples with a cement mortar. Results from pullout tests were considered successful since failure occurred at the marble, which was torn through the longitudinal axis because of the transverse strain created during the elongation of the bar. The results of the bending tests indicated that the action of the beam occurred in a linear elastic manner. Testing was also conducted with the same type of materials by Vintzileou and Papadopoulos (2001) to explore dowel action of the connections; the purpose being to determine the minimum cover required to ensure that shear failure would occur in a titanium bar and not in the marble. Test results obtained were in accordance with available experimental data regarding the dowel mechanism of steel bars embedded in concrete.

There are however differences between supplementary injection anchors and reinforced concrete, as pointed out by Gigla (1999); bars are not embedded directly to the substrate, so that the bond strength of a rod depends on the injection technology as well as properties of the existing material; and measurement of maximum test force without considerations of displacement offers limited knowledge of load bearing capacity. A study by the author evaluated the bond strength in field pullout tests considering 12 mm diameter reinforcement bars and threaded rods inserted 20 cm into stone with a cementitious grout, concluding that 0.5 mm displacement was adequate to define ultimate load for structural improvement applications, but that further research is needed to develop limit states of displacement in terms of structural safety.

What has often been overlooked in the assessment of mechanical pinning repairs

is the disadvantage of the introduction of steel and titanium reinforcement, which subjected to high loads, can deform and remain in the structure, hindering a future repair. A valuable perspective to evaluations of strength has been offered by Van Balen et al. (1999) in seeking a solution to reconnect broken stones of architectural elements as part of an anastylosis project at an archaeological site in Turkey. Considering the original brittle behavior of the stones, a technique was developed with an epoxy adhesive, filled with powdered limestone to reduce its adhesion capability so that it had a slightly lower strength than the stone, and fiberglass pins that would break at a lower load than that which would cause the stone to break. In this way an earthquake, for example, would cause the repaired stone to fracture at the same place as before. The system was analyzed using structural restoration methodology in laboratory testing with 7 to 16 mm diameter bars ranging in length from 11 to 15 cm. The treatment was designed so that the bond between the bar and the epoxy would always fail first, as it was weaker than the bond between the stone and the epoxy.

## **2. MASONRY CONDITIONS AT THE SECOND BANK**

### **2.1 HISTORICAL BACKGROUND**

Designed in 1818 by William Strickland, and constructed between 1819 and 1824, the Second Bank of the United States is one of the earliest public buildings in the country inspired by classical Greek architecture. It is also among the first monumental buildings to be constructed of Pennsylvania Blue marble, a locally quarried stone that was admired for its bluish gray hue, and was later used for many other notable Philadelphia buildings. Located on the south side of Chestnut Street between Fourth and Fifth Streets, upon its completion the Second Bank received wide praise by both residents and visitors to the city. The success of the building not only launched the career of Strickland, but helped to set a precedent for this mode of architectural design in America. Its influence was greatly advanced by the fact that several of the bank's eighteen branches were designed in a similar manner. (Sutton, 1992: 26)

As its name implies, the Second Bank was the federal government's second attempt at establishing a national banking institution, after Congress failed to renew the charter of the First Bank of the United States in 1811. As the country's financial situation fell into disarray due to the costs of financing the War of 1812, the necessity of the government to easily secure loans and regulate currency led to a federal charter for a new Bank of the United States in 1816. The main office opened in Carpenter's Hall in 1817 and became the principal depository of the United States Treasury. (Hammond, 1956: 244) In 1818 the board of directors commissioned the design of a bank building, "... desirous of exhibiting a chaste imitation of Grecian Architecture, in its simplest and

least expensive form.” (Gilchrist, 1950: 55) Strickland’s design complied with north and south facades copied from the porticoes of the Parthenon, as taken from James Stuart and Nicholas Revett’s *Antiquities of Athens*, Volume II (1787).

The Second Bank is a primary example of early nineteenth century aesthetic values; a desire for simplicity, universality, grandeur, and beauty achieved with economy. (Maynard, 2002: 255). In addition, the building represents a period of time when Philadelphia was the financial center of the country, though for political reasons the Bank’s charter was not renewed in 1836. After a brief period as the United States Bank of Pennsylvania, it served as the Custom House until 1935. The building was acquired by the National Park Service in 1939 and is now part of Independence National Historical Park.



**Figure 2.1 The Second Bank, Chestnut Street, 1859**  
Free Library of Philadelphia

## 2.2 MATERIALS AND CONSTRUCTION OF THE PORTICOES

The north and south porticoes of the building are each approached by a flight of steps and consist of an entablature and pediment resting on eight columns, each four feet, six inches in diameter at the base, and 30 feet in height. In the classical Greek Doric manner the columns consist of twenty flutings and arrises. The breadth of the building is 87 feet and the depth of the porticoes is ten feet, six inches.

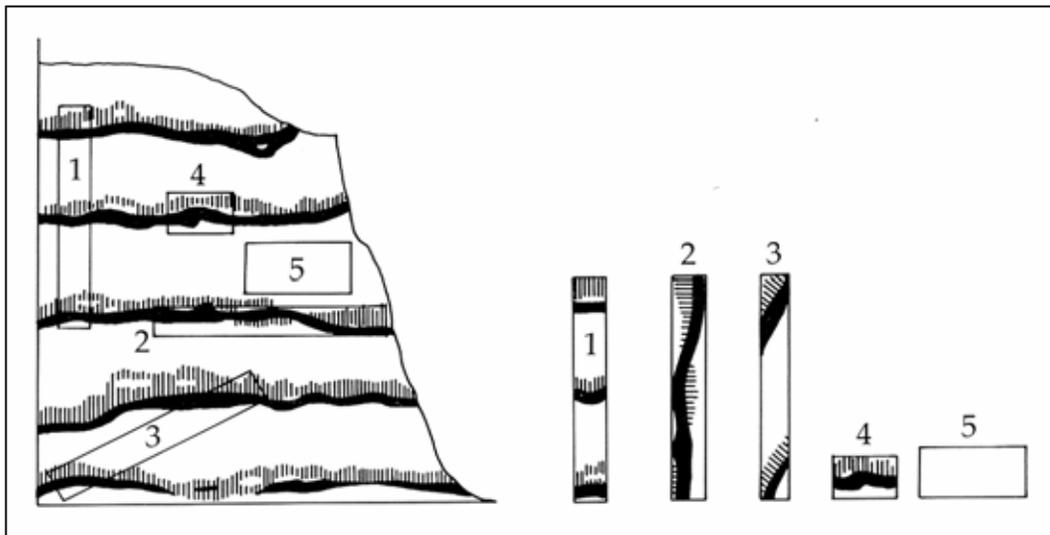
The Pennsylvania Blue marble used for the building was found in Montgomery County, a short distance from the city. The quarries in this region were opened around the 1770's and the stone remained a popular choice for major buildings until about 1840 when improved transportation methods saw the introduction of other marbles to the area from the northeastern part of the United States. (Merrill, 1910: 223).

Accounting records for 1819-21 indicate that the marble for the porticoes, a white variety of Pennsylvania Blue marble, came from Hitner's Quarry in Marble Hall, Montgomery County. (*HSR*, 1962: 5) This quarry was described in 1858 as follows:

The largest quarry of all is that of Marble Hall; here the strata dip to S. 20°, E. about 85°, presenting in one or two places a flatter inclination. This quarry is not less than some 400 feet in length, and at the top is 60 or 70 feet wide. The greatest depth to which the quarry has been sunk is 265 feet. At this depth the stratum of white marble, for which the quarry is chiefly wrought, has a thickness of 5 feet; but the usual thickness of this bed of pure white stone is 8 feet, that of the pure and clouded white together being generally about 20 feet. Mr. Hitner has quarried blocks 6 feet in thickness, though the general thickness of the blocks readily procurable does not exceed 2 ½ feet. (Rogers, 1858: 215)

Given the magnitude of the project, the builders would have controlled the operation of the quarry and the selection of the marble, which the accounting records

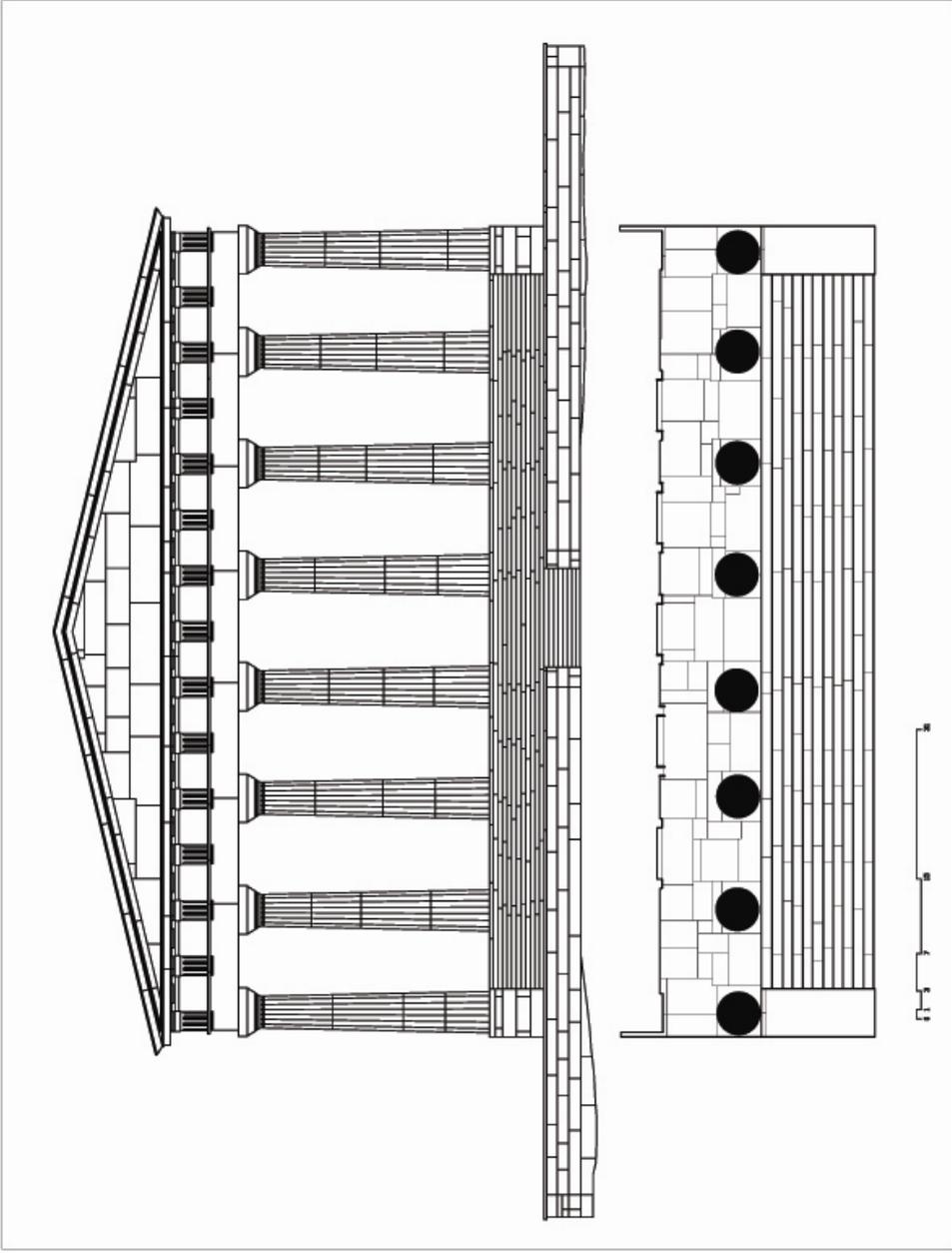
also confirm. (HSR, 1962: 5) This means they were freely able to choose the appearance and location of the stone desired, and were responsible for the fact that the drums of the columns were laid with the marble's foliation planes perpendicular to the ground, or what is often referred to as the weak direction of the marble. It is possible that Strickland wanted columns that showed a vertical pattern. It also may have been less expensive to quarry stone for a few large drums in this manner rather than many smaller drums. Or the stonemasons may have felt that it would be easier and safer to carve the flutings on the columns the way the stone was eventually laid. Whatever the reason, this decision would have been reflected in the quarrying method, and the operation would have been directed toward acquiring the desired features; whether aesthetic, economical, or for issues of workability.



**Figure 2.2 Marble from the same quarry face**

Block 5 most closely resembles marble quarried for the columns.

Rockwell. *Art of stoneworking*, 1993.



**Figure 2.3** Second Bank of the United States, South Façade  
ACL, University of Pennsylvania

Since the columns are not uniform in their number and size of drums, the largest drums, which are approximately nine feet in height, possibly reflect the largest bed of stone that was able to be either quarried or transported. Quarrying in the early 1800's would have employed the use of drills and wedges to dislodge the stone. Blocks could then be roughly squared to a rectangular shape and then roughed again to form a drum, either at the quarry or at the site. After transportation to the building site the drums would have been cut to the required lengths and the columns erected by hoisting the stones into place.

Each column consists of either four or five drums, but it is not known from the documentary evidence what type of dowels were used for their alignment. Traditional methods included the use of iron, cedar or slate dowels set in molten lead. Iron would seem to be the most likely choice at the Second Bank. While no structural iron was used in the construction of the building, iron was used for reinforcement, such as the iron chains encircling the brick piers of the basement (Gilchrist, 1950: 30), as well as iron rods used as reinforcing members of the arched openings of the bank's interior spaces. (Condit, 1960: 27) Other techniques for constructing columns also existed. Strickland's mentor, Benjamin Henry Latrobe, for example, used cannonballs inserted into hemispherical sockets to align the drums of the columns of the Bank of Pennsylvania in 1801. (Latrobe, 1994: 195) The original mortar for the buttered joints between the column drums would have been lime based.

Once the drums were in place the stonemasons would have cut an increasing number of sides on the column face to give a polygonal shape, in this case of twenty sides, and tapered the column's circumference to impart entasis. Using a caliper for

measurement, spaces between flutes could then be marked. (Rockwell, 1993: 93) “Fluting and rubbing of the columns” on the north portico was accomplished by twelve different individuals according to the accounting records. (HSR, 1962: 5) A typical practice would have been for the marble to be roughed with a point chisel and finished with a wide round-headed chisel. (Rockwell, 1993: 93) Afterwards, the surface would have been rubbed with an abrasive, such as a hard sandstone or pumice.



**Figure 2.4 Original foundation work of the north portico, 1964**  
Independence National Historical Park

Both north and south porticoes rest on foundations that include inverted arches to insure support of the columns. Strickland most likely learned of this technique from Latrobe, with whom he had apprenticed. Latrobe specified reversed arches in several buildings he designed, and John Haviland in *The Builders' Assistant* of 1818 describes their employment, “... so that if the foundations sinks the arches may resist the reaction of the ground; and then the whole wall will sink uniformly, or descend in one

body” (Haviland, 1818: 106) Archaeological excavations of the site in 1964 indicated the arches of the north portico were functioning as intended since no cracks were evident in the stone supports. (*HSR*, 1964: 1)

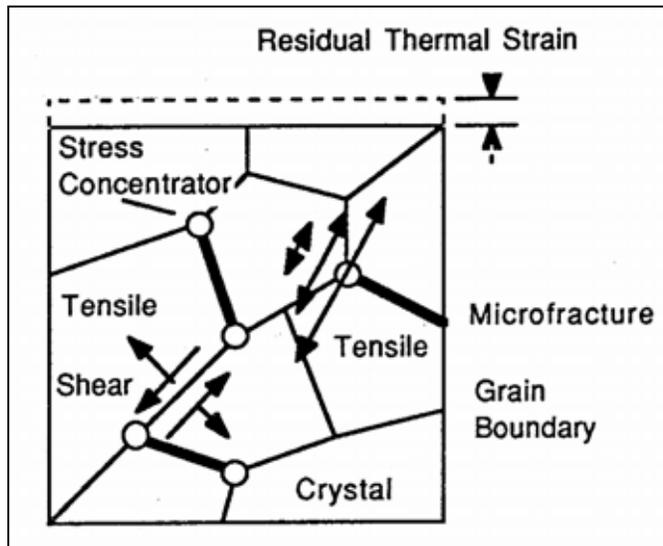
### **2.3 CHARACTERIZATION OF PENNSYLVANIA BLUE MARBLE**

Pennsylvania Blue marble has been described early on as “... a highly metamorphic variety of the ordinary magnesian limestone, crystallized and changed in tint by igneous action from within the earth, ...” (Rogers, 1858: 163) Marble consists mostly of calcite, formed by the recrystallization of limestone and possibly dolostone under pressure at great depth and at elevated temperature. Depending on the conditions involved in its geologic formation, the lattice of calcite crystals, as well as any accessory minerals, may align in a preferred orientation of their crystallographic axes and the fabric of the stone will develop a planar structure perpendicular to the direction of pressure, termed foliation. In addition, segregated masses of mineral inclusions will form distinct and visible layers throughout the marble, known as bands. It is the geologic process which gives a stone its distinctive qualities. Color change occurs, for example, where carbonaceous limestone is metamorphosed to marble in which carbon is concentrated as graphite in bands along joints, since it is along these surfaces where air and moisture have penetrated. (Winkler, 1994: 105-6) Internal stresses might also be present in the stone due to the metamorphic process, the release of which can cause microcracking after the stone is quarried, removing it from its origin. (Winkler, 1994: 205-6) A petrographic analysis of the marble at the Second Bank conducted by Jocelyn Kimmel

of the University of Pennsylvania in 1996, and geologist Elaine McGee's 1992 National Park Service study of the Pennsylvania Blue marble at the Philadelphia Merchant's Exchange provide descriptions of the stone's characteristics and mineral geometries.

Pennsylvania Blue marble contains at least 90% calcite. Replacement magnesium, to some extent, has also been identified through x-ray diffraction, confirming the presence of dolomite. (Kimmel, 1996: 14) The calcite grains are fine to coarse in size, and angular to subround in shape. The calcite is not strongly recrystallized; the stone is weakly metamorphosed, with a loose texture and a pronounced foliation fabric. (McGee, 1992: 13). The platy, micaceous mineral inclusions are typically muscovite, while other accessory minerals that have been variously identified include orthoclase, quartz, pyrite, and graphite.

Mineralogical characteristics of Pennsylvania Blue marble, such as composition, grain shape, and texture, are undoubtedly related to some of the types of stone deterioration found at the Second Bank. The main constituent of marble, calcite, is known to be thermally anisotropic, as several studies on marble deterioration have examined. (Zezza: 1985; Sage: 1988; Lindborg: 2000; Siegesmund: 2000; Weiss: 2002; Zeisig: 2002) Because of this property, thermal expansion of calcite crystals differs along different crystallographic axes and is often non-reversible. As a result, temperature changes in the material create tensile strains that can lead to micro-fractures.



**Figure 2.5 Thermal strain process in marble**  
 Sage. "Thermal microfracturing of marble", 1988.

From samples of marble at the Second Bank studied by Kimmel, micro-corrosion has been observed along grain boundaries and cleavage traces; these in turn act as weak micro-planes which augment the entry of moisture and salts into the stone. The accessory minerals, as well, disrupt and weaken the calcite matrix of the stone by forming disaggregated grains. Mica, because of its sheet-like structure, is believed to be responsible for planar failure of the marble. (Kimmel, 1996: 19)

#### **2.4 EXISTING CONDITIONS AND DECAY MECHANISMS**

During its more than 180 year history the Second Bank has endured significant deterioration of the columns on both the north and south porticoes. As early as 1891 it was noted that the "... front columns of the Custom House, exposed to the northeast storms in cold weather, became gradually dilapidated, and are now patched with pieces of new marble set into the decayed places; and such periodical restoration will always

be necessary.” (*Geological Survey of Pennsylvania*, 1891: 468) A condition survey of the building facades conducted by the Architectural Conservation Laboratory of the University of Pennsylvania in two phases (phase one in 1999 and phase two in 2003) provides the most recent assessment of the marble. The survey documented conditions of deterioration, stone characteristics, surface deposits, and previous treatments.

Although all of the columns do not display a similar amount or degree of decay; as a whole, the deterioration on the porticoes is some of the most severe found on any portion of the building. These conditions include weathering, such as contour scaling and differential erosion leading to a loss of surface detail. Erosion is especially pronounced along bands of mineral inclusions. Because of the presence of pyrite in the marble, a rust colored staining is evident on many surfaces as well. Active deterioration also includes cracking and incipient spalling of the marble on the column flutings and arrises. In these cases the outer layer or layers of stone have begun to break off in parallel layers from the columns. (See Figures 2.7 – 2.9) Cracking is almost entirely vertical or diagonal in orientation and spalling is often occurring on the arrises where two cracks in the fluting come to a head, hence dimensional loss and incipient spalling tend to be lens or wedge shaped. The crack depths are consistently oriented parallel to the surface of the columns, therefore parallel to the foliation orientation. The depth of loss is usually deeper where the cracks are wider apart and closer to the surface where they are narrower giving a diagonal profile to the shear.

**Table 2.1 Surface Area of Survey Conditions on the North Portico (in<sup>2</sup>)**

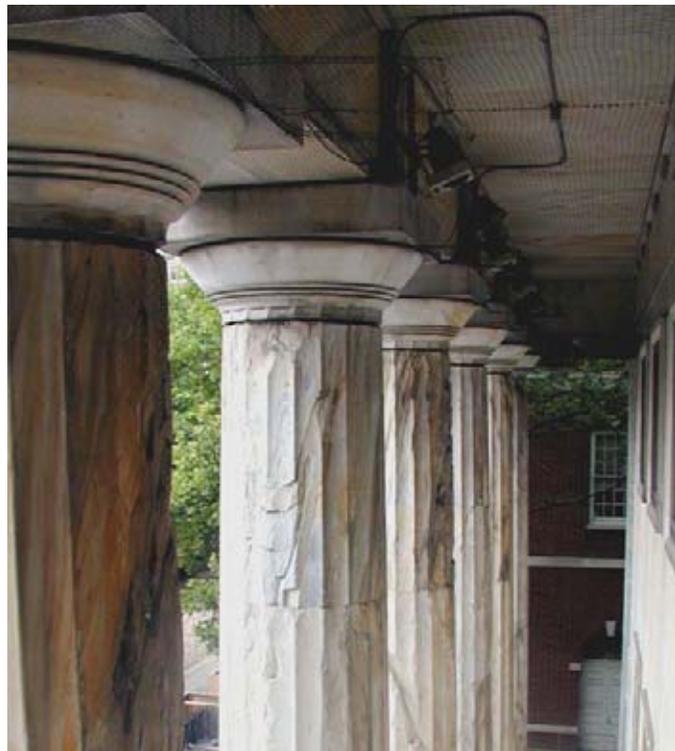
Column	Incipient spalling +½" in depth	Dimensional loss	Contour scaling	Surface erosion	Mineral inclusions
1	15	4612	6356	4683	1243
2	--	2496	3071	8486	1958
3	--	1601	8961	4459	3735
4	2	895	3172	2116	749
5	24	597	4547	2457	102
6	1570	8572	8542	2573	5243
7	56	5756	7573	2585	3773
8	584	4043	5914	3615	2945
<i>Total</i>	<i>2251</i>	<i>28571</i>	<i>48136</i>	<i>30973</i>	<i>19749</i>

Source: *Second Bank of the United States, conditions assessment of the exterior marble: phase 1*  
 – August 1999. Architectural Conservation Laboratory, University of Pennsylvania, 1999.

In general, the columns of the north portico are in better condition than those of the south portico. For both facades though, the surfaces of the columns facing the interior of the porticoes tend to be the worst. This is especially true for conditions of dimensional loss, cracking, incipient spalling, and encrustation. Areas where loss has occurred have a roughened surface, and appear to be result of progressive deterioration. These locations also display a significant amount of soiling.

Weathering of the columns at the Second Bank is most likely an interaction of many mechanisms and processes; while the marble's intrinsic qualities are also determining factors of the stone's susceptibility to decay. In addition to environmental conditions, the patterns and location of deterioration suggest other factors as well; the position of the columns on the building, the geometry of the flutings, and the way the stone was laid during construction.

An important attribute of decay is the fact that all of the drums were laid with the orientation of the marble's foliation planes perpendicular to the ground, or what is sometimes referred to as the weak direction of the stone. For a cylindrical shaped drum this also means that two opposite vertical sides display face bedding, while the other two opposite vertical sides show the planar structure of the marble in profile. Because the foliated structure of the marble is exposed in this manner, weathering can occur along weakened layers, or structural discontinuities of the stone, allowing for spalling and detachment on the face bedded surfaces of the columns. Incipient spalling is also prevalent directly above and below the mortar joints which may be allowing water entry through capillary suction. Since one of the functions of the mortar is to evenly transmit compressive load between the drums, it is also possible that an uneven bed of mortar is causing stress concentrations at the edges of the columns. (Fielden, 1982: 96)



**Figure 2.6**  
**Interior of the South**  
**portico, 2003**  
ACL, University of Pennsylvania

The arrises are projecting elements of the columns, extending out one inch from the flutings. Because of their shape, the arrises, as well as the columns as a whole, are affected multi-directionally by cyclical weathering phenomena, such as thermal movement, and, with the presence of water, freeze-thaw cycling that can cause structural stresses leading to cracking and spalling. For these types of decay mechanisms directional exposure, and in the case of heat induced degradation, thermal properties of the stone play a role. Thermal conductivity, specific heat, and reflective characteristics of the stone can affect the surface temperature and depth of heat transfer. In addition, the presence of soiling can significantly raise the surface temperature of the marble when exposed to solar radiation, as well as increase the transfer of heat from stone surface to substrate, and increase the rate of temperature decrease when cooled; creating an asymmetrical pattern of surface heating and cooling. (McGreevy, 2000: 269) The fact that deterioration is significantly greater on the south portico, which receives less shading than the north facade, points to the possibility that conditions such as cracking and spalling are a result of thermal degradation.

The presence of encrustation on the columns suggests that atmospheric pollution is a factor in the deterioration. In an urban environment, sulfur dioxide (SO<sub>2</sub>) is one of the most common sources of pollutants and the sulfation of marble a likely decay mechanism for flaking, differential erosion, and possibly cracking and spalling. Data on air pollution in Philadelphia indicates that the major sources of sulphates have been from automobile traffic and industrial processes, with peak air pollution occurring in the 1960's. (Feddema, 1987: 149) While weathering might initially be slowed by the marble's low porosity when freshly quarried, and from polishing on the stone face, the

columns at the Second Bank have been exposed to air pollutants from an early date. A visitor to the city in 1838, commenting on the effect of the gas-lights on the north portico of the building wrote that, “[e]ach of the fluted columns had a jet of light from the inner side so placed so as not to be seen from the street, but casting a strong light upon the front of the building, the softness of which, with its flickering from the wind, produced an effect strikingly beautiful.” (Hamlin, 1944: 78)

The deposition of pollutants on the stone surface depends on factors such as particle size, airflow, moisture, and the physical characteristics of the stone surface, such as roughness. Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) precipitates through the dissolution of calcite ( $\text{CaCO}_3$ ) as it reacts in the presence of sulfur dioxide and water, with the process of sulfation occurring both above and below the stone surface. Beneath the surface of the marble, fracturing of the stone can occur due to the changes in mineral volume associated with the replacement of calcite by gypsum. (Lefèvre, 2002: 332) Above the surface a white gypsum crust forms, eventually turning black in color as the network of gypsum crystals entrap soot and other pollutant particles. Water, and therefore the wetting of the stone surface, is the key factor enabling chemical attack to occur. (Camuffo, 1982: 2253) On sheltered areas of the porticoes not washed by rainwater, black crusts have developed on the columns due to the presence of moisture in the air. If the crusts detach from additional weathering or are removed by cleaning treatment, the stone underneath will have a roughened surface, then susceptible to further attack. Exposed areas, such as the outsides of the column faces, are also attacked by acid deposition, but periodic washout from rain removes the deterioration product, water soluble gypsum; leaving behind a clean though roughened surface also vulnerable

to further attack.

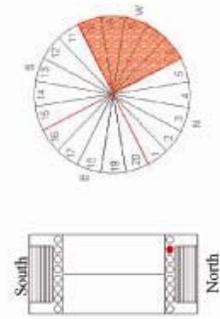
Disaggregation of the marble due to concentrations of accessory minerals, thermal microfracturing, and inherent stresses create weathering lines on which cracks can occur. This weakening of the stone is exacerbated by the presence of moisture, pollutants, and salts, further increasing the marble's porosity. Although the presence of efflorescence is not widely evident on the columns, soluble salt analysis of marble samples by Kimmel found the presence of carbonates, sulfates, and nitrates. (Kimmel, 1996: 16) Possible sources of the salts include the mineralogy of the stone itself, environmental pollution, or previous conservation treatments. Salts in solution with water are potentially damaging to marble when they penetrate into the pores of the stone. Their crystallization, known as subflorescence or cryptoflorescence, can cause stress within the pore structure and microcracks from repeated cycles of hydration and recrystallization; which depends on the size of the pores and cracks, the solubility of the particular salt, and is affected by environmental conditions, such as relative humidity and air temperature. (Honeyborne, 1998: 154) The damage from salts is further increased with the presence of several salts, each with different solubility and physical characteristics.

In addition to deterioration from mineralogical and environmental causes, the function of the columns needs to be considered, especially given that the marble's foliation planes are running perpendicular to the ground. Because the columns are load bearing elements, the compressive load of the building can be a significant cause of stress cracks. Large areas of dimensional loss have the ability to create eccentricities of vertical load leading to stress distributions that could be a source of further decay.

**Figure 2.7 North portico, column 7**  
**SECOND BANK OF THE UNITED STATES**  
**INDEPENDENCE NATIONAL HISTORICAL PARK**



**Column 7, drum 1**



Crack of 1/8" width

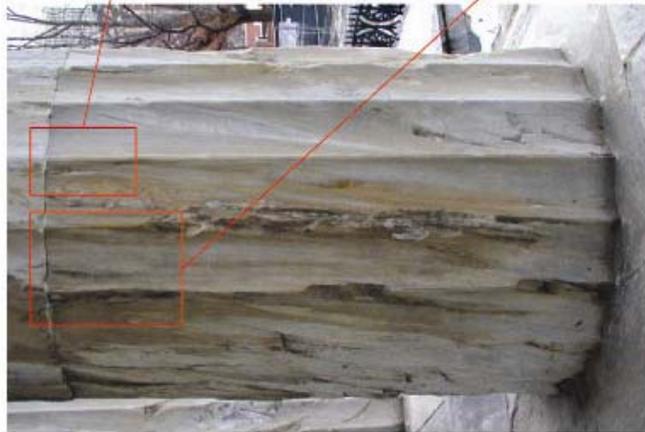
Incipient spalling stone



Dimensional loss of arris

Incipient spalling stone and dimensional loss

**Figure 2.8 South portico, column 3**  
**SECOND BANK OF THE UNITED STATES**  
**INDEPENDENCE NATIONAL HISTORICAL PARK**



Incipient spalling stone

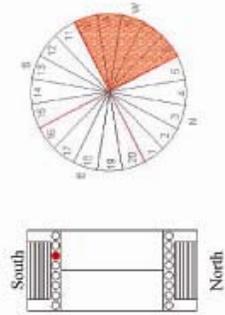


Mineral inclusions,  
possibly quartz

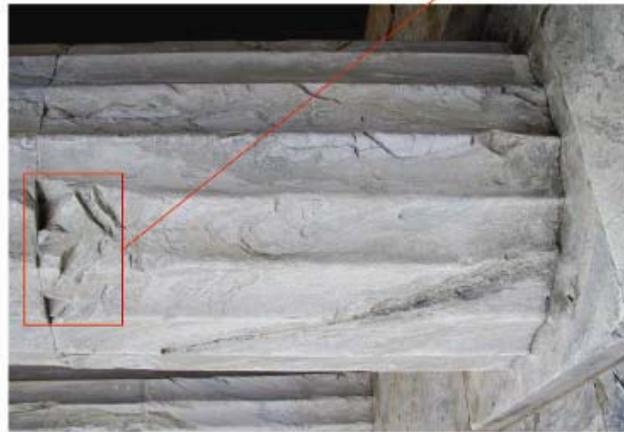


Dimensional loss, now soiled, is indicative  
of the shape of spall on other arris

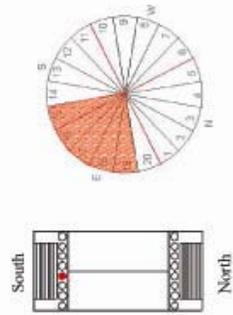
**Column 3, drum 1**



**Figure 2.9 South portico, column 5**  
**SECOND BANK OF THE UNITED STATES**  
**INDEPENDENCE NATIONAL HISTORICAL PARK**



Column 5, drum 1



Dimensional loss indicative of shape and shear plane of spall



Band of pyrite inclusions where loss has already occurred

Early stages of planar separation or incipient spalling

### **3. REPAIR CRITERIA**

#### **3.1 CHARACTERISTICS AND USE OF MECHANICAL PINNING TREATMENTS**

An ideal remedial treatment for incipient spalling stone is one in which the partially detached stone is joined to the substrate material so that further deterioration will not ensue. Few treatments exist that are able to adequately address this type of problem. One approach has often been injection grouting, either of fractures or at local points to reinforce the masonry. Grouts and adhesives, though, when applied over surface areas of fractures, can lead to damage to the stone due to properties that are incompatible with the masonry, such as water vapor transmission and thermal expansion. In addition, low viscosity adhesives have the potential to cause staining by bleeding into porous stone. Mechanical pinning treatments offer more control in the placement of reinforcement than grouts, and can be accomplished with a minimal amount, or in some cases, no adhesive at all.

A through masonry mechanical pinning treatment is accomplished by the insertion of pins into holes drilled through the face of the masonry. For the pins to provide tensile reinforcement between the spall and the substrate a connection needs to be established between the pin and stone, often referred to as a load transfer mechanism. (Eligehausen, 2001: 13) The load transfer of an adhesive bonded system occurs by bond stresses between the pin and adhesive, and adhesive and the stone. A system employing a screw augered directly into the stone transfers tension load mainly by mechanical interlock to the masonry. In the case of pins inserted into sleeves, the load is transferred to the stone due to friction and bearing force. Mechanical pinning is a repair that

involves several integrative components; pins, adhesives, and sleeves, and consideration must be given to each of their properties as well as their compatibility with the characterization and condition of the stone.

Before executing a treatment it is important to outline the goals to be achieved from the repair and the reasons the treatment is being performed. In order to prevent spalling stone from detaching, the primary requirements for mechanical pinning treatment are adequate strength of the repair and compatibility of materials. Pins must be neither too rigid nor too flexible. Strength of repair can be measured by pull out tests, shear tests, and bending tests. Bearing stress and tear out stress of the pins within the joint must also be considered, so that the stone does not fail around the pins. It is also important that if failure does occur it will do so at the joint and not cause additional deterioration of the stone.

Materials used for pins and adhesives should have compatible properties to the stone being treated. This can be determined by testing thermal coefficient of expansion, tensile strength, modulus of elasticity, and water vapor transmission of the materials to be used. Furthermore, the pins and adhesives should not cause staining or discoloration of the stone. Pins should ideally have good corrosion resistance to enhance the longevity of the repair as well as inhibiting further damage. The affordability of the repair should also be balanced with the goals of the treatment. There is a vast array of pinning materials available, each with different properties, and some more expensive than others. If adhesives are used, workability and toxicity should be considered. In addition, the repair should be retreatable and not be visually disfiguring to the stone. Since holes will be drilled into the incipient spalled stone where pins are inserted, it will be

necessary to apply a patching mortar to the surface of the stone to complete the repair. Application method should also be addressed if the stone is too fragile to tolerate drilling. In some cases pinning may need to be combined with grouting of fractures or pre-consolidation of the stone.

### **3.2 PINNING TREATMENTS AND CONSERVATION PRINCIPLES**

In addition to technical requirements, conservation treatments must also be based on sound theoretical principles. While adequate strength and durability are primary aims of any mechanical pinning repair, these need to be balanced with considerations of minimum intervention, retreatability and compatibility. The principle of reversibility has historically been a concern of conservation ethics, underlying the ideal ability to return an object to its original state before treatment. The idea of reversing a repair is important for several reasons: it stresses the significance of the material being treated and the role that any intervention imparts on the history of the object or structure; it acknowledges the fact that a repair may eventually be detrimental to the material; and also allows for the possibility that future technologies and practices may offer a better treatment choice.

Reversibility has been a desired attribute of any conservation treatment in accordance with the American Institute for Conservation's (AIC) code of ethics and several preservation charters, yet it is only recently that conservators have begun to revise this philosophy, recognizing that it is a goal that is virtually impossible to achieve. Cleaning and consolidation, as well as mechanical pinning will inevitably cause some damage or alteration to the material that can not be reversed. Mechanical pinning requires drilling holes into the stone so that even if the pins are later removed, original

fabric will still be lost.

A more logical approach has been to confine the use of the term reversibility to the description of a process rather than of a material. (Applebaum, 1987: 65) In this way the principle of reversibility is replaced by the more appropriate criteria of retreatability and compatibility. Relative to other repair options, an effective treatment that involves the use of inserted pins seeks to minimize the amount of intervention and damage to material, while at the same time including the possibility that the pins can be removed if necessary and replaced by more appropriate means. Ultimately, the effectiveness of mechanical pinning treatments, as with any conservation treatment, should rely on performance standards of materials and techniques that can be scientifically evaluated.

### **3.3 MATERIALS SELECTION**

There are many methods that can be used for mechanical pinning repairs and the choice of the proper materials for treatment will depend on repair criteria and conditions of stone deterioration. An adhesive bonded system can utilize a threaded or unthreaded pin, although a threaded pin will offer a better bond between the adhesive and pin. To improve the wetting ability of the adhesive, some surface preparation may be necessary, such as solvent wiping of the pins, especially if non-threaded pins are used. (Kinloch, 1987: 101) Friction fit systems do require a threaded pin however in order to screw them into a sleeve. Some pin materials, such as plastics, may not have appropriate stiffness at smaller diameters, so that they might only be applied using larger sizes. The strength of the repair can also be altered by the pin material, the number of pins, and the embedment depth of the pin. Issues related to treatment design will be discussed in the

following chapter.

If the stone is very friable then an adhesive bonded or friction fit system might be necessary, since a pin that transfers load from mechanical interlock could have a poor connection with the masonry. Voids in the stone will usually require grouting of fractures after a hole is drilled and then redrilling the hole to install the pinning repair. Unlike adhesive bonded systems where the pin is installed into an oversized hole, dry fit systems, such as those relying on mechanical interlock and friction fit sleeves, demand more precisely sized holes in order to function properly. In these cases it is important that the proper dimension hole can be drilled in the stone.

### **3.4 MATERIALS USED FOR PINS**

Pins are of course the primary element for this type of treatment, functioning to impart tensile and shear strength to weakened stone. Pins are manufactured in a large variety of materials, including metals, polymers and ceramics. Each material has its advantages and disadvantages, and it should be stressed that there is not one ideal type of pin for all treatments. Therefore, it is important to have an understanding of a pin's mechanical, physical and chemical properties as well as pragmatic concerns such as cost and ease of use.

Most pin materials can be purchased as rods and cut to desired lengths. Plastics can be cut using conventional metal cutting techniques, but ceramic rods require proprietary cutting because of their hardness and brittleness. This section provides an overview of the different types of pins available for this treatment. As such, it is an examination of the properties of these pins as a function of their composition.

### 3.4.1 METALLIC

Metallic pins are one of the more common choices for use in mechanical pinning treatments because of their good strength properties, availability, and in the case of stainless steel, affordability. Metals are crystalline solids characterized by the metallic bonding of the atoms, which enables electrons to move freely. The non-directionality and moderate strength of this bonding mechanism accounts for many of the common characteristics of metals; they are often very ductile, malleable, and have good thermal and electrical conductivity. Other properties, such as thermal expansion, are related to the bonding and molecular structure as well.

Imperfections in the crystalline structure called dislocations, which allow the atoms to slip over one another, also account for the ductility of metals and are an important factor in how metallic materials are formed. They are essentially made harder and stronger by controlling and restricting the movement of dislocations through heating, working, or alloying the material. (Gordon, 1979: 216) Good ductility means that metals are often easily and inexpensively fabricated but this characteristic also relates to a metallic pin's elasticity or stiffness, in addition to their failure mechanism, as when dislocations accumulate and begin to separate the crystals. When placed under load metals will behave elastically until their yield point in which case they become plastic, meaning that a certain amount deformation will be permanent. Therefore, in using metallic pins it is important to know the yield point or elastic limit of the pin, since beyond this point the repair will cease to function properly. The ultimate failure of metals is often due to ductile fracture occurring after observable plastic deformation.

Deformation can occur not just from the force of the load but is also affected by time and temperature, a condition known as creep.

The other concern when using metallic pins is the corrosion resistance of the metallic material. Corrosion of metals is an electrochemical reaction that is related to the metallic bonding of the material. Corrosion potentials vary with different metals and alloys, while the metals typically used for pins, stainless steel and titanium, have excellent corrosion resistance, due to passive oxide films that act as barriers to further oxidation.

### ***Stainless Steel***

Stainless steels are iron alloys containing a minimum of 11% chromium, which acts to provide corrosion resistance by forming a passive chromium oxide film on the steel upon exposure to air. The carbon content in stainless steel, which increases the strength and hardness of the metal, is typically kept low to prevent the chromium from being removed from the alloy in the form of chromium carbide. (Brantley, 1996: 131) There are three main classes of stainless steel; austenite, ferrite, and martensite, distinguished by the crystalline form of the iron and the molecular structure of the iron and carbon atoms. (Brantley, 1996: 135) The American Iron and Steel Institute (AISI) specifies grades of stainless steel based on their class and contents of the alloy, with austenite steels being referred to as the 300 series. Most commercially available pins and fasteners are grade 304 or 316.

Grade 304 contains approximately 18% chromium and 8% nickel; hence it is often referred to as 18-8 stainless steel. The nickel content provides metallurgical

characteristics, making the material easy to fabricate. (Parr, 1965: 27) This is a non-magnetic steel that is cold worked to obtain its mechanical properties of good tensile and shear strength. It can withstand all ordinary rusting and also resists most oxidizing acids.

Grade 316 is also a non-magnetic, cold worked stainless steel and like type 304 has a low carbon content and 18% chromium content. It also has a slightly increased amount of nickel and 2-3% of molybdenum to increase corrosion resistance, especially to pitting in chloride solutions. (Parr, 1965: 60) Grade 316 is one of the most corrosion resistant of all stainless steels, but because of the addition of molybdenum it costs slightly more than grade 304.

### ***Titanium***

Titanium's chemical, physical and mechanical properties make it one of the most appealing choices for mechanical pinning treatments. It is valued for its high strength, low density, a thermal expansion similar to stone, and excellent corrosion resistance. However, titanium is one of the more expensive metallic pins, costing about ten times as much as stainless steel. The material is expensive because of the need to avoid contamination, mainly by oxygen and nitrogen, while the metal is molten. (Street, 1994: 198) Titanium pins' excellent properties make them ideal for architectural conservation, and in some cases their longevity and compatibility may justify their cost.

ASTM B 348-02 specifies 35 grades of titanium. Grades 1 through 4, the unalloyed grades of titanium, are generally used for applications requiring good corrosion resistance and physical properties. Higher grades of alloyed titanium are often

used for high performance applications, such as the aerospace industry. These can contain up to 25 percent added elements to increase strength requirements at the expense of corrosion resistance. The most notable architectural conservation application of titanium rods was for treatment of surface and structural degradation at the Acropolis monuments in Athens in which grade 2 titanium was selected. (Zambas, 1986: 138)

Titanium's excellent corrosion resistance can be attributed to the formation of a passive oxide surface film, making it resistant to moist chlorine gas, chloride solutions and nitric acid. It is also resistant to dilute concentrations of sulfuric and hydrochloric acid and to most organic acids at room temperature. Titanium also has excellent resistance to either general corrosion or to pitting attack by most salt solutions. (Ogden, 1961: 567-8)

### **3.4.2 THERMOPLASTICS**

Thermoplastics are a group of synthetic materials, belonging to a larger materials class known as polymers. A polymer is a chain of smaller units of elements or molecules referred to as monomers, chemically bonded together by a process called polymerization. It is the composition and atomic bonding of the monomers, and the configuration of the linkages, or strands that defines the properties of the polymer. "Whereas the covalent forces within the strand are of the strong primary type, the interstrand forces are secondary and thus weak, except when cross-linking is present. The secondary forces involve either van der Waals or hydrogen bonds." (Cotterill, 1985: 226) Thermoplastics, as a result, display characteristics of being both elastic and viscous. These properties are evident with plastic pins; under mild loading conditions

they will return to their original shape if the load is removed, while under long-term heavy loads they will exhibit viscous behavior. (Schweitzer, 2000: 6) Unlike thermoset polymers, which assume a permanent shape once they are formed, thermoplastic materials tend to be more flexible, tougher and less brittle. They are also easily molded and extruded for mass production.

While thermoplastics have mechanical properties that make them suitable for use as pins or rods, their strength properties can be greatly improved through reinforcement; usually by the addition of fibrous materials such as glass or carbon. Glass fiber is the most widely used reinforcing material, either in the form of filaments or chopped strands, because of its tensile strength and elastic behavior. (Murphy, 1998: 69)

The corrosion resistance of plastics materials varies among the different polymers, but it is important to note that they do not experience specific corrosion rates. They are usually completely resistant to a specific corrodent or they deteriorate rapidly. (Schweitzer, 2000: 24). Most serious degradation of plastics in outdoor applications is from exposure to ultraviolet (UV) radiation which can cause embrittlement and cracking.

### ***Nylon***

Nylon, the trade name for crystalline polymers known as polyamides, is available in a large variety of grades, the nomenclature of the grade reflecting the constituents of the material and the forming process. One forming method is by the polymerization of a diamine and a dicarboxylic acid. The polymer that is created is a polyamide structure consisting of repeated amide groups. The grade refers to the number

of carbon atoms in the diamine and dicarboxylic acid respectively used to produce the material. For example, nylon 6/6 is the reaction product of hexamethylene diamine and adipic acid, both of which are compounds containing six carbon atoms. Nylons are also produced from single reactants, such as an amino acid or an amino acid derivative. In this case the nylon grade will be referred to by a single number. Caprolactam, which contains six carbon atoms is the raw material of nylon 6. (Kohan, 1973: 18)

Polyamides have good tensile and flexural strength, and excellent resistance to a broad range of chemicals, as well UV degradation and ozone. For conservation purposes the most commonly used thermoplastic pins are nylon 6, nylon 6/6, and glass reinforced versions of both types. They are an economical choice for mechanical pinning applications, costing slightly more than stainless steel pins.

The principal consideration when evaluating the use of nylons is their water absorption, since this will affect the dimensional stability and mechanical properties of the pins. Nylons absorb more or less water depending on the type of nylon, the environmental humidity, and the crystallinity of the part. The absorption of water can induce significant changes in the modulus of elasticity, yield stress, and toughness of the material. (Kohan, 1973: 329) Nylon 6/6 and nylon 6 will both gain about 2.5% by weight when conditioned to equilibrium moisture content at 50% relative humidity. (MacDermott, 1997: 129) Grades 6/10 and 11 have the lowest moisture absorption, and therefore the best dimensional stability, however they are not as strong as nylon 6 and nylon 6/6.

With the addition of glass reinforcement nylons achieve greater tensile strength and stiffness, better dimensional stability, and improved creep resistance. Reinforced

nylon is a more brittle compound and in some cases elastomeric modifiers are added to decrease brittleness. (Murphy, 1998: 128) Glass-reinforced nylon 6/6 absorbs moisture, but measurably less, and with less direct effect on properties. They also have increased resistance to light, temperature and oxidation. (MacDermott, 1997: 131)

### ***Teflon***

Teflon is the trade name for polytetrafluoroethylene (PTFE) and is best known for its excellent resistance to chemical corrodents. This characteristic derives from the material's carbon-fluorine bond, among the strongest of known organic compounds. The fluorine acts as a protective shield for other bonds of lesser strength within the main chain of the polymer. (Schweitzer, 2000: 27) As a result, Teflon is chemically inert in the presence of most materials. But because of its low surface energy, the material is unsuitable for adhesive bonding in its natural state; it would therefore be necessary to alter its surface chemically or physically to improve wetting prior to bonding. (Kinloch, 1987: 105) Due to the disadvantages and advantages of its properties, this material's use may only be warranted for specific conditions. In threaded rod form its cost is generally about five times that of nylon. And like most plastics, the mechanical and physical properties of Teflon can be improved by reinforcement.

### ***Engineering Plastics***

Engineering plastics are synthetic polymers that have been developed with load bearing characteristics and high performance properties, so that they can be used in the same manner as metals or ceramics. (Schweitzer, 2000: 3) They are often used for

industrial applications at elevated temperatures or those requiring high impact resistance. Though generally expensive, many of these materials are commercially available as pins or rods, and have many desirable attributes for mechanical pinning. Polyetheretherketone (PEEK), for example, is a high temperature resistant engineering thermoplastic with good mechanical properties, excellent chemical and fatigue resistance plus thermal stability. Its cost in threaded rod form is comparable to titanium. These types of plastics reflect a trend in materials development technology where properties can be developed for select applications, many of which coincide with conservation needs.

### **3.4.3 CERAMIC**

The term ceramic encompasses a wide variety of inorganic, non-metallic materials that are defined as, "... a solid composed of a mixture of metallic, or semi-metallic and non-metallic elements, in such proportions as to give the properties ... of hardness, durability, and resistance [to heat, electricity, and corrosion]." (Cotterill, 1985: 120) The method in which ceramics are hardened is usually by heat or chemical process. The type of ceramic materials that are used for mechanical pinning applications are of a class known as advanced ceramics. Unlike traditional ceramics, these materials, which include oxide, boride and nitride ceramics, are produced from high purity synthetically prepared materials and processed by specialized conditions. Advanced ceramics that display the most ideal structural properties are fine-grained, pore-free materials that are harder and stiffer than steel, and more heat and corrosion resistant than metals or polymers. "In addition to their good tensile and compressive mechanical

properties, the use of some ceramic materials in the structural restoration of finishing layers in buildings can also be considered advantageous because of their almost unlimited stability with time, their good adhesion to binding mortars and the fact that their expansion coefficients are compatible with those of the surrounding materials.” (Fiori, 1995: 198)

These unique characteristics can be attributed to the interatomic bonding mechanisms of the material; usually a combination of covalent, where the atoms share valence electrons, and ionic, which occurs when electrons are exchanged between elements of differing electronegativities. In both cases the atoms or ions are tightly packed, and because of the high concentration of bonds ceramics tend to be mechanically hard and resistant to chemical attack. (Cotterill, 1985: 121) Conversely, ceramics are often brittle, meaning deformation does not occur easily, because the directionality of the covalent bonds makes dislocation motion difficult. Thus, failure can start from small flaws before plastic deformation is possible. Unlike elastic materials, once failure has begun, cracks propagate quickly and fracture will occur instantaneously.

Properties of ceramics depend to a great extent on the raw materials and processing techniques used. Not all types of ceramic pins are manufactured the same, so it is important to be aware of the grade and purity of the raw materials, as well as the forming and hardening processes. Most manufacturers produce ceramic parts as custom designed components, though some stock ceramic rods. Threaded rods, however, require fabrication according to design specifications, or they can be manufactured by post kiln diamond grinding of smooth rods. Both of these processes will add

significantly to the cost of the pin.

### ***Alumina***

Alumina ( $\text{Al}_2\text{O}_3$ ) is the most common of the oxide ceramics because of the abundance of the raw materials and its relative ease in manufacturing. This material has good compressive strength, hardness, and a low coefficient of thermal expansion. Because it is an oxygen-based ceramic, alumina is already highly oxidized, giving it exceptional chemical resistance properties. (Cotterill, 1985: 121) It is one of the more affordable choices for advanced ceramic parts, though unthreaded alumina pins cost three or four times the price of stainless steel pins.

The mechanical properties of the ceramic will vary according to the purity of the alumina. Lower grades, those containing between 85% to 95% alumina are easier to manufacturer and to shape, while high purity alumina ceramics, with up to 99.9% alumina, are more costly because of the expense involved in producing the raw material. Ceramic grade alumina is produced by the Bayer process involving chemical digestion of bauxites. Alumina of greater purity requires successive activations and washings. (Jones, 1993: 37) Plasticizers are often added to the alumina to assist in the forming or extruding of the material before sintering.

### ***Silicon Nitride***

Silicon nitride ( $\text{Si}_3\text{N}_4$ ) materials were originally developed for the aerospace

and automotive industries because of their high strength, excellent wear resistance, and good thermal shock properties. It is one of the strongest of all advanced ceramics but also one of the most expensive to produce; generally costing ten times as much as alumina ceramic parts. Their performance in relation to their cost makes them useful in many industrial applications. While silicon nitride pins have been used in architectural conservation, their high cost means that they are rarely a feasible choice. (Fiori, 1995: 203)

In cases where silicon nitride pins are to be used though it is important to be aware of the different procedures by which the pins are manufactured since the material's properties, as well as its cost, depend largely on the fabrication method. The ceramic is formed from synthetic silicon nitride powder, but it is difficult to produce as a fully dense product because the raw material does not readily sinter, instead the powder dissociates into silicon and nitrogen. (Jones, 1993: 135) Sintered silicon nitride (SSN) relies on the addition of oxide additives to aid the sintering process, while hot pressed silicon nitride (HPSN) utilizes a combination of high pressure and high temperature to achieve densification, requiring fewer additives. (Jack, 1986: 268) Another manufacturing process is known as reaction bonded silicon nitride (RBSN), where the powder is formed and then heated in a nitrogen atmosphere so that the nitrogen penetrates the pores, with very little shrinkage to the material. This is the least expensive method of making silicon nitride ceramics but the final product is also the most porous, therefore having reduced mechanical and physical properties. (Jones, 1993: 135)

**Table 3.1****Comparison of physical and mechanical properties of materials used for pins**

	Tensile strength (10 <sup>3</sup> psi)	Yield strength (10 <sup>3</sup> psi)	Flexural strength (10 <sup>3</sup> psi)	Modulus of elasticity (10 <sup>6</sup> psi)	Coefficient of thermal expansion (10 <sup>-6</sup> in./in. °F)
Stainless steel grade 304	85	35		28	9.2
Stainless steel grade 316	85	35		28	9.2
Titanium grade 2	50	40		17	4.8
Nylon 6	11.8		15.7	0.38	83
Nylon 6/6	11.5		17	0.42	80
Nylon 6/6 30% glass fiber	23		35	1.2	32
Teflon 25% glass filled	2.0 - 2.7		2	0.24	70
PEEK 30% glass fiber	22.5 - 28.5		33 - 42	1.3 - 1.6	1.2
Aluminum oxide	36		21.5 - 50	59	4.6
Silicon nitride hot pressed	100		109	46	1.8

### **3.5 ADHESIVES USED FOR PINNING TREATMENTS**

Adhesives are used in mechanical pinning treatments to secure the pins in position and to establish a bond between the stone and the pin. An adhesive can be defined as “... a material which when applied to surfaces of materials can join them together and resist separation.” (Kinloch, 1987: 1) The phenomenon of adhesion can also be explained in physical and chemical terms as “... the state in which two surfaces are held together by interfacial forces which may consist of valence forces or interlocking forces or both.” (Packham, 1992: 19) For the purposes of this repair the adhesive system consists of the stone substrate, the adherend pin, and the adhesive.

For this evaluation of mechanical pinning treatments synthetic organic adhesives, specifically epoxy resin and acrylic resin adhesives, were considered. These kinds of adhesives are termed polymeric, since they have long chains of repeating monomer units that are created through a reaction process of polymerization. Synthetic resin adhesives can be divided into two groups: thermoplastic and thermoset. In thermoplastic resins, of which acrylic adhesives are an example, the monomers are linked together to form a two dimensional linear chain. As a result, the material is soluble in a variety of solvents and can also be reheated and reformed. Thermoset materials, so called because they assume a permanent shape when heated, are characterized by a three dimensional network of chemically bonded monomers. Because of their more complex structure these adhesives are infusible and insoluble in all solvents, though in some cases they may swell. (Torraca, 1968: 306) Epoxy resins are an example of a thermoset adhesive.

Many of the mechanical, physical and chemical properties of both

thermoplastic and thermosetting adhesives are influenced by the glass transition temperature and the molecular weight of the polymer. The glass transition temperature ( $T_g$ ) is reflective of the softness of the polymer, since it indicates the temperature at which a glassy material starts to change to a rubbery one. Below the  $T_g$  the intermolecular bonds of the polymer chain become stiff, affecting the modulus of elasticity and thermal expansion of the material. Above the  $T_g$  the material will begin to behave as a liquid. (Horie, 1987: 18) Tensile strength and elasticity are also influenced by the molecular weight of the resin. Polymers with high molecular weights have a tendency to be harder and stronger, as well as being more viscous in solution. (De Witte, 1984: 32) The  $T_g$  of a polymer increases slightly with increased molecular weight because the chains have less freedom of movement. In addition the  $T_g$  will decrease over time, so that the polymer will exhibit cold flow or creep, especially under loading conditions. (Horie, 1987: 20) Consideration of mechanical properties, such as modulus of elasticity, will depend on the requirements of the treatment, especially where conditions of the stone demand a repair that must accommodate flexibility.

Fillers are often added to polymers in order to alter the viscosity or thixotropy of the resin in solution for the needs of the application process, or to reduce the shrinkage of the material upon setting. These materials include micro balloons, fumed silica, and calcium carbonate. (Horie, 1987: 179) One of the primary selection parameters for an adhesive used for mechanical pinning treatments is that it be injectable. It must therefore have adequate viscosity and thixotropic properties in order for the adhesive to flow during application and not sag once in place. Additionally, the adhesive will need to have sufficient density for a seated pin to remain suspended in the adhesive and form a

uniform bond.

### **3.5.1 EPOXY ADHESIVES**

Epoxy adhesives are typically two component systems that include the epoxy resin and a hardener which reacts with the epoxide and cross links the molecules, transforming it into a thermosetting material. There are a large number of epoxide systems and fillers available with varying properties. In general, though, epoxy adhesives have high strength, good adhesion to many materials, low shrinkage, and good resistance to acids, bases and organic solvents. However, they tend to be stiffer than many other adhesives.

For conservation applications a low molecular weight aliphatic epoxide resin is preferred over more common aromatic resins like diglycidal ether of bisphenol A (DGEBA), since the latter is prone to discoloration. (Horie, 1987: 173) Consideration must also be given to the type and quantity of hardener that is used, since too low or too high a degree of cross-linkage can result in an inferior final product. (Amoroso, 1983: 378) For working at normal temperatures, the hardener is usually an amine, which is largely responsible for the adhesion properties of the polymer, but may also cause discoloration of the final product. For this reason, modified amines are usually used, though they have the drawback of slowing the curing rate unless they are applied with heat. (Selwitz, 1992: 8)

Because of their favorable mechanical properties epoxy resins are often used as mortars and adhesives, usually with fillers. When using fillers it is important that the additives have good mechanical strength and high degree of purity. They should also not react with the resin and hardener, and leave only a minimum of cavities. (Amoroso,

1983: 398) Epoxy adhesives have often been used in repairs involving pins, rods, and anchor bolts because they bond well with the adherands, although the most suitable adhesive will depend on its compatibility with both the pin and the stone substrate.

### **3.5.2 ACRYLIC ADHESIVES**

Acrylic resins are thermoplastic polymers, the majority of which are made from two types of monomers; acrylates, derived from acrylic acid, and methacrylates, derived from methacrylic acid. (Horie, 1987: 103) “Some of their most important and appreciated properties are their stability to ultraviolet light, their solubility in several organic solvents, their reversibility, their satisfactory water repellency and their consolidating action.” (Charola, 1985: 739) Acrylic polymers are usually applied in solution with solvents, though they can also be applied as emulsions or as prepolymers. When dissolved in solution the polymer will cure through solvent evaporation, which may lead to some shrinkage upon setting. Retention of the solvent may also affect the properties of the resin. As adhesives, acrylic polymers, in general are considered to have good flexibility, toughness, color stability and bond strength. (Packham, 1992: 15)

The most widely used acrylic resin for conservation applications is Acryloid<sup>®</sup> B-72, a copolymer of ethylmethacrylate and methylacrylate formulated to a molar ratio of 70:30. Often used as a consolidant, B-72 is especially noted for its stability and reversibility. Its strength and hardness properties occur without brittleness, and because of its  $T_g$  of 40° C it is unlikely to cold flow under normal conditions, but may be a concern over time. (Koob, 1986: 7) While little research has been done on the use of B-72 as an adhesive, some testing has suggested that even though its shear strength

properties are significantly less than that of common structural adhesives, the tensile strength properties of B-72 are similar to those of epoxy adhesives in marble to marble bonding. (Podany, 2001: 27)

Utilizing the adhesive's characteristic of reversibility, B-72 has also been applied as a barrier film before the introduction of a secondary adhesive. "It appears that the B-72 is sufficiently strong to safely be part of a structural joint and to provide a reversible barrier between the substrates and the less reversible structural adhesive." (Podany, 2001: 40) However, with respect to mechanical pinning treatments, the nature of the pin and adhesive joint embedded in the stone is such that the introduction of solvents to dissolve a barrier film might be difficult to accomplish.

### **3.6 USE OF SLEEVES FOR FRICTION FIT PINNING METHODS**

Sleeves can be used in mechanical pinning repairs in place of an adhesive as a means of transferring load between the pin and the substrate. This type of pinning system relies on friction and bearing force to establish contact between materials where a threaded pin is inserted into a slightly undersized sleeve. Friction is defined as, "... a force of resistance to movement that is developed at the contact face between objects when the objects are made to slide with respect to each other." (Ambrose, 2002: 91) The mechanisms of how friction is generated occur at a microscopic level and include the interaction of surface asperities and mechanical deformation. For this evaluation of mechanical pinning repairs, flexible nylon tubing of grade 6 and 11 were considered because of their suitability for conservation purposes amongst commercially available stock. The materials' physical and chemical properties have been discussed in the

section on thermoplastic pins, while their function for application as a sleeve was assessed empirically.

### **3.7 PROPRIETARY SYSTEMS**

Mechanical pinning treatments can also be accomplished using materials and methods developed for other applications. Expansion anchors are often used in the construction industry because of the ease of not having to use an adhesive. They will have lower load capacities than adhesive seated anchors, but function better for applications at elevated temperatures where epoxy resin adhesives do not perform well. Expansion anchors function either by friction, where the anchor is fit into an undersized hole, or by compression, in which an expansion mechanism compresses against the wall of the drilled hole by torque control of a nut on the exposed end of the anchor.

Sleeve style anchors are designed as fasteners for through masonry construction where the quality of the brick and mortar is inconsistent or voids are present between wythes of brick walls. These typically include nylon or steel mesh sleeves into which threaded rods are inserted and seated in an epoxy adhesive or cement grouts. As the adhesive flows out of the mesh it keys itself to the sleeve so that they anchoring system will work if there are cavities in the wall. Other patented systems that were examined for conservation application are described below.

#### **3.7.1 HELIFIX<sup>®</sup> DRYFIX MASONRY REPAIR**

The Helfix patented system involves the procedure of driving a stainless steel tie into a pre-drilled undersized hole in the masonry. The DryFix tie requires no adhesive

because the tie cuts a threaded groove into the stone. According to the manufacturer, they combine axial strength to withstand all anticipated wind loadings in both tension and compression with sufficient flexibility to accommodate normal building movement. The ties are available in both 304 and 316 grade stainless steel in 8 mm and 10 mm diameters. Because of their unique threaded design they also require a patented insertion tool attached to a drill in order to auger the pin into the stone.

### **3.7.2 CINTEC<sup>®</sup> ANCHOR SYSTEMS**

The Cintec anchor system is similar to the sleeve style anchors. It uses a hollow stainless steel anchor of grade 304 or 316 ranging in size from 15 to 30 mm in diameter with an endplate and a flood hole on the surface fitted inside a polyester-based mesh sock. The system is inserted into a pre-drilled oversized hole in the stone and flooded with a pressure injected cement grout through the anchor. Once filled with the appropriate amount of grout the sock mesh expands to provide a bond that conforms with any cavities in the substrate.

### **3.7.3 ORTHOPEDIC SURGICAL BONE SCREWS**

A screw used for medical applications was also considered for mechanical pinning repairs in stone. Designed as implants for fracture fixation of bone, orthopedic surgical bone screws have deep threads and a spiral tip designed for thread cutting when inserted into bone. Unlike most masonry screws, they are manufactured in corrosion resistant materials such as titanium and stainless steel 316 and available in fully threaded lengths, depending on the various manufacturers, of up to 120 mm. Typical

sizes of thread diameters range from 2 to 7 mm and in most cases are produced with a recessed hex insert on the head to allow for application with a hex drill bit. As for insertion in bone, installation of bone screws in masonry requires an undersized hole.

## **4. EXPERIMENTAL TREATMENT DESIGN**

### **4.1 OVERVIEW**

Documentation and analysis of the conditions of the exterior marble at the Second Bank have identified a significant occurrence of incipient spalling and loss from past spalling on the columns of both the north and south porticoes. This spalling stone is often wedge-shaped, defined by vertical and diagonally oriented cracks in the fluting eventually leading to loss of stone on the column arrises. Examination and measurements of dimensional loss indicate that the typical maximum depth of the spall ranges from 1 to 2 inches with a shear plane sloping towards the column surface at the narrowest span of the spall. It is believed that spalling is occurring, especially on the arrises, due to differential movement of the stone caused by thermal stresses and inherent stress of the marble, combined with the orientation of the marble's foliation planes perpendicular to the ground. As a result of this active deterioration these areas on the columns are unable to resist normal tensile forces, leading to eventual detachment. Mechanical pinning of the incipient spalling stone is considered the best approach to preventing further detachment and loss by providing resistance to overcome the stresses causing deterioration. Grouting of detached areas can also be applied in conjunction with the pinning treatment and is considered an assistance to the repair by filling fractures and voids, helping to secure the spall to the substrate.

The mechanical pinning treatment as designed for the Second Bank is a remedial treatment to address spalling of the stone caused by the above mentioned decay mechanisms. This does not preclude the possibility that other causes, such as

eccentricities of load affecting the structural performance of the columns, may be a contributing factor as well. If this assessment is revised then the design of the repair would need to change accordingly. As such, the strength of the repair as designed for this evaluation will be sufficient to address only the specific deterioration mechanisms identified. Designing and installing the repair to be stronger than necessary might inhibit the ability to monitor further decay due to other causes, as well as potentially cause further damage to the stone.

Few guidelines exist for this type of conservation treatment. In addition to the current conservation literature, building codes, performance standards, commercial literature, engineering literature, and evaluation reports of masonry anchors were reviewed to provide general recommendations in designing the repair. Most studies of masonry anchors are for steel fasteners attached to concrete, though testing results for titanium dowels in marble have suggested some correspondence in assessing the behavior of masonry anchors and pinning treatments with other materials. (Vintzileou, 2001: 904) It is important to note that many of the pin materials that will be evaluated for this repair, such as nylon, are of lower strength than steel, and marble generally has greater mechanical strength properties than concrete.

The repair criteria, in conjunction with the characteristics and conditions of the stone, are used to guide the selection of materials used for the treatment. The design of the repair will address how the materials are implemented and how, as a system, they are expected to perform. Repair criteria, as summarized from Chapter 3 are as follows:

- Adequate strength to resist tensile and shear forces
- Compatibility of repair materials and stone, including factors such as thermal expansion coefficient and modulus of elasticity

- Retreatability, the ability to remove the pins and reapply the same or a different repair method
- Longevity, including resistance to corrosion and staining
- Affordability
- Ease in installation

The approach to the repair is based on achieving these requirements by means of a simple and direct treatment design. In terms of ethical considerations, this is in keeping with the conservation principle of minimum intervention, therefore minimizing the drilling of holes and the loss of original material. The intention is also to use components that are easily manufactured and available. The fewest number of materials used allows for a treatment that is inexpensive and easy to install, with less likelihood of error. Because the pins will act as connectors between spalling stone and substrate, the introduction of unnecessary complexity to the configuration can cause variations of load distributions and unintended stresses to the stone. Large deviations in the pins' position can alter their effectiveness or lead to failure. Therefore, a rational and simple treatment design, if assembled correctly, should be expected to function as implemented and be easier to evaluate. Treatment decisions will rely on the process of calculation and testing to the greatest extent possible, and where necessary the conservator's best judgment.

#### **4.2 FAILURE MODES**

Failure mechanisms of the repair are the inability of the treatment to perform according to the design requirements. By examining modes of failure and influences that threaten failure, it is possible to define how the repair should function as well as its parameters. Pinning treatments in stone may structurally fail either by pin failure, by breakage of the stone around the pin, or pullout of the pin. Failure of the pin will depend

on the size of the pin and the type of pin material; yielding of the material in the case of metallic and plastic pins, brittle failure for ceramic pins. This can occur by shearing or yielding due to the gravity load of the spalling stone. Tensile failure of the pin is unlikely given that the expected stresses associated with differential movement are far less than the tensile strength of the selected pins. It would also require that contact forces holding the pin to the stone, whether bond stress, bearing stress, or frictional forces, be greater than the tensile strength of the pin.

The stone is also susceptible to cracking and breakout due to the effect of the inserted pins. This can be caused if pins are placed too close to a free edge, or if the pins are spaced too close together. This type of failure can also occur in cases where the properties of the pin, such as modulus of elasticity and thermal expansion coefficient, are not compatible with the stone.

Pullout failure of the pin will occur if the load transfer mechanism of the particular pin is of inadequate strength. For bonded pins, this could be due to insufficient adhesive properties; for friction fit pins which rely on the use of a sleeve, the pin or the sleeve may fail due to inadequate expansion force or coefficient of friction on the contact area of the hole. This failure mechanism will depend on the amount of surface area between the forces holding the pin in place and the stone, a function of both the pin size and its embedment depth.

### **4.3 DESIGN CONSIDERATIONS**

Design begins with studying the characteristics of the spalling stone in order to determine areas of detachment, a projected shear plane, and the thickness of the spall. At

the Second Bank this was done by probing the open cracks with a thin gauge (0.5 mm) wire. Most detachment is occurring tangentially to the surface of the column. The shape and shear plane of the spall, if it were to detach, can be estimated by the propagation of the cracks. A projected shear plane is useful for determining the thickness of the spall if no restraint is introduced. Where cracks are running vertically the shear plane is generally vertical as well. If the cracks are oriented diagonally, widening the span of the spall, the depth will also be greater, creating an inclined shear plane. Pins will be inserted perpendicular ( $90^\circ$ ) to the actual or projected shear plane on the vertical axis.

The various pinning techniques used require slightly different application techniques. Application methods will be discussed in a greater detail in the following chapter. Adhesive bonded pins will be inserted into an oversized hole to allow space for the adhesive. Mechanical interlock pins such as wide flange screws or Helifix wall ties require an undersized hole and should be installed according to the manufacturer's instructions. For friction fit pins that are inserted into flexible sleeves, the diameter of the drilled hole should equal the outside diameter of the sleeve and the threaded pin, so that it fits securely, should be of a slightly larger diameter to the inside diameter of the sleeve.

Treatment design is based on a combination of the following factors: the number and size of the pins, embedment depth of the pin, and the geometry of an array of pins; including spacing, edge distance, and angle of insertion.

#### **4.3.1 NUMBER AND DIAMETER OF PINS**

The treatment should ideally be accomplished with the fewest number of pins of the smallest size necessary. The size and number of pins used will be based on the shear and tensile strength requirements of the repair. The number of pins used will also be a factor of the appropriate amount of coverage of the spall that is deemed necessary. Therefore, the number of pins will need to be chosen based on an analysis of the conditions of the stone. Given the scale of the spalling stone, in many cases the repair could conceivably be accomplished with one pin of the proper diameter and sufficient embedment depth. However, a minimum of two pins is considered preferable in order to secure the spall in place, and reduce the ability of the spall to rotate on the axis of the pin. The added benefit of a redundancy of pins is that should one pin fail the repair might still function, though at a lower capacity. The number of pins used needs to be balanced with the fact that too many pins can cause stress distribution and cracking of the spall. Layout of the pins will be addressed in the section on pin configuration.

Shear loading for the repair is determined to be the weight of the spall. Because of the classical Greek architectural feature known as a sinkage, an indentation of approximately 3 to 4 inches located at the top of the columns, the arrises due not come in to contact with the capital and it is felt that they are not significantly affected by the bearing load of the columns. Any changes in this assessment, or for spalls located deeper within the column where progressive loss has occurred, will require taking into account compressive load on the column when determining the required shear strength of the pins.

The shear stress for the repair can be calculated as force, the gravity load of the spall, divided by the cross-section area of the pin. Using calculation, the appropriate diameter for a pin or pins can be determined. In practice, the pin will not completely shear if using materials such as steel or nylon, so what is required in these cases is not the ultimate shear stress, but the yield stress, where the pin material becomes plastic and failure is likely. In using multiple pins the assumption for this calculation is that each pin carries an equal share of the load. The shear requirement for the pin or pins is shown in the following equation.

$$s = \frac{F}{n\pi d^2/4}$$

where

s = shear stress or yield stress of the pin or pins

F = force applied to the pin

n = number of pins

$\pi d^2/4$  = cross sectional area of the pin, with d being the pin diameter

Since the force applied to the pin in shear is the mass of the spall, knowing the density of the stone and estimating the volume of the spall based on measurements, mass can be calculated. The shear plane, and therefore the dimensions of the spalling stone, is only a prediction, therefore a factor of safety is introduced by defining the volume based on the maximum known dimension of the length, width, and thickness of the spall. For this application with Pennsylvania Blue marble the density is given as 2.7 g/cm<sup>3</sup>, or 0.1 lb/in<sup>3</sup>. (Owen, 1849: 119).

The following equation is used to determine mass.

$$D = \frac{m}{v} \quad \text{or, } m = vD$$

where

D = density of the stone

v = volume of the spall

m = mass of the spall

The mass of the spall, m, or the volume and density, vD, can be substituted in the equation for the applied force, F.

$$s = \frac{vD}{n\pi d^2/4}$$

Then solving for d, the diameter of the pin.

$$d = 2\sqrt{\frac{vD}{ns\pi}}$$

These calculations provide a minimum pin diameter for the repair in shear where only the diameter of the pin intersects the shear plane. For pins inserted at 45° to the shear plane the cross sectional area of the pin would need to be multiplied by  $\sqrt{2}$ . It will be found that for the scale of the spall being treated most of the pin diameter values derived from calculations will be quite small. In these cases the bending of the pin would become a concern of the repair. To account for bending, insertion angles, and other concerns, such as wet weight of the stone and condition of the stone, a safety factor of 5 is applied to the dimension calculated for the diameter, and a minimum nominal diameter of 1/8 inch (3mm) is specified.

The equation can also be solved for the number of pins, n, if the diameter is chosen.

$$n = \frac{4vD}{s\pi d^2}$$

Unless experience or testing indicate otherwise, guidelines for a maximum diameter of the pin are taken from ASTM C 1242 “Standard guide for design, selection, and installation of exterior dimension stone anchors and anchorage systems”, which recommends that the diameter for rod anchors and dowels should not exceed one quarter of the stone (in this case spall) thickness. This guideline can be used inversely to determine the thickness of spall that can be pinned. For example, if calculation shows that one pin of 1/2 inch diameter is needed for the repair then the minimum thickness of spall would need to be 2 inches. If the spall thickness is less than 2 inches, two pins of smaller diameter would be required in order to meet this parameter.

The tensile capacity of the repair will also be affected by the pin size, so that a larger pin diameter in conjunction with embedment depth can give the repair greater tensile strength. Tensile capacity can not be calculated without a knowledge of the bond stress and stress distribution of the pinning systems, and would most likely have to be determined from testing. However, the same principle of determining total shear strength using multiple pins can be applied, in that the total tensile strength of the repair will be factored by the number of pins employed.

#### **4.3.2 EMBEDMENT DEPTH**

Embedment depth of the pin is one of the most important variables in determining the tensile strength of the repair. The tensile capacity of the treatment is

governed either by the strength of the stone substrate, the strength of the pin, or the strength of the forces holding the pin in place. The goal of the repair is for the treated stone to exceed its current tensile strength. It can be assumed from pin material selection that the strength of the pin will be greater than the strength of the stone. Therefore, the tensile strength of the repair will be a function of the bond stress or frictional forces and the amount of surface area of the pin that is adhered to or bearing against the stone.

In general, a deep embedment depth of the pin will give greater strength than a shallow depth. But in the absence of known adhering strength or friction forces for the specific materials and stone used in this treatment, the effective embedment depth will have to be determined by evaluation, based on the materials used and the load transfer mechanism of the pinning system. In transmitting the load from the spall to the substrate it cannot be assumed that stress will pass uniformly across the joint. It is more likely that the stress will be concentrated close to the perimeter of the joint. This means that for bolts or rods screwed into a base material the load is primarily being carried by the first few threads. (Edwards, 1991: 469) And it is often found to be the case when a rod is less stiff than the substrate material into which it is being anchored. (Gordon, 1978: 139) This is the expected behavior of mechanical interlock and friction fit pins, where it is believed that a deeper embedment will have less effectiveness. For adhesive bonded pins some research on anchors in concrete has suggested that a uniform bond stress model can be used to design most typical anchor installations. (Cook, 1993: 133)

For through masonry pinning the embedment depth of the pin in the spall will be predetermined by the spall's thickness. The pin will be inserted into a predrilled hole to a distance of 1/4 to 1/2 inch from the surface to allow for application of a patching

mortar. According to ASTM C 1242 dowel embedment in stone should be a minimum of two-thirds of the thickness of the stone, or in this case the spall. Using this requirement, the minimum thickness of spall that can be pinned is 3/4 inch.

Embedment depth of the pin in the substrate is a significant factor in determining the strength of the repair, and should be at least equal to the depth of the pin in the spall, but no less than four times the dowel diameter as specified by ASTM C 1242. This guideline is a common practice in conservation for pinning through cracks and fractured stone. This will ensure that the resistance forces in the substrate are at least equal to the forces being applied in the spall. A deeper embedment depth may be necessary to form enough resistance to the forces associated with the stresses causing deterioration, but the proper embedment depth will need to be determined by testing. The goal of the treatment is to keep the repair as localized as possible and to not insert the pins any further into the stone than needed.

### **4.3.3 SPACING AND EDGE DISTANCES**

In addition to pin diameter and embedment depth the spacing of the pins can also affect the strength of the repair, since pins which are spaced close together will have a compound influence on the stone resulting in lower individual capacities. Of greater concern though is the potential for splitting or breakage of the stone due to nonuniform stress distribution and edge tear out. This type of failure can be minimized or prevented by prescribing minimum edge distances and spacing of the pins. The minimum edge distance is the distance a pin should be located away from the free edge of the spall, as well as a masonry joint. Because the forces applied in shear for this treatment are of

being as important as they would be in larger applications. Given the scale and shape of the spalling stone at the Second Bank, material selection and application will also have a significant influence on splitting or breakage failure. The stiffness of the pins used or stresses caused by drilling of the holes may be more likely to cause damage than the layout of the pins.

The American Concrete Institute (ACI) has addressed design issues regarding minimum edge distances and minimum spacing distances for masonry anchors, requiring a minimum spacing for post-installed anchors of 6 anchor diameters, measured center-to-center. (ACI 318-02: 424) Post-installed anchors, in contrast to cast-in place anchors, are those that are installed in hardened concrete, therefore similar to the concept of a mechanical pinning treatment. This value is a minimum distance at which failure can be prevented, not at which load reduction is anticipated.

With regard to recommended spacing distances, the ACI has developed a design approach for anchoring to concrete based on a model in which ultimate pullout failure of the anchor occurs along with a shallow concrete cone. (ACI 318-02: 414) The radius of the base of the failure cone, located at the surface of the concrete, is used to establish spacing distances between adjacent anchors, and the height of the cone reflects the anchor's effective embedment depth. While this model is useful for establishing the zone of influence of an anchor, and therefore spacing distances, it should be noted that the *failure mode* is not necessarily applicable to pinning of a spall, since stresses causing deterioration in the marble are occurring at a discontinuity behind the surface of the stone. Because the spall and substrate are confined by one another cone failure might not occur. The methods and values for spacing derived from this approach, as well as

from evaluation reports of proprietary anchors, are useful for design of this repair, but differences between application and substrate material should be kept in mind.

Spacing distance can be specified as a function of either the effective embedment depth of the pin or the pin diameter, with most evaluation reports of masonry anchors using the latter. A review of International Conference of Building Officials (ICBO) testing reports on variety of adhesive bonded anchors and masonry screws has found that the spacing distance for which the allowable load capacity of the anchor is not influenced by neighboring anchors is in the range of 12 to 18 times the diameter. 12 diameters will be used as the recommended center-to-center spacing distance for this repair. This is consistent with the minimum spacing distance which, according to evaluation reports, is usually half the distance of recommended spacing distances.

The ACI specifies that minimum edge distances should be determined by testing. This type of evaluation has been conducted on marble in which titanium dowels of various diameters were embedded with cement mortar, and has found that a distance of 4 dowel diameters is sufficient to prevent breakout failure for shear loading against the strong direction of the marble, while 6 dowel diameters is necessary for loading against the weak direction of the marble. (Vintzileou, 2001: 903) The authors found that these values were consistent with testing of anchors in concrete, even though marble is a stronger base material. The testing done for the study, like most studies of edge tear out, was performed on pieces of marble with uniform thickness, unlike the spall conditions found at the Second Bank, in which the thickness typically decreases or tapers closer to the free edge of a crack. However, experimental data also indicated that over 1000

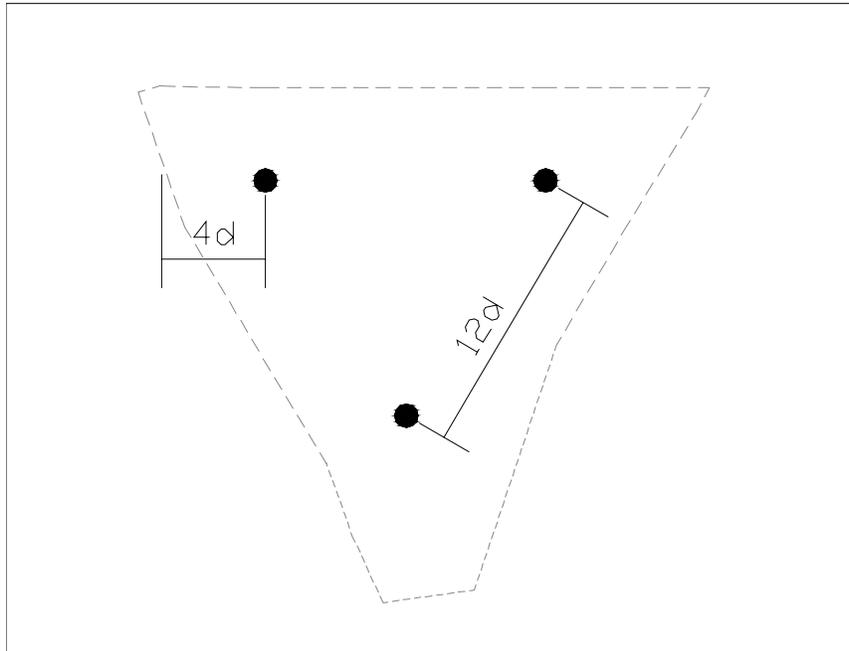
pounds of force was necessary for the marble to fail when using a 6 mm diameter dowel. Therefore, an edge distance of 4 pin diameters is felt to be a conservative value for a minimum edge distance and will be used for this repair.

The spacing distances chosen for this treatment are first estimates of values that, in the absence of test data for this repair, should ideally be confirmed to determine if they are appropriate. It is likely that these recommendations will vary according to different pinning techniques and materials that are used.

#### **4.3.4 PINNING CONFIGURATION**

The configuration of the repair will rely on installing the pins based on the previously outlined considerations. The design factors are summarized below.

- Minimum thickness of spall that can be pinned = 3/4 inch
- Pin diameter is determined by calculation of shear strength
- Minimum pin diameter = 1/8 inch
- Maximum pin diameter = 1/4 spall thickness
- Minimum pin embedment depth in spall = 2/3 spall thickness
- Minimum pin embedment depth in substrate = equal to the embedment depth in  
the spall, but not less than 4 pin diameters
- Effective embedment depth in substrate will be determined by testing
- Spacing of pins = 12 pin diameters
- Minimum spacing = 6 pin diameters
- Edge distance = 4 pin diameters



**Figure 4.1 Example of pin spacing distances on spall**

It will be necessary to define areas where pins can be inserted by subtracting out areas that do not meet minimum requirements of thickness and edge distance. The 'pinnable' area will be the thickest part of the spall and in most cases include the arrises. Ideally, pins inserted through the thickest sections allow for the most contact between pinning surface and stone. The span of multiple pins within the area of stone that can be pinned should be maximized to give the most coverage, and the pins' locations should divide the weight of the spall as evenly as possible. In arranging multiple pins within the spall the layout should be symmetrical in order to avoid eccentricities of load on the pins. (Ambrose, 2002: 327)

A conservation practice which could be adopted for this repair is to install two pins in a dovetail manner, in which each of the pins intersects the shear plane at  $45^\circ$  angles on the horizontal axis. For application to the columns at the Second Bank this

would mean that the pins would be inserted through the flutings. In cases where the spall is wide enough this method could be used since the configuration allows for the opportunity to pin through a greater area of spall, as well as providing lateral shear restraint to the repair. This approach, as with any design, should be properly evaluated before treatment application.

## **5. TESTING PROGRAM**

### **5.1 OBJECTIVES**

Based on the treatment requirements for incipient spalling of the marble columns at the Second Bank, a testing program was designed to assess and compare the performance of a range of mechanical pinning techniques, using a variety of repair materials and methods. Stone assemblies were fabricated in order to evaluate the tensile and bending strengths of different pinning systems relying on characteristics of the deterioration, namely the typical depth of spall. Of great importance is the tensile capacity of the repair. The fracturing of the stone associated with incipient spalling is thought to occur as concentrated tensile stresses increase, leading to eventual detachment. The insertion of pins is designed to transfer a tension load between the spall and the substrate in order to resist these forces. Therefore, pullout tests of individual pins inserted in stone were conducted to evaluate the tensile strength of the pinning systems. This data could also be compared to the known tensile strength of the stone to study failure mechanisms of the pinning methods.

In addition, the introduction of reinforcement from pinning will affect the flexural or bending behavior of the stone. Bending, a combination of tension and compression is a mechanism of reaction to forces applied perpendicular to the length of the pin. Bending stress correlates to the stiffness of a material and an evaluation of this property will help to indicate how the treatment might alter the repaired stone's response to weathering conditions such as thermal movement, which is also a probable cause of the deterioration. Bending tests of single pinned sandwich assemblies were conducted to

acquire data, both quantitative and observational, that would provide a means of assessing the behavior of the treatment and the compatibility of the repair materials with the stone. These results could also be compared with the stone's modulus of rupture, or ultimate bending stress.

There are many variables involved in designing a mechanical pinning repair: pin material; size of the pin, both diameter and length; and the load transfer mechanism, utilizing adhesives as well as dry fit systems. Testing was focused on comparing different load transfer mechanisms and pin materials. These factors were isolated by performing both pullout and bending tests on assemblies in which applications involved a similar amount of intervention, and therefore a limited range of pin sizes. The pins used were generally of the minimum size diameter specified by the treatment design guidelines developed in Chapter 4, which is 1/8". The length of the pins was chosen based on the expected amount of embedment depth believed necessary to reasonably treat spalls of 1" to 2" in thickness.

Because Pennsylvania Blue marble is no longer quarried, an alternative stone was required to conduct the testing program. A quantity of Columbus Ohio limestone was readily available at the Architectural Conservation Lab, and was chosen because of its comparable properties to the Pennsylvania Blue marble; a crystalline limestone composed primarily of calcite with a similar density.

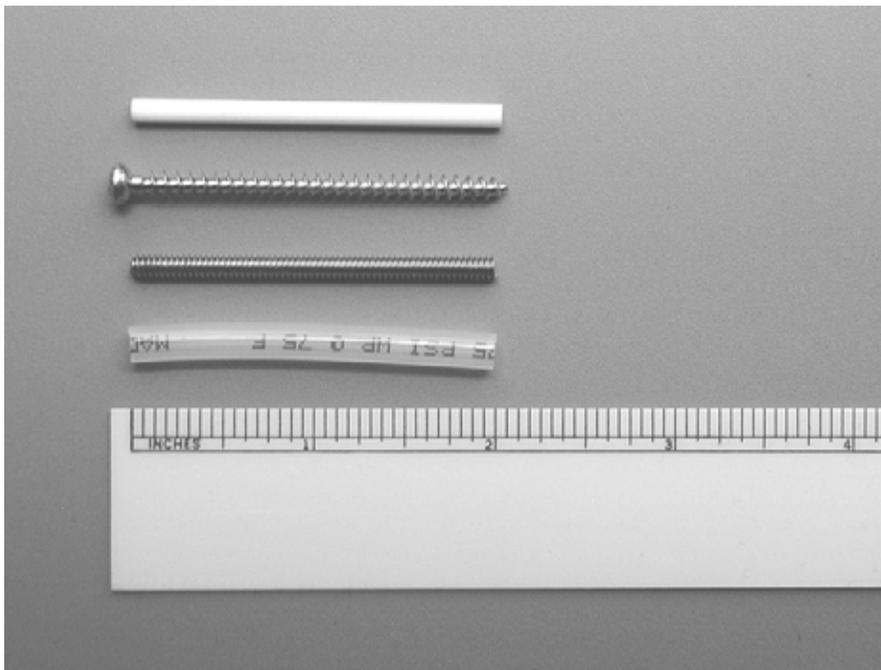
**Table 5.1 Comparison of stone properties**

	Columbus Ohio limestone	Pennsylvania Blue marble
density, g/cm <sup>3</sup>	2.5	2.5
water absorption, %	2.6	0.93
modulus of rupture, psi	1653-1827	n/a
tensile strength, psi	761	n/a

Sources: *Conservation study of the exterior and interior masonry of the Ohio Statehouse*, 1991  
 Appendix D: "Tensile strength of Columbus Ohio limestone", 2004  
 Kimmel, J. *Characterization and consolidation of Pennsylvania Blue marble*, 1996

## 5.2 PINNING SYSTEMS SELECTED FOR EVALUATION

The treatments selected for evaluation represented a range of techniques and materials that can be used to accomplish the repair and their ability to fulfill the repair criteria as outlined in Chapter 3. Selection was divided between two categories: dry fit systems and adhesive bonded, or 'wet' systems. Pin materials included stainless steel threaded rods and bone screws, as well as unthreaded alumina ceramic pins. In using small diameter pins, glass reinforced nylon was determined to have insufficient stiffness for any of the pinning systems. Other materials were not selected because of their prohibitive cost: titanium, Teflon, PEEK, and silicon nitride ceramic pins. Proprietary systems such as Helifix<sup>®</sup> wall ties were considered to have too large a diameter for the application needs.



**Figure 5.1 Pins and sleeves used for testing program**

From top to bottom: ceramic pin, bone screw, stainless steel threaded pin, nylon tubing used for sleeve

Where a standard stainless steel threaded pin was used the size chosen was 6-32, which is approximately 9/64" in diameter. The standardized nomenclature for threaded rod sizes is a two part

identification where the first number refers to the diameter of the rod, and the second number to the number of threads per inch. Threaded rod diameters of less than 1/4" are given as a nominal diameter; their value in inches can be determined by multiplying the number by 0.013 and then adding 0.06 to the product. Thus a size 6 diameter is equal to 0.138 inch.

The selection of adhesives was limited to a commercial epoxy and a custom formulation with B-72 acrylic resin. The use of B-72 as a barrier coat combined with epoxy was not utilized since the advantages of the system, namely the ability to remove the repair, was not considered feasible given the configuration of the joint. (Podany, 2001)

### **5.2.1 ADHESIVE BONDED SYSTEMS**

For an adhesive bonded pinning treatment an adhesive is injected into a predrilled hole and then the pin inserted, forming a bond between the pin and the stone. Most conservation and engineering literature, as well as ASTM 1242, recommend an oversize hole between 1/8" to 1/16" larger in diameter than the pin. For this evaluation, oversized holes of 1/16" larger were drilled. In addition to being injectable, the requirements of the adhesive are that it have a non-sag viscosity, as well as sufficient density so that the pin will be suspended, forming a uniform bond between the pin and the surface area of the hole. Application procedures by injection are explained in the section on fabrication of assemblies.

### ***Threaded stainless steel pin seated in epoxy adhesive***

The pin used for this application was stainless steel grade 316, size 6-32 diameter. This grade of steel has good strength properties and corrosion resistance. The epoxy selected was Sikadur<sup>®</sup> Injection Gel, manufactured by Sika; a two component, high modulus, high strength adhesive. The resin, which is diglycidal ether of bisphenol A, and hardener, an aliphatic amine, are mixed at a ratio of 1:1 by volume. The adhesive has the consistency of a smooth, non-sag paste and is intended by the manufacturer for grouting of anchor bolts, dowels, and pins.

### ***Threaded stainless steel pin seated in acrylic adhesive***

A stainless steel 316 threaded pin of 6-32 diameter was also used with an acrylic adhesive. The resin chosen was Paraloid<sup>®</sup> B-72, a copolymer of methyl acrylate and ethyl methacrylate, manufactured by Rohm and Haas. A B-72 adhesive is desirable because of its good stability and weathering resistance, as well as the fact that, unlike epoxies, it can be redissolved by common solvents and the pin removed if necessary. The resin, in solid form, is dissolved in solvent and after application the adhesive cures as the solvent evaporates. Acetone was chosen as the solvent because of its quick evaporation rate and low toxicity, and the adhesive was formulated at a ratio of 1:1 by weight, prepared using procedures outlined by Koob. (1986: 10) To improve the density and thixotropic properties of the adhesive, Ultra-Pflex<sup>®</sup> precipitated calcium carbonate, manufactured by Specialty Minerals, was added, which also aided in reducing shrinkage during curing. (Horie, 1987: 178) To achieve the required properties of the adhesive, 40% by weight of calcium carbonate was added to the resin-solvent solution. This

would represent a formulation by weight of 5 parts resin, 5 parts acetone, and 4 parts calcium carbonate; although from preparation of test batches of the adhesive it was found that 15-20% solvent evaporation occurred during the process of sifting the calcium carbonate into the solution. The solvent was not replenished and the final composition of the adhesive as applied actually included only 4 parts acetone.

### ***Smooth ceramic pin seated in acrylic adhesive***

A pinning system utilizing a ceramic pin was chosen for evaluation because of the material's good compatibility with stone. Alumina pins of 99% purity were used because of their affordability relative to other ceramics. These pins have good strength properties, as well as a thermal expansion coefficient and modulus of elasticity similar to stone. Unlike the stainless steel pins, ceramic pins are not commercially available in threaded form, so smooth rods of 1/8" diameter were used as a comparison with the 6-32 threaded rods. The pins were seated in B-72 adhesive, formulated as outlined in the previous section.

### **5.2.2 DRY FIT SYSTEMS**

These methods of pinning rely on friction and bearing force of the materials in order to transfer load between the pin and the substrate.

### ***Stainless steel threaded pin inserted into a nylon sleeve***

This system used a stainless steel grade 316 threaded pin of 6-32 diameter inserted into a sleeve of nylon 11 tubing, with an inside diameter of 3 mm and an

outside diameter of 5 mm. Compared to other grades of nylon, grade 11 has good flexibility and dimensional stability. The drilled hole is the same diameter as the outside diameter of the tubing, while the sleeve's inside diameter is slightly smaller than the diameter of the pin. The pin was inserted using an application tool fabricated from a hexagonal shape steel bar. A threaded hole 1/4" in depth was drilled into one end of the bar so it could be attached to the end of the pin. The pin could then be screwed into tubing inserted in the stone and after application the tool was unscrewed from the pin. To prevent twisting and kinking of sleeve, the nylon tubing was cut into sections 1/2 to 1 inches in length.

### ***Bone screws***

A mechanical pinning system that requires neither an adhesive nor sleeve was also evaluated using orthopedic surgical bone screws. The screws used are made of stainless steel 316 and have a thread diameter of 4 mm with a core diameter of 2 mm. The threads number 14 per inch. The head of the pin, 6 mm in diameter, has a recessed hex head, so that a hex key can be used for installation. The screws have deep threads and a spiral tip designed for thread cutting when inserted in bone. From trial applications with limestone it was determined that an undersized hole of 9/64" (3.6 mm) was required.

## **5.3 FABRICATION OF ASSEMBLIES**

To prepare assemblies for testing, samples of stone were cut from larger blocks of limestone using a circular water saw. Assemblies for pullout tests and bending tests of pinning systems required different size samples, described in the following sections.

After cut to the appropriate dimensions, the stone was washed with deionized water and a nylon bristle brush, and then allowed to air dry for 24 hours.

Installation of the pins required the drilling of various size holes of diameters ranging from 9/64" to 5/16" and at depths of 1/2 inch to 1 1/2 inches, depending on the pinning technique and the test to be performed. Holes were drilled in the stone samples on a drill press set at the slowest speed (450 rpm) using carbide tipped masonry drill bits. Frequent withdrawing of the drill from the hole during drilling aided in extracting accumulated stone debris. Since masonry drill bits were not available in 64<sup>th</sup> inch fractions the next smallest size drill bit was used and then the hole was enlarged to the necessary size using a standard bit. For example, a 9/64" diameter hole required drilling first with a 1/8" masonry drill bit and then again with a 9/64" drill bit. During rotary drilling in stone, small drill bits can easily weaken and break from overheating. In order to prevent heat build up of the drill bits and the stone, drilling was periodically suspended and the bit quenched in water. After drilling, the holes were blown clean with compressed air, flushed with deionized water and wiped with acetone using a cotton swab.

Threaded stainless steel pins were cut to the required lengths from a longer rod with a band saw. Any rough edges on the ends of the pins were smoothed using a Dremel rotary tool with a drum sander attachment. The pins were soaked in acetone and wiped clean with a cotton rag to remove any coating of grease. No preparation of the ceramic pins or bone screws was necessary since both of these types of pins were acquired from the manufacturer at the appropriate lengths. Nylon tubing used for the applications was cut to the necessary length using a steel blade.

### **5.3.1 ASSEMBLIES FOR PULL OUT TESTS**

Assemblies for pullout tests were prepared using stone cubes measuring 2" x 2" x 2". The five selected pinning systems were to be tested with individual pins at a variety of embedment depths for a total of 11 types of assemblies, with each assembly type being tested in triplicate. Holes were drilled at the required diameters, with spacing and edge distances as recommended from the treatment design guidelines in Chapter 4. All of the pins were inserted so that the pin extended a minimum of 1" above the surface of the stone for gripping by the testing apparatus.

With the exception of the ceramic pins seated in B-72, all of the assemblies were fabricated so each pinning method would be evaluated at 1/2" and 1" embedment depths. Because an adhesive bonded smooth ceramic pin was expected to have a weaker pullout strength than the other pinning methods, this system would be tested at three different diameter/length ratios. The testing results could then be used as baseline data to calculate a mean bond stress for this pinning technique. With a known bond stress for an adhesive bonded system, and assuming a uniform stress distribution, predicted values of pullout strength can be determined for future applications with different size pins.

**Table 5.2 Assemblies for pullout tests of adhesive bonded pinning systems**

	<i>pin</i>	<i>pin diameter</i>	<i>hole diameter</i>	<i>embedment depth</i>	<i>adhesive</i>
P1	stainless steel	6-32	13/64"	1"	epoxy
P2	stainless steel	6-32	13/64"	1/2"	epoxy
P3	stainless steel	6-32	13/64"	1"	B-72
P4	stainless steel	6-32	13/64"	1/2"	B-72
P5	alumina ceramic	1/8"	3/16"	1"	B-72
P6	alumina ceramic	1/8"	3/16"	1 1/2"	B-72
P7	alumina ceramic	1/4"	5/16"	1"	B-72

**P1, P2 *Threaded stainless steel pin seated in epoxy adhesive***

Sikadur<sup>®</sup> Injection Gel is packaged by the manufacturer in a 22 ounce dual cartridge system known as Sikadur<sup>®</sup> AnchorFix-4 for application with a dual cartridge dispensing gun and nozzle that both mixes the components and injects the adhesive. Since the injection nozzle was too large for application into the required size hole (13/64" diameter), Teflon tubing (3/16" O.D.) was fit onto the end of the nozzle. The adhesive was injected beginning at the bottom of the hole, slowly withdrawing the dispensing gun to fill the hole to the stone surface. The stainless steel pin was then pushed into the hole, twisting the pin during insertion. Back pressure was applied using a 1/4" thick cosmetic sponge surrounding the hole and pin. Assemblies were set with the pin in a vertical position during the cure time of the adhesive.

**P3, P4 *Threaded stainless steel pin seated in B-72 adhesive***

**P5, P6, P7 *Smooth ceramic pin seated in B-72 adhesive***

The B-72 adhesive was injected using a 50cc luer lock style syringe. Instead of a needle, Teflon tubing (1/8" O.D.) was attached to the syringe using a luer lock fitting.

Adhesive was injected beginning at the bottom of the hole, slowly withdrawing the syringe to fill the hole to the stone surface. The pin was then pushed into the hole, twisting the pin during insertion. Back pressure was applied using a 1/4" thick cosmetic sponge surrounding the hole and pin. Assemblies were set with the pin in a vertical position during the cure time of the adhesive.



**Figure 5.2 Injection of B-72 adhesive**



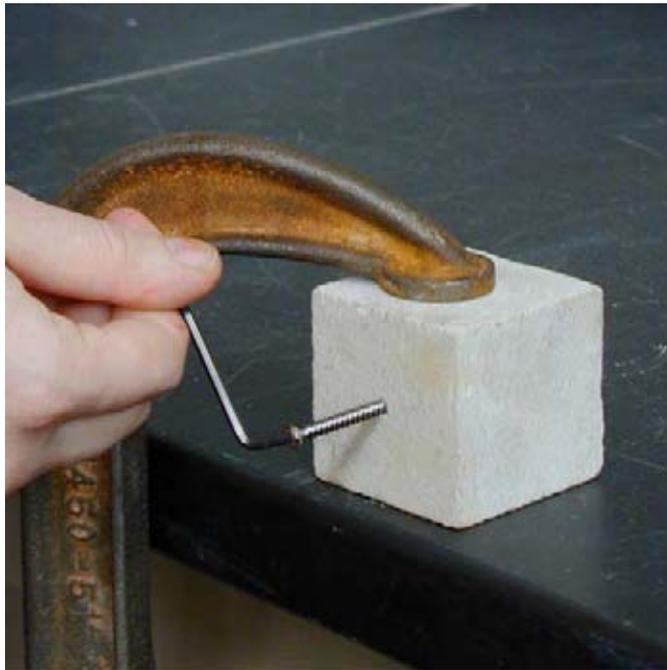
**Figure 5.3 Insertion of pin**

**Table 5.3 Assemblies for pullout tests of dry fit pinning systems**

	<i>pin</i>	<i>pin diameter</i>	<i>hole diameter</i>	<i>embedment depth</i>	<i>sleeve</i>	<i>sleeve diameter</i>
P8	stainless steel bone screw	4 mm	9/64" (3.6 mm)	1/2"	—	—
P9	stainless steel bone screw	4 mm	9/64" (3.6 mm)	1"	—	—
P10	stainless steel	6-32	5 mm	1/2"	nylon 11	5 mm OD 3 mm ID
P11	stainless steel	6-32	5 mm	1"	nylon 11	5 mm OD 3 mm ID

**P8, P9 Bone screw**

Bone screws were inserted into an undersized hole using a hex key. Application required occasionally backing out the screws in order to remove stone debris cut by the threads.



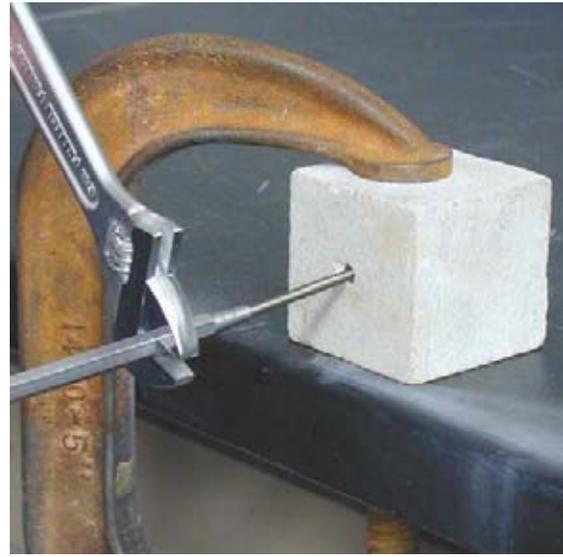
**Figure 5.4 Application of bone screw with hex key**

**P10, P11 *Stainless steel threaded pin inserted into a nylon sleeve***

Nylon tubing of the required length was inserted into the hole. The pin was applied using a tool fabricated from a hexagonal shape steel bar. One end of the pin was screwed into the tool, which was then used to torque the pin into the nylon sleeve, first by hand and then using a wrench attached to the tool. After application the tool was unscrewed from the pin.



**Figure 5.5** Insertion of nylon sleeve



**Figure 5.6** Insertion of pin using application tool and wrench

**5.3.2 ASSEMBLIES FOR BENDING TESTS**

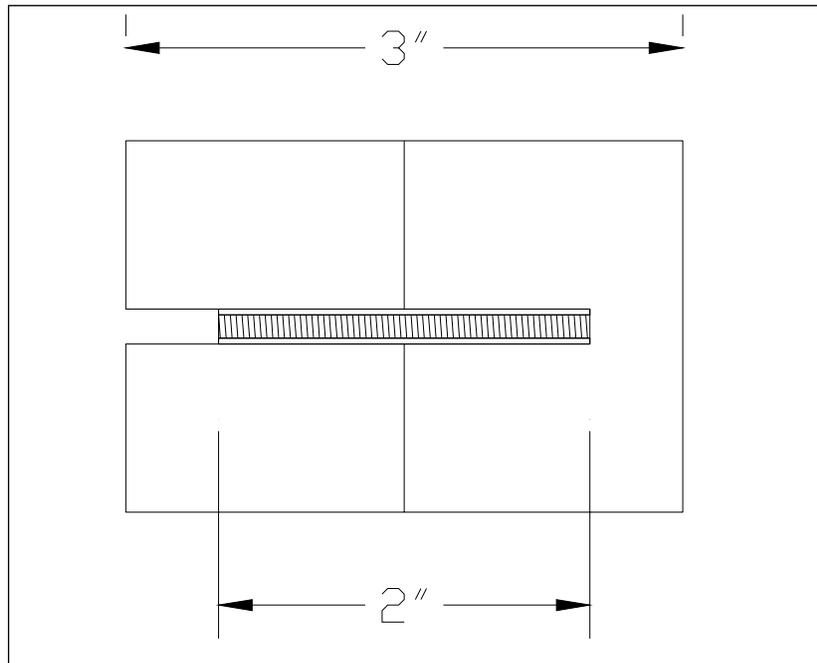
The bending tests were to be conducted on two part assemblies in which each piece of stone measured 2" x 2" x 1 1/2", so that the total assembly measured 2" x 2"x 3" with a center joint. A hole of the required diameter was drilled through the center of the face of each half of the assembly. One half was drilled through the entire 1 1/2" thickness of the stone sample, the other half drilled to a 1" depth. Fitting the two halves together created

an assembly with a 3" total length and a 2 1/2 " length hole. (See Figure 5.8) This allowed for application of a 2" length pin through one end, and when installed would be equidistant of 1" on each side of the joint, with a 1/2" recess at the application end. The five pinning methods were each tested with 2" embedment in the assembly for a total of five assembly types, each type tested in triplicate. Since a precise fit between the two pieces was required to form a uniform joint and level edge of the stone surfaces, the samples were cut from the same block of stone. In some cases drilling through the entire sample resulted in spalling around the circumference of the hole when the drill bit exited the stone. For this reason, the two parts were drilled separately rather than attempting to drill them as an assembly. Where spalling occurred in drilling through one half, these pieces could then be turned around so the damaged face would be at the exterior surface of the assembly instead of the joint. To ensure alignment of the holes between the two halves, the first part of the assembly was used as a guide in order to drill a starter hole on the second half. The first piece was then removed and the sample drilled to 1" depth.

Since bone screws have a 6 mm head and the friction fit system requires an oversized tool for installation, countersunk holes of 1/4" diameter and 1/2" in depth corresponding to the 1/2" recess below the stone surface were drilled on assemblies for both these pinning methods



**Figure 5.7** Assembly for bending test



**Figure 5.8** Cross section of assembly for bending test

**Table 5.4** Assemblies for bending tests of adhesive bonded pinning systems

	<i>pin</i>	<i>pin diameter</i>	<i>hole diameter</i>	<i>length of pin</i>	<i>adhesive</i>
B1	stainless steel	6-32	13/64"	2"	epoxy
B2	stainless steel	6-32	13/64"	2"	B-72
B3	alumina ceramic	1/8"	3/16"	2"	B-72

***B1 Threaded stainless steel pin seated in epoxy adhesive***

The two sections of the assembly were secured together with duct tape. Sikadur® Injection Gel epoxy was injected using a dual cartridge dispensing gun with Teflon tubing (3/16" O.D.) fit onto the end of the nozzle. Adhesive was injected beginning at the bottom of the hole, slowly withdrawing the dispensing gun to fill the hole to the stone surface. The pin was then pushed into the hole, twisting the pin during insertion. Back pressure was applied using a 1/4" thick cosmetic sponge surrounding the hole and pin. Since the pin was to be recessed in the assembly, a Teflon-coated micro-spatula was used to insert the pin below the stone surface. Assemblies were set with the pin in a vertical position and the duct tape remaining on the assembly during the cure time of the adhesive.

***B2 Threaded stainless steel pin seated in B-72 adhesive***

***B3 Smooth ceramic pin seated in B-72 adhesive***

The two sections of the assembly were secured together with duct tape. The B-72 adhesive was injected using a 50cc luer lock style syringe with Teflon tubing (1/8" O.D) attached to the syringe using a luer lock fitting. Adhesive was injected beginning at the bottom of the hole, slowly withdrawing to fill the hole to the stone surface. The pin was then pushed into the hole, twisting the pin during insertion. Back pressure was applied using a 1/4" thick cosmetic sponge surrounding the hole and pin. Since the pin

was to be recessed in the assembly, a Teflon-coated micro-spatula was used to insert the pin below the stone surface. The duct tape remained on the assembly during cure time. Assemblies were set with the pin in a vertical position during the cure time of the adhesive.

**Table 5.5 Assemblies for bending tests of dry fit systems**

	<i>pin</i>	<i>pin diameter</i>	<i>hole diameter</i>	<i>pin length</i>	<i>sleeve</i>	<i>sleeve diameter</i>
B4	stainless steel bone screw	4 mm	9/64" (3.6 mm)	55 mm	—	—
			countersink 1/4" dia. 1/2" length			
B5	stainless steel	6-32	5 mm	2 1/4"	nylon 11	5 mm OD 3 mm ID
			countersink 1/4" dia.			

**B4 Bone screw**

The two sections of the assembly were secured together using clamps. Bone screws were inserted into an undersized hole using a hex key. Application required occasionally backing out the screws in order to remove stone debris cut by the threads.

**B5 Stainless steel threaded pin inserted into a nylon sleeve**

The two sections of the assembly were secured together using clamps. To prevent twisting and kinking of the nylon tubing, a 2" length was cut into three equal sections, each 2/3" in length. The three pieces of tubing were inserted into the hole. The pin was applied using a tool fabricated from a hexagonal shape steel bar. One end of the pin was screwed into the tool, which was then used to torque the pin into the nylon

sleeve, first by hand and then using a wrench attached to the tool. After application the tool was unscrewed from the pin, leaving 1/4" of pin extended in the countersunk hole.

#### **5.4 TESTING**

By definition, the condition of incipient spalling implies active deterioration. The testing program did not attempt to simulate a weakened plane of stone subjected to the stresses associated with the deterioration as they would occur on the building. Rather, the pullout and bending tests provide assessments of the strength of the pinning system in a stone substrate on assemblies that most closely resemble conditions of complete detachment, or the worst case scenario. The two-part bending test assemblies, for example, create a joint which has no bending strength without the insertion of the pin. For the pullout tests a load is applied to the pin at the stone surface where the stone has no tensile strength.

Assemblies of adhesive bonded systems for both pullout and bending tests were allowed to cure for three weeks. All testing was conducted at the Mechanical Testing Facility, Laboratory for Research on the Structure of Matter, at the University of Pennsylvania, under the direction of Dr. Alex Radin.

#### **5.4.1 PULL OUT TESTS**

##### ***Standard Test***

ASTM E 488-96, Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements

##### ***Purpose***

This test is intended to measure the strength of the load transfer mechanism between the pin and the stone sample. Values from testing are given as load (in pounds of force) required to displace the particular pin and measurement of the corresponding displacement (in inches). The acquired data gives a tensile profile of the treatment for a comparison of different pinning methods and for developing design recommendations.

##### ***Apparatus***

Instron 4206 electromechanical testing machine. Wedge grip connected to a 5000 lbs. capacity load cell with a universal joint.

##### ***Procedure***

Eleven different assembly types were tested, each type in triplicate for a total of 33 tests. Assemblies were secured to the testing platform with clamps at two opposite diagonal corners. Load was applied to the free end of the pin, perpendicular to the stone surface at a rate of 0.1 inches/minute.



**Figure 5.9 Setup for pullout tests**

***Calculations and Results***

Table 5.6 Results of pullout tests

assembly type	mean maximum load (lbf)	standard deviation	standard error
P1 stainless steel pin seated in epoxy	1162	27.3	15.9
P2 stainless steel pin seated in epoxy	649	84.1	48.6
P3 stainless steel pin seated in B-72	74	11.5	6.6
P4 stainless steel pin seated in B-72	41	8.3	4.8
P5 ceramic pin seated in B-72	87	5.0	2.9
P6 ceramic pin seated in B-72	99	19.6	13.9
P7 ceramic pin seated in B-72	73	23.9	13.8
P8 bone screw	279	46.1	26.6
P9 bone screw	440	38.4	22.2
P10 stainless steel pin in nylon sleeve	36	11.3	6.5
P11 stainless steel pin in nylon sleeve	58	14.7	8.5

## ***Discussion***

The data from testing can be evaluated in several ways. First, as a comparison between the strength of the different pinning methods installed with a similar amount of intervention, as well as with the tensile strength of the stone. Second, since each pinning system was installed at two, and sometimes three different embedment depths, some analysis of the design of a particular pinning technique can be suggested. Lastly, data and observations can be used to assess the behavior and failure of the treatment methods and materials, which is also dependant on the stone's tensile strength. To reestablish strength along a weakened plane of the stone that is failing due to tensile stresses, a pinning system must distribute tensile forces between the spall and the substrate. In order for this to occur the pinning system must be stronger than the tensile strength of the stone. But this also means that the pinning technique has the potential to cause damage to sound stone, especially if the strength of the pinning system exceeds the forces associated with deterioration.

The results of testing showed that a system using stainless steel pins seated in epoxy (P1, P2) provides the greatest tensile strength. This was not an unexpected result. The epoxy seated steel pin at 1/2" embedment (P2) had a mean pullout load of 649 lbf, while those assemblies at 1" embedment (P1) had a mean pullout load of 1162 lbf. Both of these pinning systems, though at different loads, failed causing a circular detachment of stone about 3/4" diameter at the surface centered on the pin; and where the pins were completely removed, a cone shaped volume of stone surrounding the pin was observed.



**Figure 5.10 Cone shape failure from epoxy seated pins at 1" and 1/2" embedment depths**

In some cases cracks appeared on the face and sides of the assembly. While this should not be dismissed, it was felt that the cracks were primarily an influence of the placement of the clamps holding the stone in place. The depth of the failure cone attached to the pin was approximately 1/4". Below the failure cone, the epoxy was bonded to the pin, with a thin layer of stone grains adhered to the adhesive. Taking into account the surface area of stone detachment with the maximum load, the failure of the P2 assemblies are consistent with the known tensile strength of the stone, which is 761 psi. The P1 assemblies, however, demonstrate failure occurring along with a similar cone shape segment of stone attached to the pin, but when maximum load was achieved for a 1" embedment. One explanation for this might be that the stress distribution along the 1" length of the bonded pin gives a greater load capacity, but the characteristics of failure are similar because of the stress concentration near the surface where the stone has the least resistance.

The pinning systems utilizing B-72 adhesive, both with stainless steel threaded pins (P3, P4) and with smooth ceramic pins (P5, P6, P7), all had fairly low pullout strength. A comparison at 1" embedment of the stainless steel pin (P3) and ceramic pin (P5) shows the ceramic pinning system to be only slightly stronger, 87 lbf versus 74 lbf, but in both cases neither was able to achieve even a tenth of the strength value attained with epoxy (P1). Both systems did however have a small improvement of tensile strength with deeper embedment depths or larger diameter/length ratios. For all of the B-72 applied pins, pullout usually occurred with a jagged layer of adhesive attached to the pins and some adhesive still attached to the surface area of the hole. Failure primarily occurred within the adhesive bond line which was approximately 1/32" in thickness. It is important to note that during pullout tests the adhesive is subjected to shear as well as tensile stresses. It is known that B-72 is not as strong in shear as epoxy adhesives, although the brittle behavior of the adhesive upon curing may have been due to the addition of calcium carbonate. Properties of the resin and the filler are probably both contributing reasons for the weak performance of these pinning systems. The results of these pinning methods also make it difficult to draw any clear inferences between different pin materials used with the same adhesive, or with the case of the ceramic pins, to calculate a meaningful bond stress.

Of the dry fit systems the application with bone screws provided the greatest tensile strength. These were not as strong as an epoxy seated pin; at 1" embedment depth (P9) the bone screw had a mean load capacity of 440 lbf. No visible deformation of the threads was noticeable after pullout of the pins, and no damage to the stone occurred other than the scraping of stone debris from the surface area of the hole as the

pin was withdrawn. While the pinning technique displayed greater strength at 1" embedment (P9), 440 lbf, than at 1/2" (P8), 279 lbf, a difference of 161 lbf, or 58%, it is believed that as a mechanical interlock method the bone screws have a nonuniform stress distribution, such that a greater embedment depth would have less influence on the strength of the pinning system. The strength increase from the different embedment depths was greater than it was thought it might be, but whether inserting the pins more than 1" could significantly increase the load capacity of the pinning system can only be determined from further testing.

The insertion of stainless steel pins in nylon sleeves also had low pullout strength compared to the other pinning systems. At both 1" (P11) and 1/2" (P10) embedment, failure of the pinning system occurred between the sleeve and the surface area of the hole, a result of a low bearing force or coefficient of friction between the nylon sleeve and the stone.

For all of the pinning systems evaluated, possibly sources of error in testing should be considered. These include improper application of the pinning methods; with adhesive bonded pins this might mean an inconsistent bond line between the stone and pin. Any discontinuities or irregularities of the stone could also account for variables in testing values.

## 5.4.2 BENDING TESTS

### *Standard Test*

ASTM C 99-87, Standard Test Method for Modulus of Rupture of Dimension Stone

### *Purpose*

This test, also known as a three point bending test, is used to establish the modulus of rupture of the sample. For this evaluation, the objective was to study the bending behavior in addition to determining possible failure, or rupture of the assembly. Values from testing and calculation are given as bending stress (in pounds/square inch) of the assembly and deflection (in inches) at which stress occurs.

### *Apparatus*

Instron 4206 electromechanical testing machine. 5000 lbs capacity load cell

### *Procedure*

Two-part assembly is laid horizontally on the supporting blades spaced 2 inches apart and equidistant from the loading blade, with all three blades parallel. Load is applied at a rate of 0.1 inches/minute.

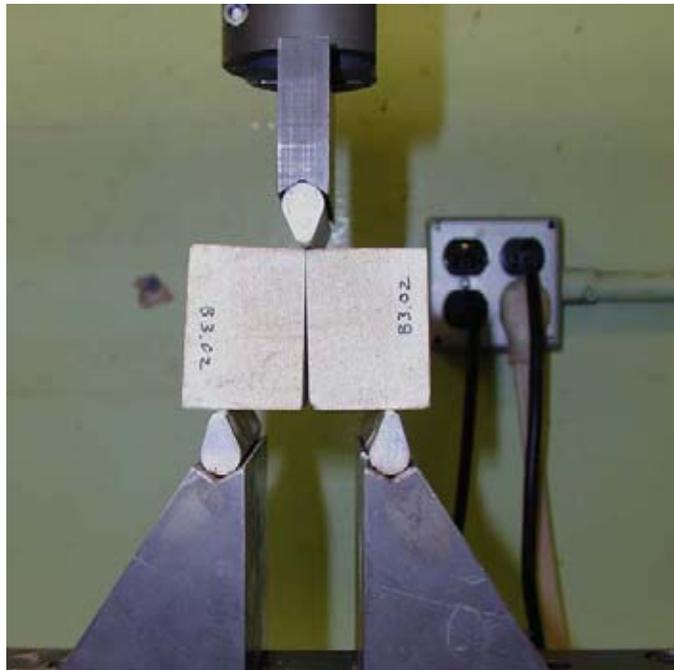


Figure 5.11 Setup for bending tests

### ***Calculations and Results***

Bending stress was calculated for each assembly as follows:

$$B = 3Wl/2bd^2$$

Where

B = bending stress, psi

W = load, lbf

l = length of span, in.

b = width of assembly, in.

d = thickness of assembly, in.

Table 5.7 Results of bending tests

\*Bending stress calculated at 0.125 inch deflection

assembly type	mean bending stress (psi)	standard deviation	standard error
B1 stainless steel pin seated in epoxy	1741	333.4	192.5
B2 stainless steel pin seated in B-72	129*	43.9	25.3
B3 ceramic pin seated in B-72	92	16.2	9.4
B4 bone screw	689	91.4	52.8
B5 stainless steel pin in nylon sleeve	668*	293.0	169.2

### ***Discussion***

The insertion of pins is designed to provide supplementary reinforcement to the stone, but the repair must also be compatible with the stone's critical properties. An ideal pinning repair would be one in which the bending strength of the pinning system matches the strength of the stone. If the repair constricts the stone's flexibility it will likely result in concentrating stress elsewhere, leading to additional damage. In most cases it will be preferable to install a pinning method with a lower rather than a greater bending strength. Because the assemblies for bending have a joint of complete detachment, the strength of the assembly is governed by the pinning system. This allows for an evaluation of the behavior and failure at the joint when subjected to bending stresses.

All of the assemblies exhibited some form of failure at the joint, with the exception of those in which an epoxy seated stainless steel pin was applied (B1). At a mean maximum stress of 1741 psi, all of the B1 assemblies resulted in fracture of the stone outside the span of the pin, where the support blades held the stone. This stress value for failure of the stone is consistent with the known modulus of rupture for the stone, which is 1653-1827 psi. That the assemblies did not fail at the joint, with almost no displacement, indicates that the pinning system is stiffer than the properties of the stone. Since bending is a combination of tension and compression and it is known from the pullout tests that the epoxy seated steel pins have high tensile strength, this is not a surprising result.

The high modulus epoxy adhesive certainly played a large role in the behavior of the B1 assemblies, since the stainless steel pins seated in B-72 (B2) showed significantly less bending strength. Because the B-72 adhesive does not provide as much tensile strength, bending of the pin occurred at the joint along with displacement from the two stone halves. The strength of the assembly was largely a function of the properties of the stainless steel pin. At 1/8" deflection the load was removed and a mean bending stress was calculated of 129 psi. The pin at this point had already deformed plastically and had begun to slip from the hole, causing very minor damage to the stone around the circumference of the hole.

The assemblies comprising a stainless steel pin inserted in a nylon sleeve (B5) also exhibited a similar behavior. Again, load was removed at 1/8" deflection and a mean bending stress calculated of 668 psi. As with the B2 assemblies this much deflection would represent failure of the stone so there was no need to proceed with

testing. From pullout tests it is known that both of the B2 and B5 systems have similar tensile strengths but the greater bending strength of the stainless steel pin in a nylon sleeve is probably attributed to a better performance of the pinning system under compression.

Plastic failure of the bone screws (P4) also occurred at 689 psi with generally very little deflection. Failure of the pinning system occurred on the half of stone in which the tip of the screw was inserted, since the head of the screw provided restraint on the other side.

Ceramic pins have similar stiffness properties to the stone, but the assemblies utilizing these pins were conducted with B-72 (B3) which contributed very little to the bending strength of the pinning system. The pins failed at the joint by brittle fracture with a mean modulus of rupture for the assembly of only 92 psi at very little deflection.

As with the pullout tests, possibly sources of error in testing should be considered. These include improper application of the pinning methods, and discontinuities or irregularities of the stone that could account for variables in testing values.

## **6. CONCLUSIONS**

### **6.1 CONSIDERATIONS FOR TREATMENT APPLICATION**

Testing of mechanical pinning systems was conducted in an effort to gain a greater understanding of the strength and behavior of several different pinning methods that could be used for the repair of incipient spalling stone on the columns of the Second Bank. It should be noted that there are many factors in defining the strength of the repair and the results of these tests only provided data for a defined set of variables. In addition to the materials used, the strength of a pinning system can usually be improved with a larger diameter pin and greater embedment depth. Furthermore, the testing evaluated the capacity of individual pins while installation of a mechanical pinning repair would in most cases employ multiple pins. This fact would not only change the strength of the repair, but also the behavior of the treated stone.

Assessing the strength of the pinning systems as determined from laboratory testing must be regarded with respect to the objectives of the repair. If the goal of the treatment is to attempt to arrest or slow the decay process, in other words to restrain displacement to a degree that would prevent continued cracking, spalling and loss of the stone, then only epoxy seated steel pins demonstrated a level of strength that might be considered a qualified success. The application of bone screws as well exhibited significant tensile strength, and this type of pin at the proper diameter, length, and number of screws employed could possibly be sufficient to accomplish the repair. While the epoxy seated pins provided adequate tensile resistance to secure spalls in place, the testing also identified certain disadvantages of the pinning method that are of serious

concern. Pullout tests indicated that failure of the pinning system occurred with significant damage to the stone around the circumference of the hole. Correlating this damage to failure as it might occur in field conditions is difficult though, since the plane of the spall and substrate are confined by one another, unlike the testing format in which the pin was removed from the surface. Bending tests also found the repair to be exceedingly stiff, inhibiting flexural movement of the repair at the joint so that failure occurred elsewhere in the stone. It could not be determined from the testing program if bone screws would cause similar damage if their application achieved greater tensile capacity, but their bending strength from testing did allow for failure at the joint with not damage to the surface.

The other systems tested; ceramic and stainless steel pins seated in B-72, and steel pins inserted into a nylon sleeve all had fairly low tensile and bending strength. An understrength repair, however, is not necessarily unsuccessful. The benefit of such a repair being that, though it is unlikely to secure the spall in place, it might be able to deter dimensional loss; meaning preventing spalled stone from falling off the building. Implementing a treatment in this manner would need to be weighed against the ability of other treatment options and the need for intervention.

It is apparent from the testing program that the greater the strength of the repair, the greater the potential for damage to the stone. An imperative of implementing a mechanical pinning treatment, therefore, is to try to control the possible failure mechanisms while increasing strength. The bone screws failed whereby the threads scraped stone debris from the surface area of the hole. If they fail in this manner with greater tensile capacity, then they may be an acceptable treatment option. An ideal

adhesive bonded system would be one where, at an acceptable load value, pullout occurred between the pin and the adhesive, rather than causing detachment of stone. To achieve this result with the proper strength adhesive it is possible that smooth pins may be a preferable choice to threaded pins.

Given the conditions at the Second Bank, it is also essential that the introduction of restraint be able to accommodate movement and changes in the stone. While the function of the pinning treatment is to induce stresses that will resist the internal forces causing deterioration, if these stresses are greater than the strength of the stone it will lead to additional fracture and damage. This was clearly demonstrated in testing a pinning system using epoxy, and emphasizes the importance of using compatible materials. The properties of the Sikadur<sup>®</sup> Injection Gel, while strong, showed an incompatibility with the stone. Though it has a lower modulus of elasticity, the adhesive's modulus of rupture is greater than that of the stone, resulting in a potential to cause damage. This is of particular concern on exposed elements, like the column arrises, which are susceptible to cyclical weathering and flexural thermal movement. If an epoxy resin were used to accomplish the repair then this property of the adhesive should be carefully considered.

Pin and adhesive selection should also take into account other measures of compatibility that are not necessarily related to strength, such as thermal expansion coefficient; an important factor in understanding the stresses that can occur due to temperature changes. Stone, and in particular marble, has a low coefficient of thermal expansion compared to most other materials. Most of the pins used in the testing program were stainless steel and have a thermal expansion coefficient three times that of

marble, while one of the benefits of using a ceramic material is its similar properties to stone, minimizing some of the stresses and strains affected by repair components.

The application of pins to provide reinforcement creates a complex system, the mechanics of which cannot be fully understood due to the number of unknown parameters; the magnitude and concentration of the internal forces causing the deterioration, and the distribution of stresses of the pinning system inserted in both the substrate and the spall. This situation underscores the importance of the compatibility of the repair materials with the stone, as well the ability to remove the treatment if and when necessary, in an effort to prevent damage from an improperly functioning repair. One of the objectives of this study was to compare a common pinning method, an epoxy seated steel pin, to alternative techniques, with a stated criteria that included retreatability of the repair. Though many of the systems evaluated demonstrated insufficient strength, they were all designed with a degree of retreatability. The advantage of a pinning technique employing bone screws for example is that it could possibly be removed if necessary, providing the screw has not been significantly deformed. It is recommended that any design and evaluation of mechanical pinning treatments take this criterion into account.

## **6.2 RECOMMENDATIONS FOR FUTURE RESEARCH**

This evaluation presented only preliminary testing of mechanical pinning systems. Future testing should be conducted with other combinations of pin materials and diameters, adhesives, and embedment depths. The testing results with bone screws suggest that these could be an adequate pinning system for treatment application and

further testing of their strength properties with different lengths and diameters would help to determine their viability. Ceramic pins have many favorable properties and it is recommended that these pins be evaluated with adhesives other than what was used for the testing program. The testing demonstrated the disadvantages of the epoxy seated pinning system chosen for evaluation. A more suitable and less stiff epoxy is required. Though the B-72 adhesive provided insufficient strength, other acrylic resins could be evaluated as an alternative to epoxies.

Further consideration and testing should be given to the behavior of multiple pins and pinning configurations. It would be of great benefit to know the strength and behavior of a repair with pins inserted at angles or dovetail design. In addition, weatherability testing, such as freeze-thaw cycling, should be conducted to determine the durability of any repair recommended for application, as well as a comparison with other treatment options, such as injecting drilled holes with 'spot welds' of adhesive.

## **APPENDICES**

- A. MANUFACTURERS AND SUPPLIERS OF MATERIALS
- B. TECHNICAL DATA OF ADHESIVES AND FILLERS
- C. TESTING DATA
- D. TENSILE STRENGTH OF COLUMBUS OHIO LIMESTONE

## **APPENDIX A:**

### **MANUFACTURERS AND SUPPLIERS OF MATERIALS**

McMaster-Carr Supply Co.  
Dayton, NJ 08810  
732 329 3200  
www.mcmaster-carr.com

*threaded stainless steel rod, nylon tubing*

Rohm and Haas Company  
Philadelphia, PA 19106  
215 592 3000  
www.rohmhaas.com

*Acryloid® B-72 acrylic resin*

Vesuvius McDanel Co.  
Beaver Falls, PA 15010  
724 843 8300  
www.techceramics.com

*alumina ceramic pins*

Specialty Minerals Inc.  
Bethlehem, PA 18017  
610 882 8720  
www.mineralstech.com

*Ultra-Pflex® precipitated  
calcium carbonate*

Diverse Surgical Supplies  
Fresno, CA 93710  
559 435 8935  
www.diversesurgical.com

*orthopedic surgical bone screws*

Sika Corporation  
Lyndhurst, NJ 07071  
201 933 8800  
www.sikacorp.com

*Sikadur® Injection Gel epoxy adhesive*

## **APPENDIX B:**

### **TECHNICAL DATA OF ADHESIVES AND FILLERS**

**Product Data Sheet**  
Edition 9.2003  
Identification no. 386  
Sikadur Injection Gel

## Sikadur® Injection Gel

High-modulus, high-strength, structural,  
non-abrasive, smooth epoxy paste adhesive

<b>Description</b>	Sikadur Injection Gel is a 2-component, 100% solids, moisture-tolerant, high-modulus, high-strength, structural epoxy. When mixed it gives a smooth, non-abrasive, paste adhesive. It conforms to the current ASTM C-881 and AASHTO M-235 specifications.
<b>Where to Use</b>	<ul style="list-style-type: none"> <li>■ Structural crack repairs not exceeding 1/4 in. (6 mm) width.</li> <li>■ Mechanical grouting . . . bolts, dowels, pins, machine and 'robotic' base plates, bearing pads, etc.</li> <li>■ Waterproofing tunnels, cable vaults, tanks, basements, etc.</li> <li>■ Re-anchoring of veneer masonry.</li> <li>■ Wood-truss repairs.</li> <li>■ Preventive maintenance - grout large cracks on new or existing structures to seal off reinforcing steel from the elements of corrosion.</li> <li>■ Anchor grouting . . . bolts, dowels, pins and special fasteners.</li> <li>■ As a pick-proof sealant around windows, doors, lock-ups, etc. inside correctional facilities.</li> </ul>
<b>Advantages</b>	<ul style="list-style-type: none"> <li>■ Unique, non-abrasive texture permits application with automated pressure-injection equipment.</li> <li>■ Tolerant of moisture before, during, and after cure.</li> <li>■ High-modulus, high-strength, structural-paste adhesive.</li> </ul>

### Typical Data (Material and curing conditions @ 73°F (23°C) and 50% R.H.)

<b>Shelf Life</b>	2 years in original, unopened container.		
<b>Storage Conditions</b>	Store dry at 40°-95°F (4°-35°C). <b>Condition material to 65°-75°F (18°-24°C) before using.</b>		
<b>Color</b>	Gray.		
<b>Mixing Ratio</b>	Component 'A' : Component 'B' = 1:1 by volume.		
<b>Consistency</b>	Smooth, non-sag paste.		
<b>Pot Life</b>	Approximately 30 minutes. (60 gram mass)		
<b>Tensile Properties: (ASTM D-638)</b>			
<b>14 day</b>	Tensile Strength	4,300 psi (29.7 MPa)	
	Elongation at Break	1.3%	
	Modulus of Elasticity	4.1 x 10 <sup>6</sup> psi (2,829 MPa)	
<b>Flexural Properties (ASTM D-790)</b>			
<b>14 day</b>	Flexural Strength (Modulus of Rupture)	6,700 psi (46.2 MPa)	
	Tangent Modulus of Elasticity in Bending	7.5 x 10 <sup>6</sup> psi (5,175 MPa)	
<b>Shear Strength (ASTM D-732) 14 day</b>	Shear Strength	3,700 psi (25.5 MPa)	
<b>Bond Strength (ASTM C-882):</b>			
<b>Hardened concrete to hardened concrete</b>			
<b>2 day (dry cure)</b>	Bond Strength	3,000 psi (20.6 MPa)	
<b>2 day (moist cure)</b>	Bond Strength	2,500 psi (17.2 MPa)	
<b>14 day (moist cure)</b>	Bond Strength	2,600 psi (17.9 MPa)	
<b>Hardened concrete to steel</b>			
<b>2 day (dry cure)</b>	Bond Strength	3,300 psi (22.7 MPa)	
<b>14 day (moist cure)</b>	Bond Strength	2,600 psi (17.9 MPa)	
<b>Heat Deflection Temperature (ASTM D-648)</b>			
<b>7 day</b>	[fiber stress loading = 264 psi (1.8 MPa)]		120°F (49°C)
<b>Water Absorption (ASTM D-570) 7 day</b>	(24 hr. immersion)		0.11%
<b>Compressive Properties (ASTM D-695)</b>			
<b>Compressive Strength, psi (MPa)</b>	<b>40°F* (4°C)</b>	<b>73°F* (23°C)</b>	<b>90°F (32°C)</b>
<b>4 hour</b>	-	-	300 (2.1)
<b>8 hour</b>	-	300 (2.1 MPa)	6,500 (44.8)
<b>16 hour</b>	100 (0.7)	7,500 (51.7)	7,000 (48.3)
<b>1 day</b>	1,400 (9.6)	8,000 (55.1)	9,500 (65.5)
<b>3 day</b>	7,600 (52.4)	8,500 (58.7)	10,000 (68.9)
<b>7 day</b>	9,000 (62.1)	9,000 (62.1)	10,000 (68.9)
<b>14 day</b>	10,000 (68.9)	10,000 (68.9)	10,000 (68.9)
<b>28 day</b>	10,000 (68.9)	10,000 (68.9)	10,000 (68.9)
<b>Compressive Modulus 7 day</b>	2.7 X 10 <sup>6</sup> psi (1,863 MPa)		

\*Cured and tested at the temperatures indicated.



- Excellent adhesion to masonry, concrete, wood, steel and most structural materials.
- Paste consistency ideal for vertical and overhead applications.
- Fast-setting (FS) version also available.
- Convenient easy mix ratio A:B = 1:1 by volume.
- Excellent lubricity for deep penetration.

<b>Coverage</b>	1 gal. yields 231 cu. in. of epoxy paste adhesive.
<b>Packaging</b>	4 gal. units
<b>How to Use</b>	
<b>Surface Preparation</b>	Surface must be clean and sound. It may be dry or damp, but free of standing water. Remove dust, laitance, grease, curing compounds, impregnations, waxes and any other contaminants. <b>Preparation Work: Concrete</b> - Should be cleaned and prepared to achieve a laitance and contaminant free, open textured surface by blastcleaning or equivalent mechanical means. <b>Steel</b> - Should be cleaned and prepared thoroughly by blast cleaning.
<b>Mixing</b>	Sikadur Injection Gel is specially designed and formulated to be mixed and applied with automated pressure-injection equipment. Follow the recommendations and directions supplied by the equipment manufacturer. <b>Pre-mix each component.</b> Proportion equal parts by volume of Component 'B' and Component 'A' into a clean pail. Mix thoroughly for 3 minutes with Sika paddle on low-speed (400-600 rpm) drill until uniform in color. Mix only that quantity that can be applied within its pot life.
<b>Application</b>	<b>As a structural adhesive</b> - Apply the neat mixed Sikadur Injection Gel to the prepared substrates. Work into the substrate for positive adhesion. Secure the bonded unit firmly into place until the adhesive has cured. Glue line should be kept as thin as possible, not to exceed 1/4 in. (6 mm) <b>To seal injection ports and cracks for injection grouting</b> - Place the neat mixed material over the cracks to be pressure-injected and around each injection port. Allow sufficient time to set before pressure-injecting. <b>To anchor bolts, dowels, pins</b> - Annular space around bolt should not exceed 1/8 in. (3 mm); depth of embedment is typically 10-15 times the bolt diameter. Grout with neat Sikadur Injection Gel. <b>To grout cracks</b> - Use automated injecting equipment or manual method. Set appropriate injection ports based on the system used. Cracks up to 1/4 in. (6 mm) wide may be grouted. <b>To anchor bolts, dowels, pins in hollow masonry or concrete block</b> - Consult Technical Service. <b>To seal baseplates and bearing pads</b> - Inject in-place baseplate and bearing pads with Sikadur Injection Gel. Apply up to 1/4 in. (6 mm) thick. <b>As a pick-proof sealant</b> - use automated or manual method. Apply an appropriate size bead of material around the area being sealed. Seal with neat Sikadur Injection Gel.
<b>Limitations</b>	<ul style="list-style-type: none"> <li>■ Minimum substrate and ambient temperature 40°F (4°C).</li> <li>■ Do not thin. Addition of solvents will prevent proper cure.</li> <li>■ Material is a vapor barrier after cure.</li> <li>■ Not for sealing cracks under hydrostatic pressure.</li> </ul>
<b>Caution</b>	<b>Component 'A' - Irritant; Sensitizer</b> - Contains epoxy resin. Can cause skin sensitization after prolonged or repeated contact. Skin and eyes irritant. High concentrations of vapor may cause respiratory irritation. Avoid skin contact. Use only with adequate ventilation. Use of safety goggles and chemical resistant gloves is recommended. In case of exceedance of PELs, use an appropriate, properly fitted NIOSH approved respirator. Remove contaminated clothing. Consult MSDS for more detailed information. <b>Component 'B' - Irritant; Sensitizer</b> - Contains amines. Contact with eyes or skin may cause severe burns. Skin and eye irritant. High concentrations of vapor may cause respiratory irritation. Avoid skin contact. Use only with adequate ventilation. Use of safety goggles and chemical-resistant gloves is recommended. In case of exceedance of PELs, use an appropriate, properly fitted NIOSH approved respirator. Remove contaminated clothing. Consult MSDS for more detailed information.
<b>First Aid</b>	<b>Eyes:</b> Hold eyelids apart and flush thoroughly with water for 15 minutes. <b>Skin:</b> Remove contaminated clothing. Wash skin thoroughly for 15 minutes with soap and water. <b>Inhalation:</b> Remove person to fresh air. <b>Ingestion:</b> Do not induce vomiting. <b>In all cases, contact a physician immediately if symptoms persist.</b>
<b>Clean Up</b>	Ventilate area. Confine spill. Collect with absorbent material. Dispose of in accordance with current, applicable local, state, and federal regulations. Uncured material can be removed with approved solvent. Cured material can only be removed mechanically.

KEEP CONTAINER TIGHTLY CLOSED  
NOT FOR INTERNAL CONSUMPTION  
CONSULT MATERIAL SAFETY DATA SHEET FOR MORE INFORMATION

KEEP OUT OF REACH OF CHILDREN  
FOR INDUSTRIAL USE ONLY

Sika warrants this product for one year from date of installation to be free from manufacturing defects and to meet the technical properties on the current technical data sheet if used as directed within shelf life. User determines suitability of product for intended use and assumes all risks. Buyer's sole remedy shall be limited to the purchase price or replacement of product exclusive of labor or cost of labor.

NO OTHER WARRANTIES EXPRESS OR IMPLIED SHALL APPLY INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. SIKA SHALL NOT BE LIABLE UNDER ANY LEGAL THEORY FOR SPECIAL OR CONSEQUENTIAL DAMAGES.

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Phone: 514-897-2810  
Fax: 514-894-2792

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Carretera Libre Celaya Km. 8.5  
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C.P. 76920 A.P. 136  
Phone: 52 42 25 0122  
Fax: 52 42 25 0537



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## **Paraloid® B-72 Solid Grade Thermoplastic Acrylic Resin**

Paraloid® B-72 general-purpose thermoplastic acrylic resin is similar to Paraloid® B-66 acrylic resin but capable of forming softer films. The approximate hardness (KHN) is 10-11 compared to 12-13 for Paraloid® B-66 resin.

Paraloid® B-72 acrylic resin is unique in possessing a high tolerance for ethanol. The property allows its use in applications not tolerant of strong solvents. The alcohol dispersions may be cloudy or milky. However, they form clear, coherent films.

Paraloid® B-72 has low reactivity with sensitive phosphorescent and luminescent pigments to produce stable, durable, non-yellowing coatings. It is compatible with vinyls, cellulose, chlorinated rubbers, and silicones. It is well suited for white and metallic aerosols, clear coatings for wood, nitrocellulose modified coatings for general product finishing, pigment dispersion (fluorescent), flexographic printing inks, and gravure plastic coatings.

### **Solubility**

Information about the solvent compatibility of Paraloid® B-72 acrylic resin can be found in Rohm and Haas brochure 82A114--*Paraloid® Solid Grade Resins, Solvent Selection Chart*.

### **Typical Properties**

Physical Form	Pellets
Chemical Composition	EMA Copolymer
Tg, °C	40
Bulk Density, 25 °C, lb/gal	9.6
Solubility Parameter	9.3
Ultimate Hardness of Clear Films, KHN	10 to 11

## Product Specifications

Appearance, as-is visual	Free of visible foreign matter.
Appearance of solution* visual	Clear to slightly turbid, viscous liquid, free of sediment, foreign particles or polymer granules.
Color of solution, APHA	30, maximum
Turbidity Bentonite, scale	3, maximum
Viscosity, corrected, cps Brookfield LV spindle #2, 12 rpm, 25°C corrected to 40% solids	470 – 770

\* Solution preparation: weigh into a pint jar 120 g sample and 180 g toluene. Solution is about 40% solids.

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## PERFORMANCE MINERALS FOR SPECIALTY APPLICATIONS ULTRA-PFLEX®

### precipitated calcium carbonate (pcc)

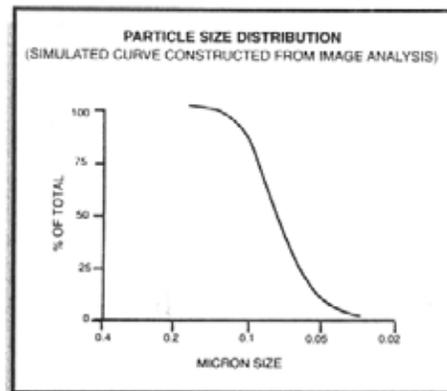
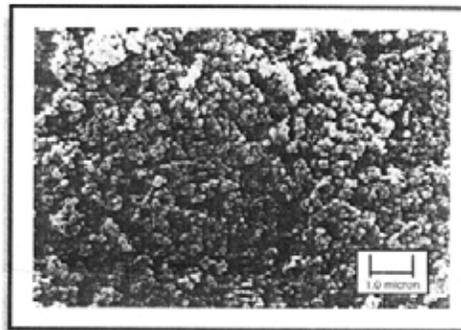
ULTRA-PFLEX® precipitated calcium carbonate (pcc) is a surface treated, premium quality, high performance, ultra-fine pcc. In **sealants**, particularly pvc plastisol, polysulfide, and polyurethane systems, ULTRA-PFLEX® pcc is a rheological additive providing thixotropy and viscosity control resulting in improved sag and slump characteristics of the sealant. In **rigid pvc** extrusion and molding applications, ULTRA-PFLEX® pcc enhances both notched Izod and falling weight impact strength while providing high surface gloss, whiteness and smooth appearance to the part surface. The multi-functional aspect of ULTRA-PFLEX® pcc provides the formulator with a unique tool with which to solve demanding performance problems, while offering significant cost savings potential.

#### Typical Properties

Average Particle Size (microns)	0.07
+325 Mesh Residue, (weight percent)	0.1
Specific Gravity	2.7
Dry Brightness (Hunter Y, Rd value)	98
Bulk Density (pounds/ft <sup>3</sup> )	15
(grams/cc)	0.24
Tap Density (pounds/ft <sup>3</sup> )	30
(grams/cc)	0.48
Surface Area (meters/grams)	19

#### Chemical Composition (typical - before treatment)

Calcium Carbonate	CaCO <sub>3</sub>	98%
Magnesium Carbonate	MgCO <sub>3</sub>	<0.1%
Iron as	Fe <sub>2</sub> O <sub>3</sub>	<0.1%
Moisture (% weight loss @ 110°C)	H <sub>2</sub> O	<0.2%



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**APPENDIX C:**

**TESTING DATA**

PULLOUT TESTS

BENDING TESTS

## PULLOUT TESTS

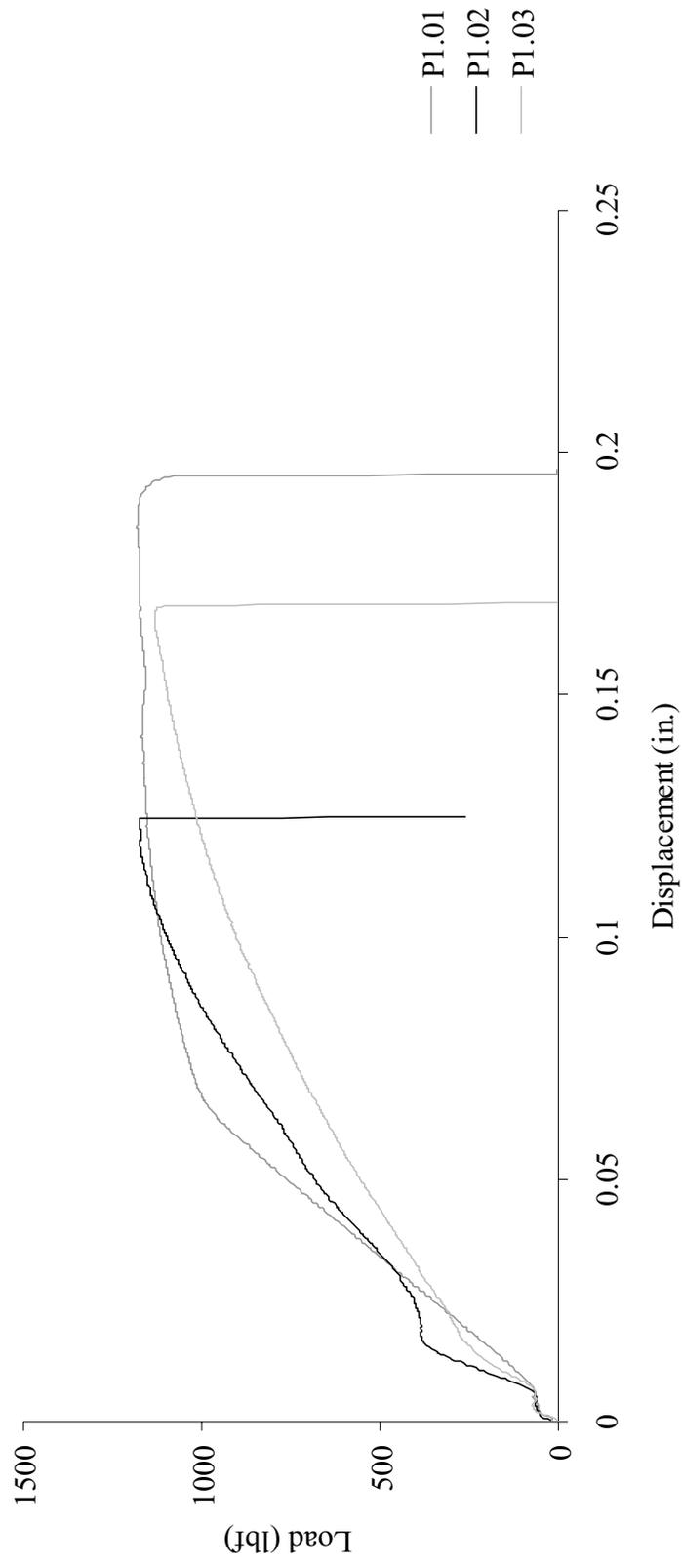
Standard Test: ASTM E 488

Performed by: Dr. Alex Radin at Mechanical Testing Facility, LRSM,  
University of Pennsylvania

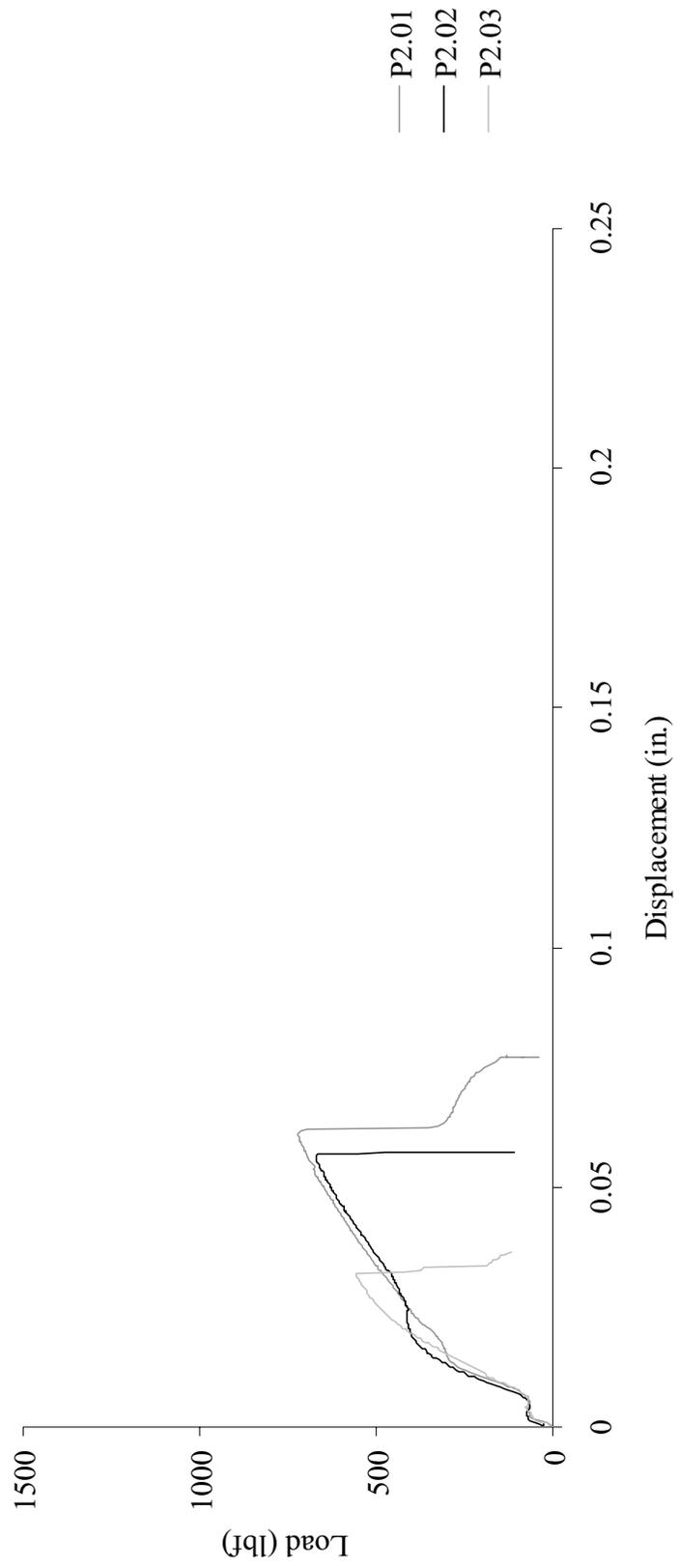
Date: February 18-19, 2004

assembly	maximum load (lbf)	displacement (in.)
P1.01	1180	0.184
P1.02	1176	0.124
P1.03	1131	0.166
P2.01	720	0.061
P2.02	671	0.056
P2.03	556	0.032
P3.01	82	0.028
P3.02	60	0.036
P3.03	78	0.062
P4.01	32	0.024
P4.02	44	0.015
P4.03	48	0.021
P5.01	91	0.068
P5.02	82	0.039
P5.03	90	0.044
P6.01	<i>no test</i>	<i>no test</i>
P6.02	85	0.031
P6.03	113	0.035
P7.01	50	0.034
P7.02	72	0.027
P7.03	97	0.034
P8.01	317	0.115
P8.02	293	0.053
P8.03	228	0.017
P9.01	396	0.038
P9.02	464	0.068
P9.03	460	0.130
P10.01	48	0.006
P10.02	36	0.092
P10.03	25	0.005
P11.01	61	0.012
P11.02	43	0.011
P11.03	72	0.023

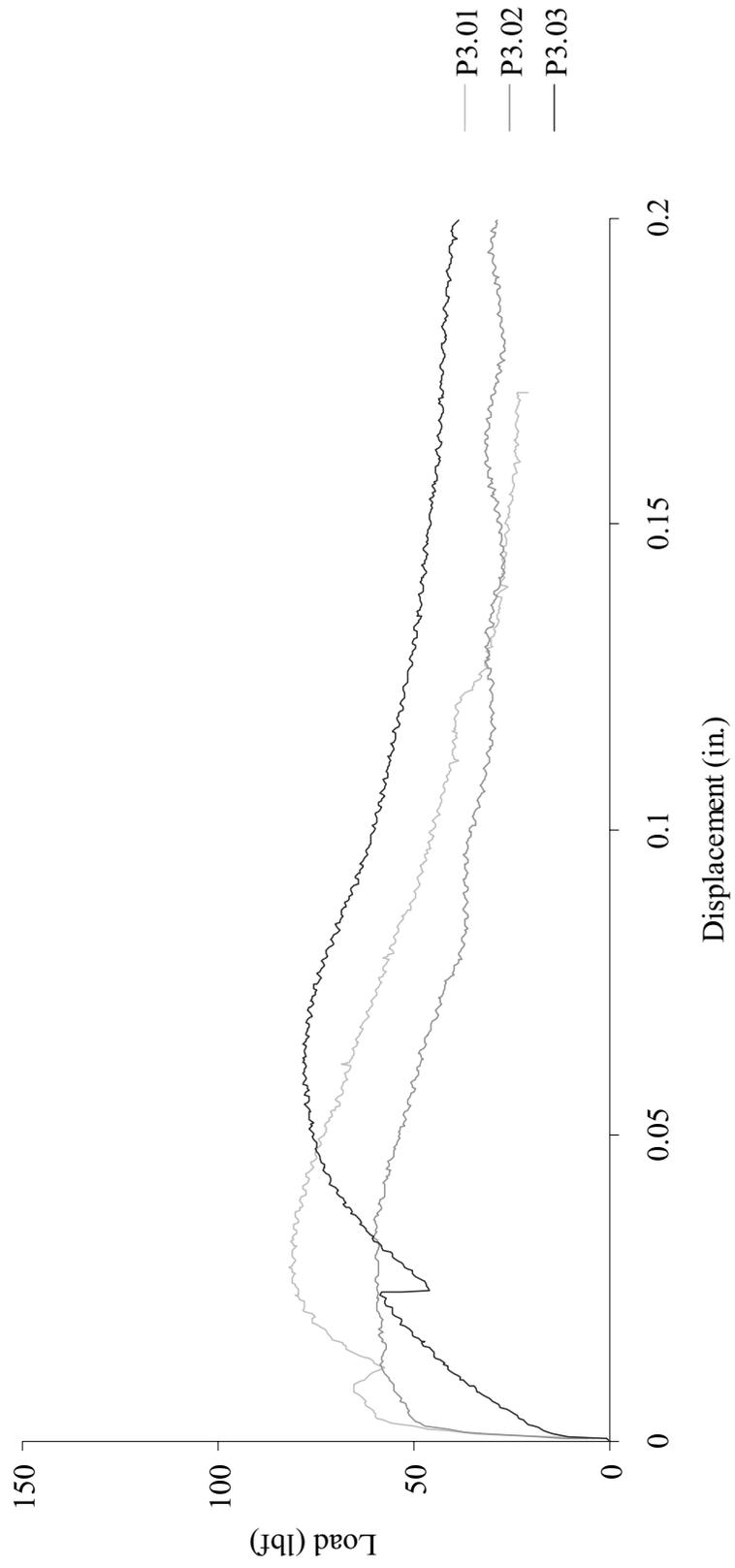
### Pullout Test Assembly P1



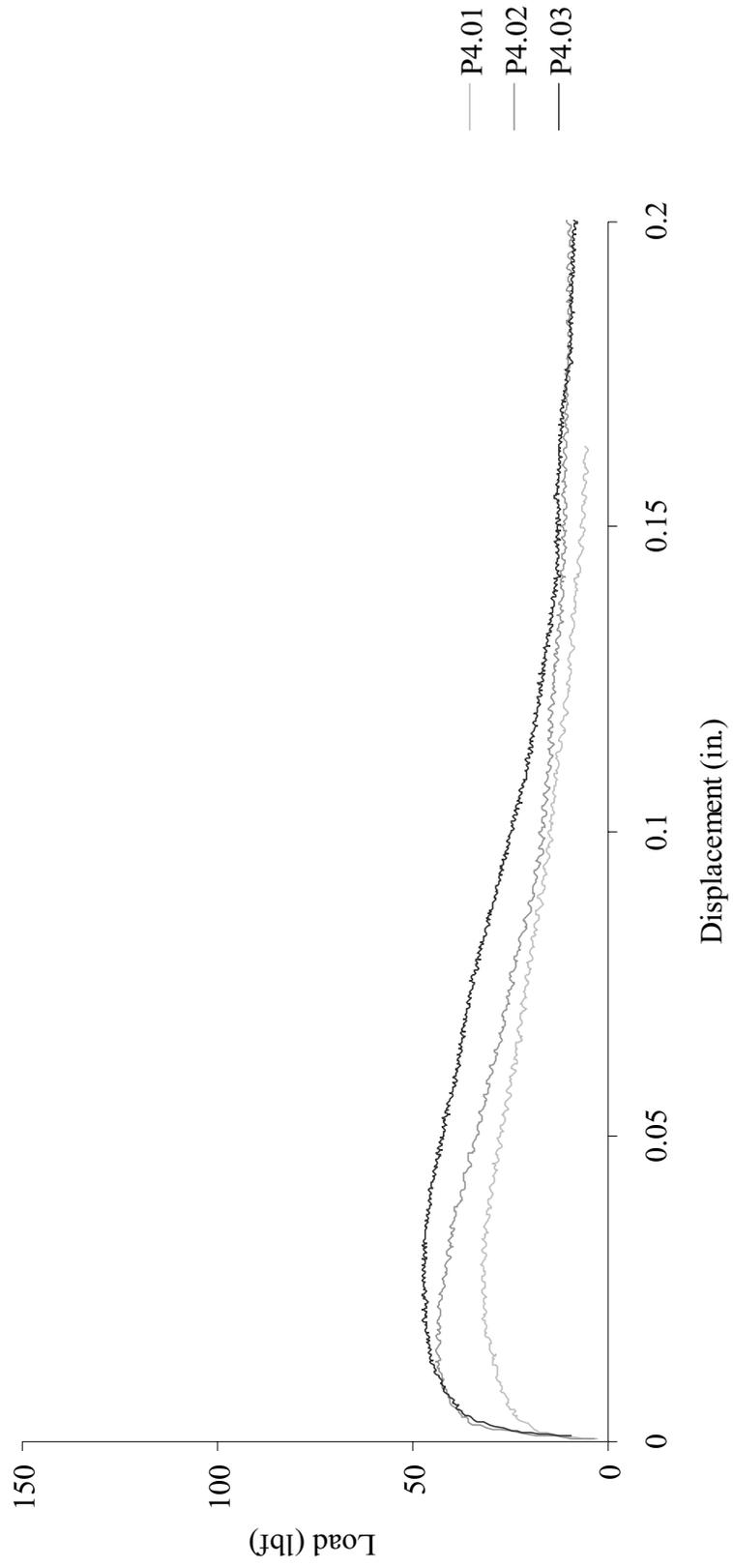
### Pullout Test Assembly P2



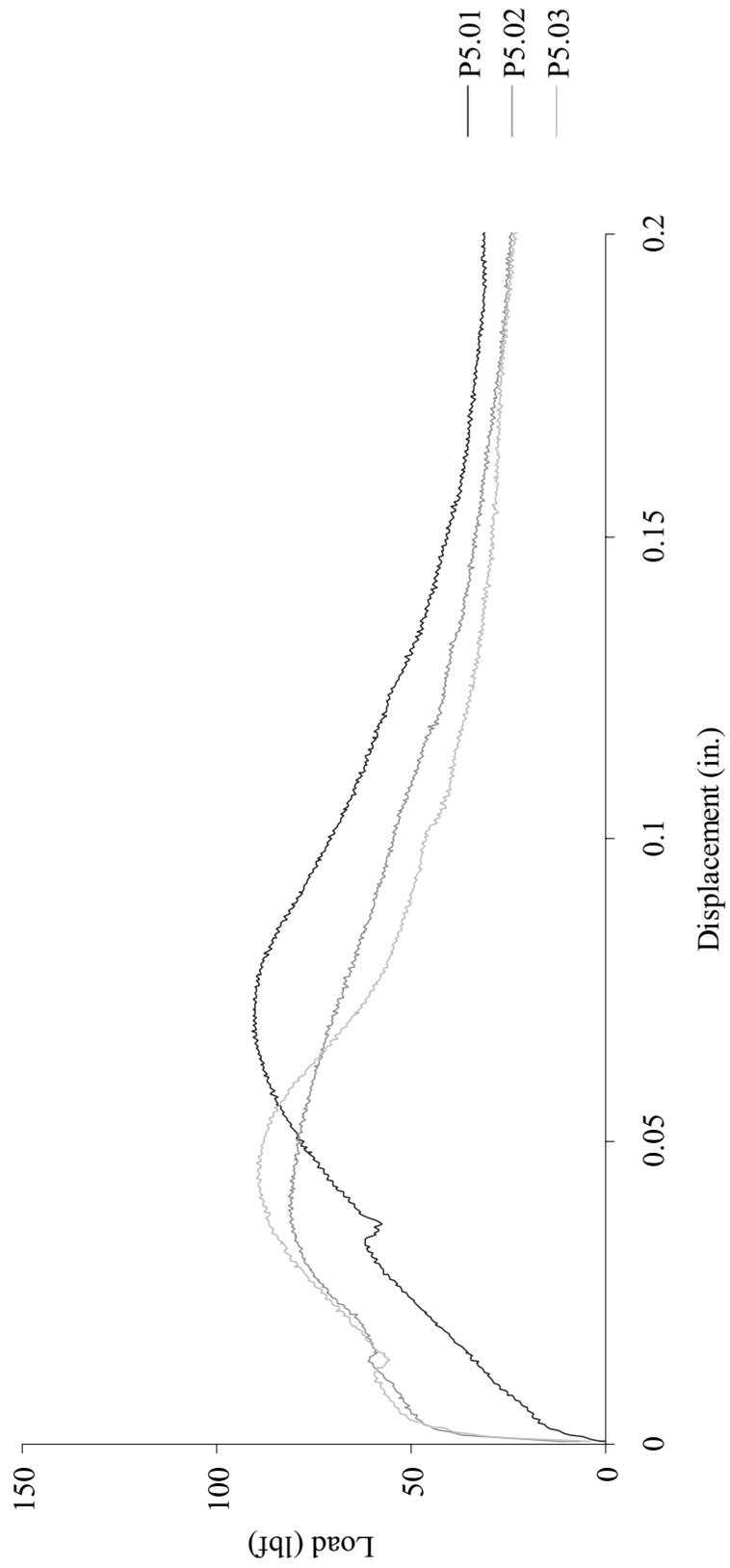
Pullout Test Assembly P3



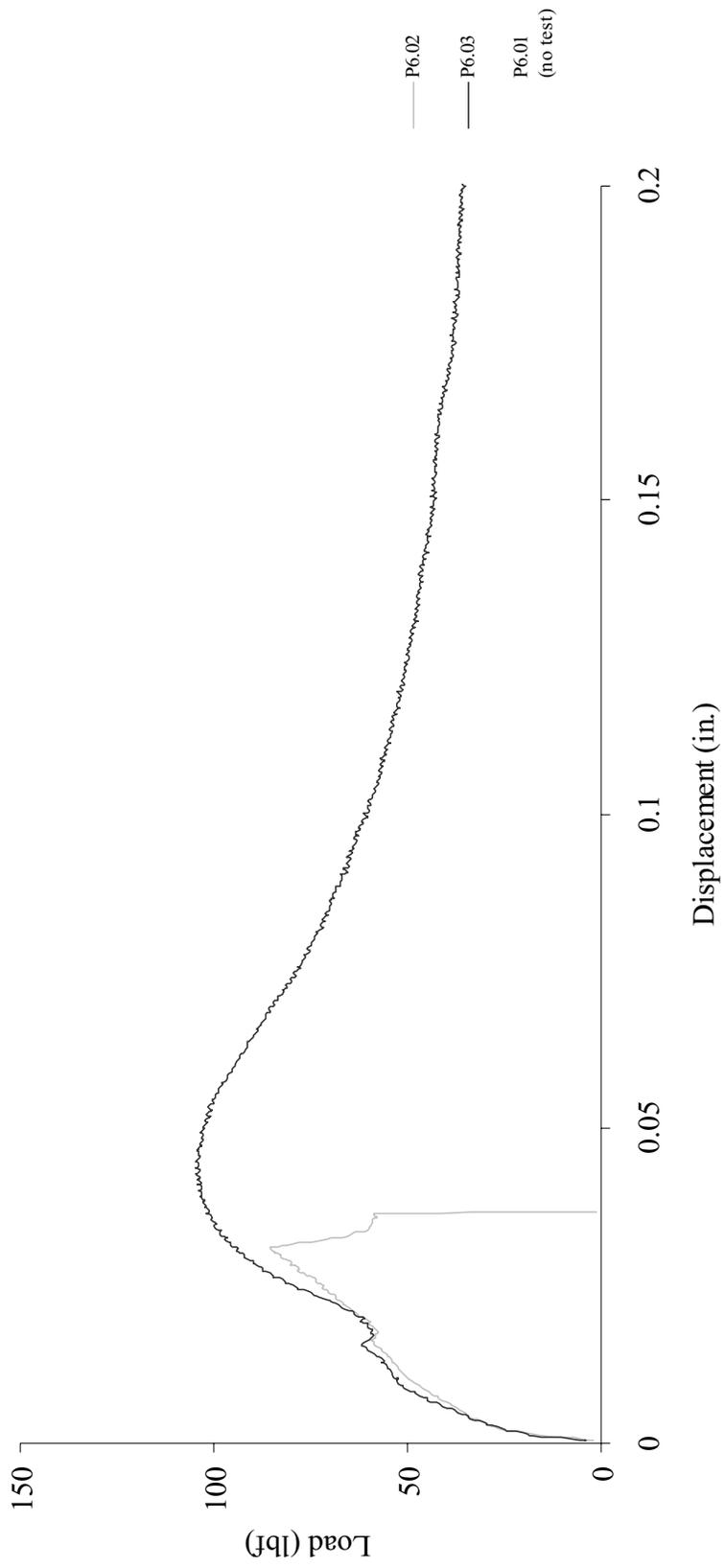
Pullout Test Assembly P4



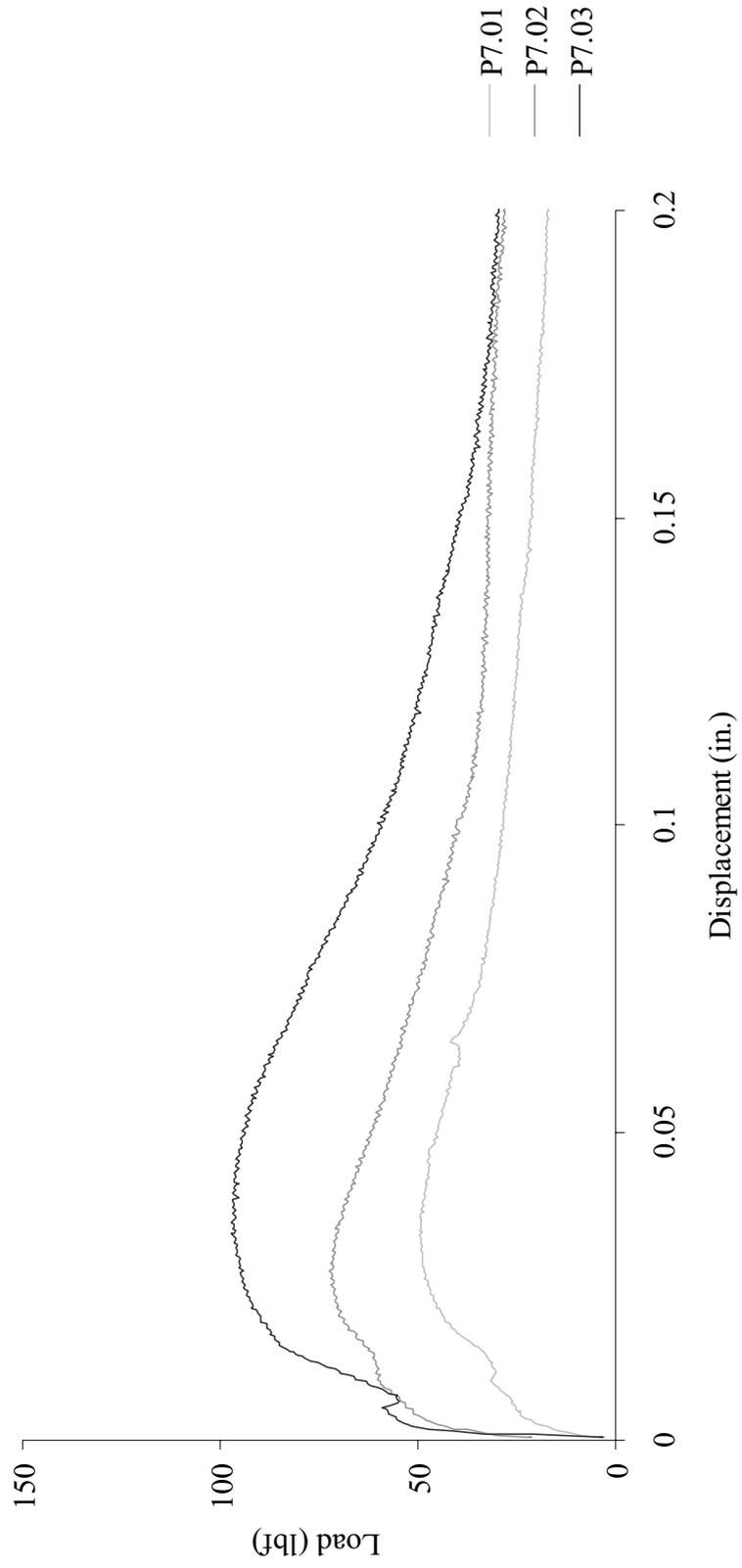
Pullout Test Assembly P5



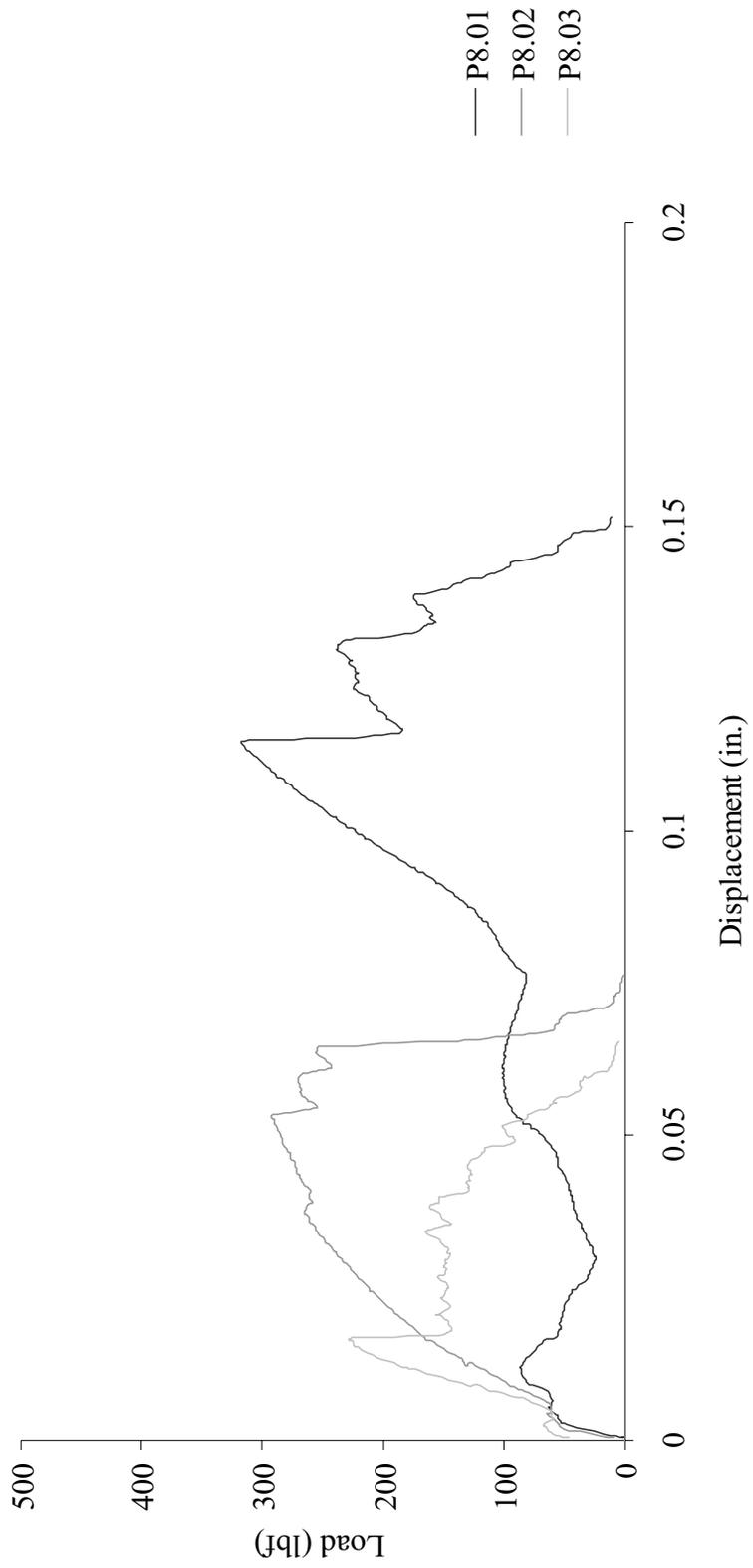
Pullout Test Assembly P6



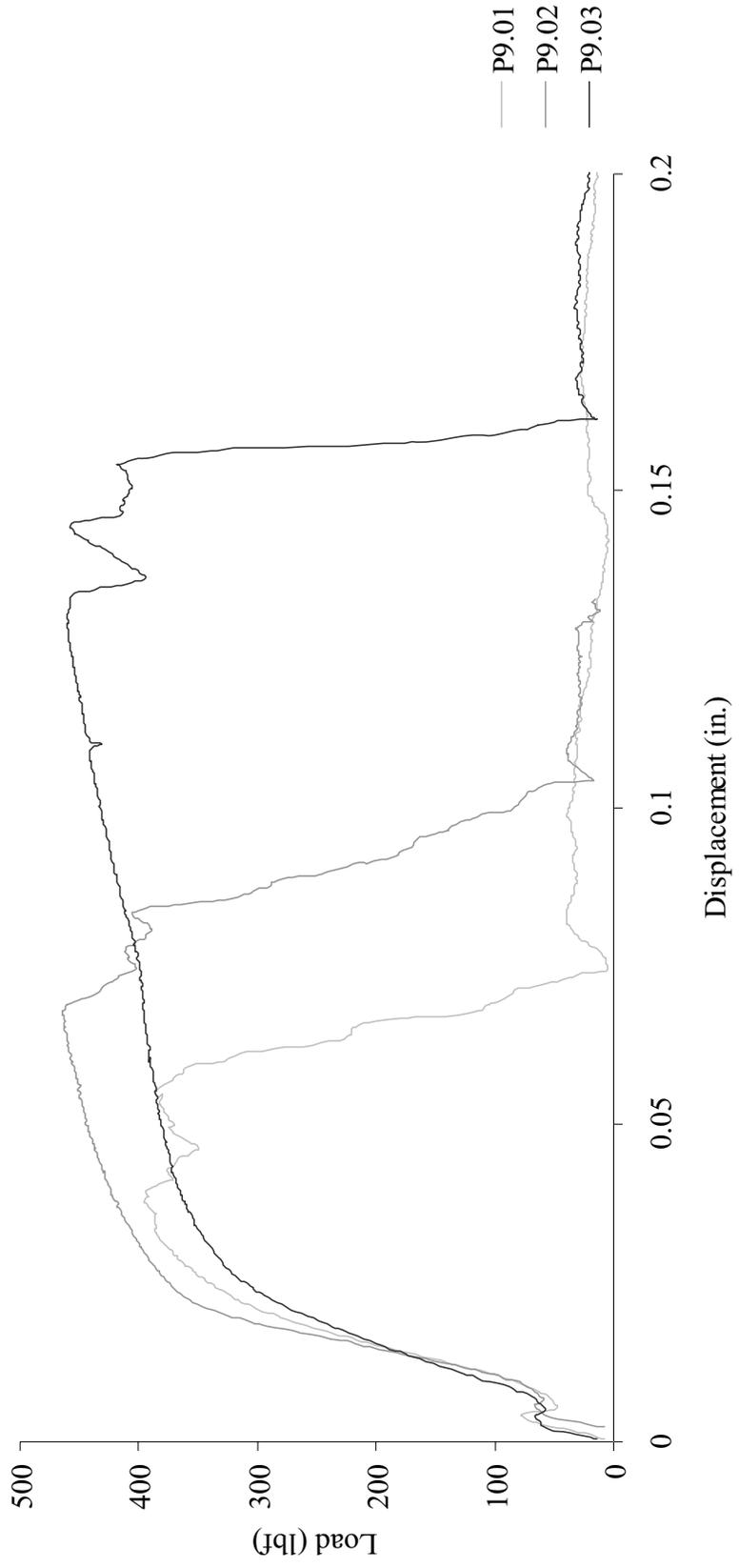
Pullout Test Assembly P7



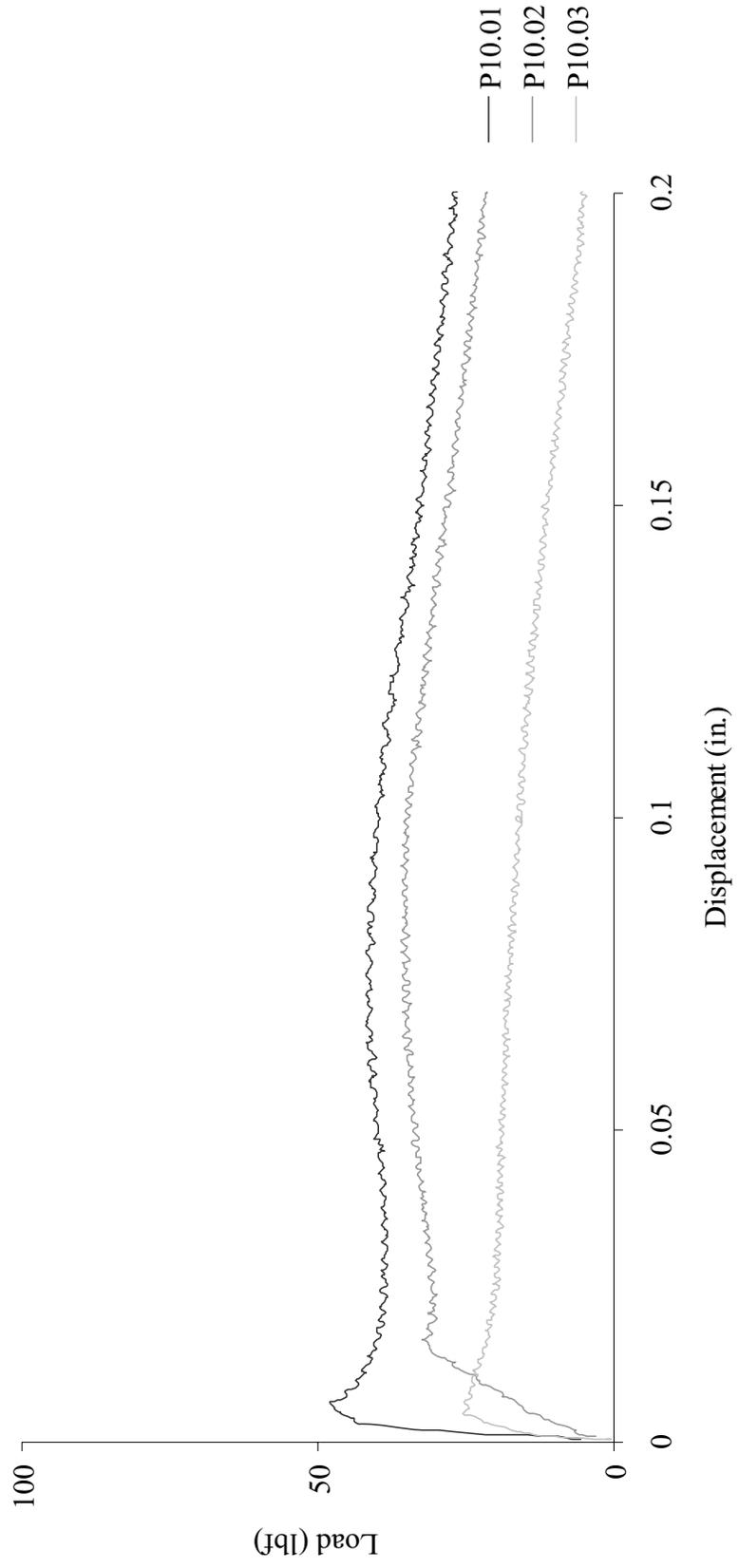
Pullout Test Assembly P8



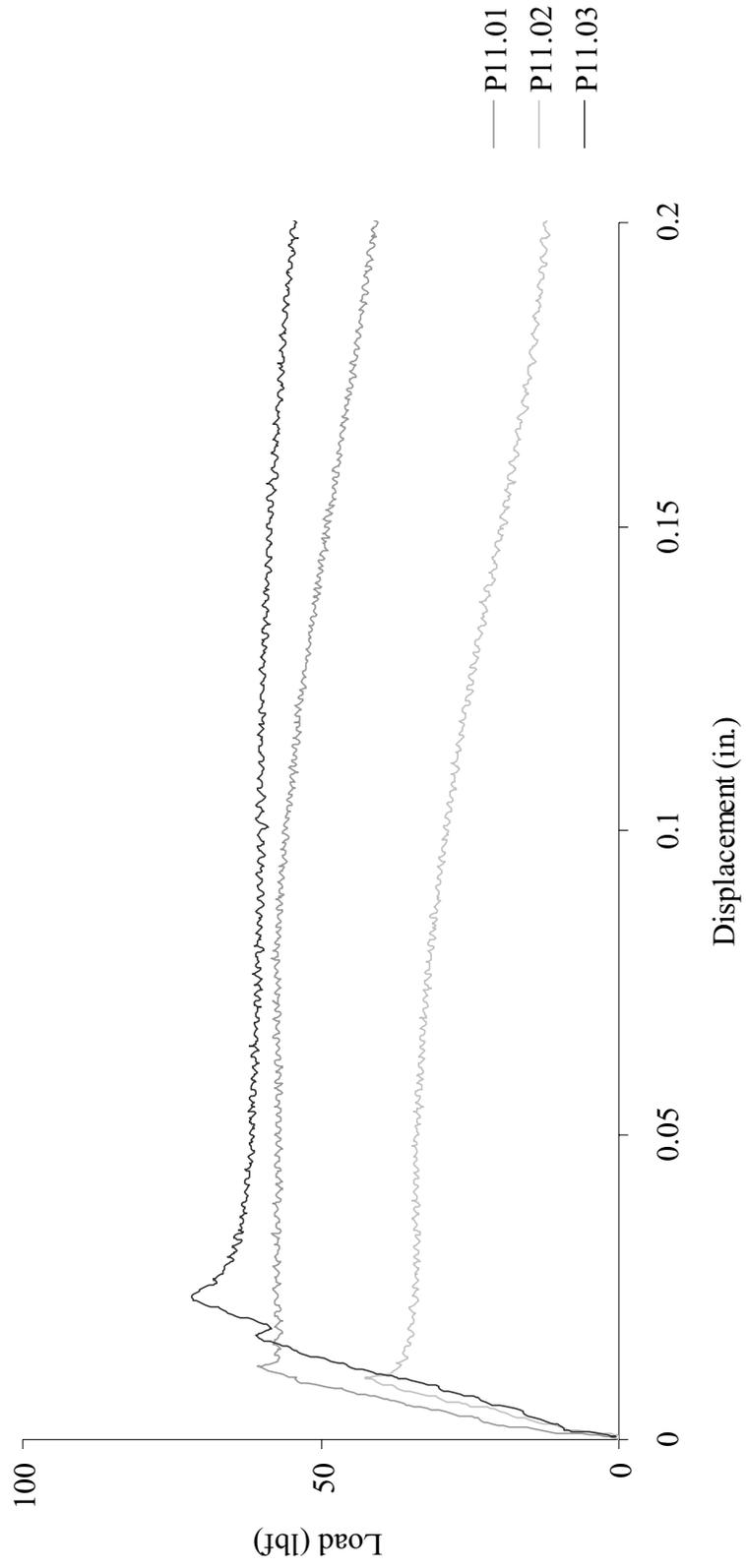
Pullout Test Assembly P9



Pullout Test Assembly P10



Pullout Test Assembly P11



## BENDING TESTS

Standard Test: ASTM C 99

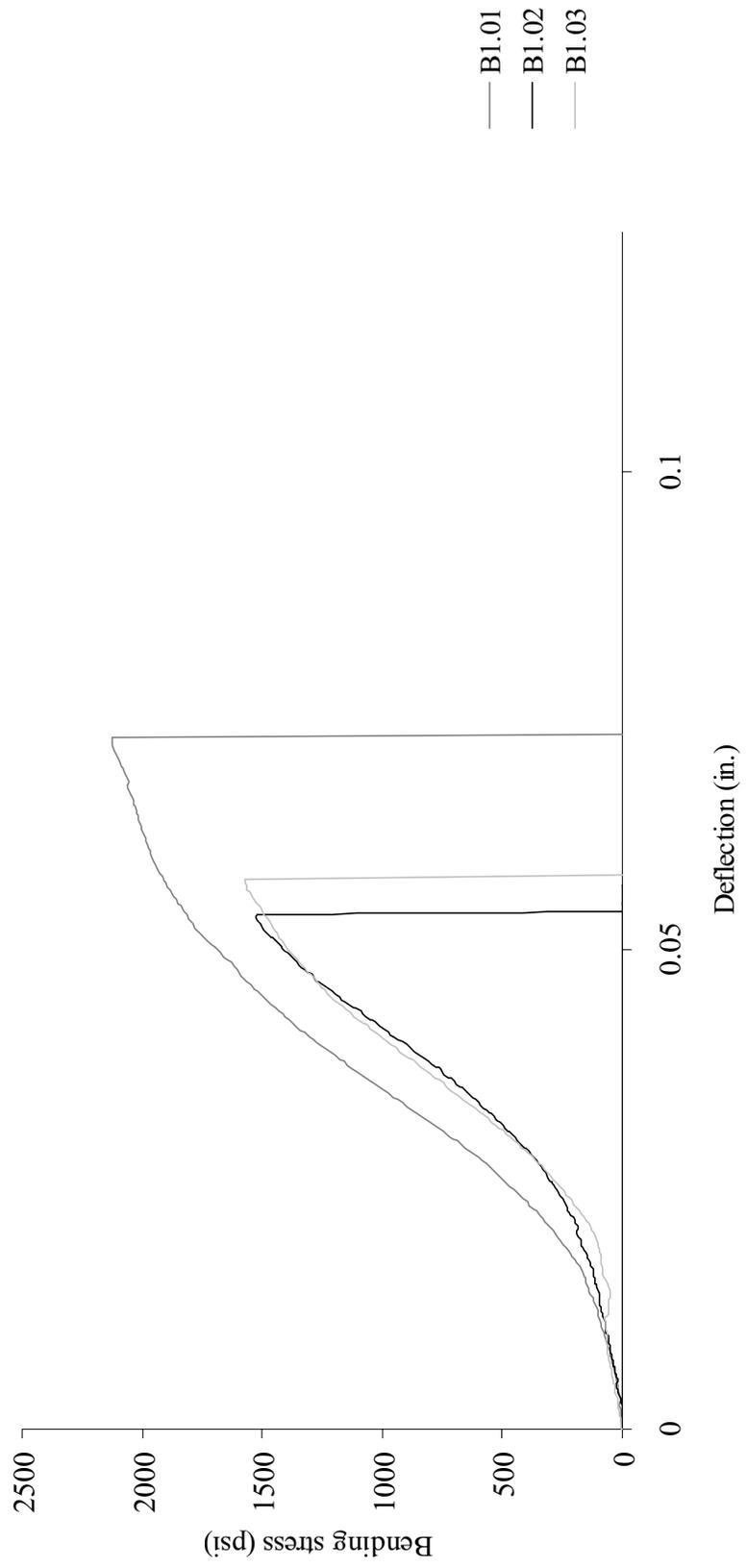
Performed by: Dr. Alex Radin at Mechanical Testing Facility, LRSM,  
University of Pennsylvania

Date: February 20 and 23, 2004

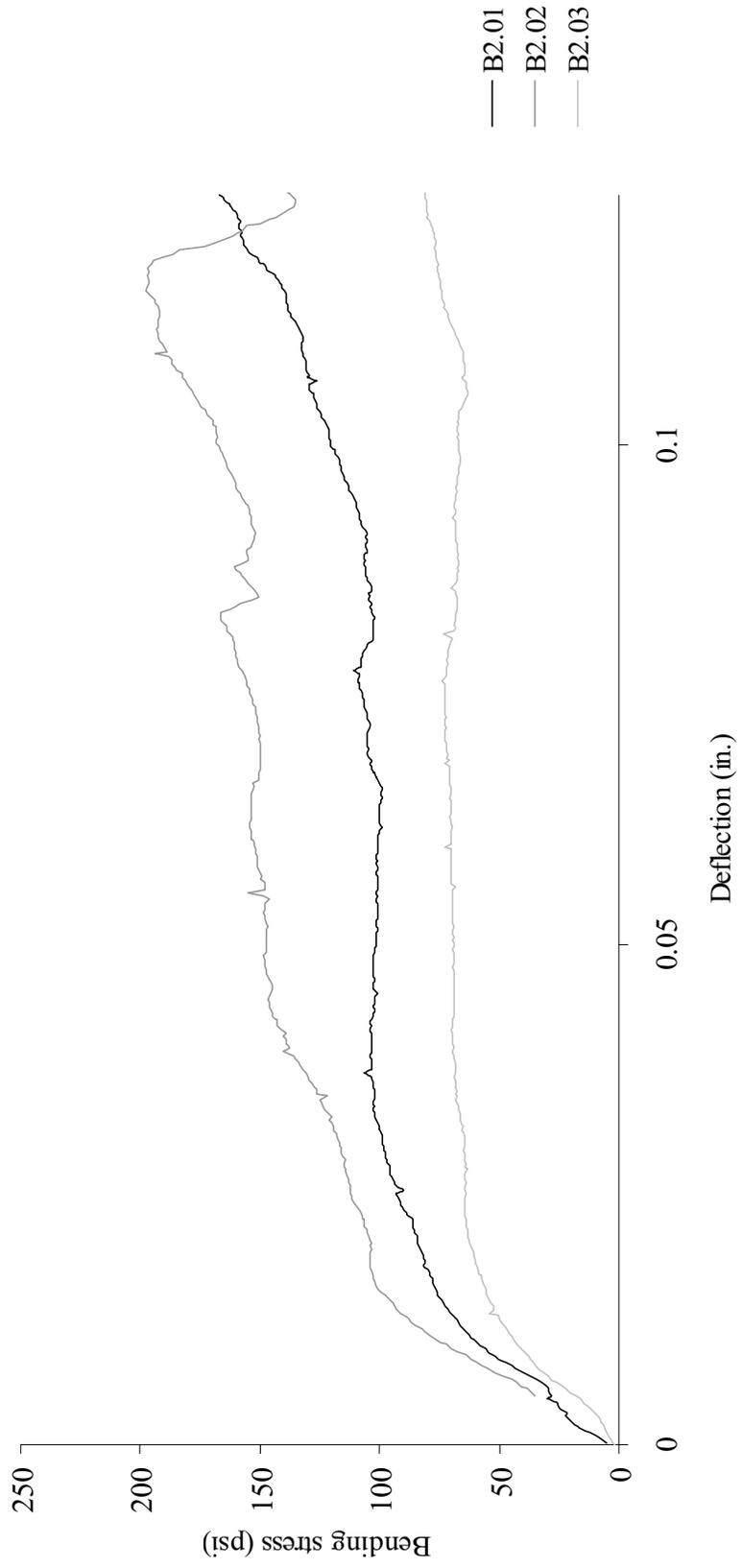
assembly	load (lbf)	bending stress (psi)	deflection (in.)
B1.01	4998	2125	0.072
B1.02	3818	1527	0.053
B1.03	4189	1571	0.057
B2.01	445*	167	0.125
B2.02	357*	138	0.125
B2.03	229*	81	0.125
B3.01	206	85	0.017
B3.02	203	81	0.011
B3.03	278	111	0.014
B4.01	1744	654	0.028
B4.02	1653	620	0.053
B4.03	2112	792	0.065
B5.01	2408*	992	0.125
B5.02	1125*	422	0.125
B5.03	1522*	589	0.125

\* load removed at 0.125 in. deflection

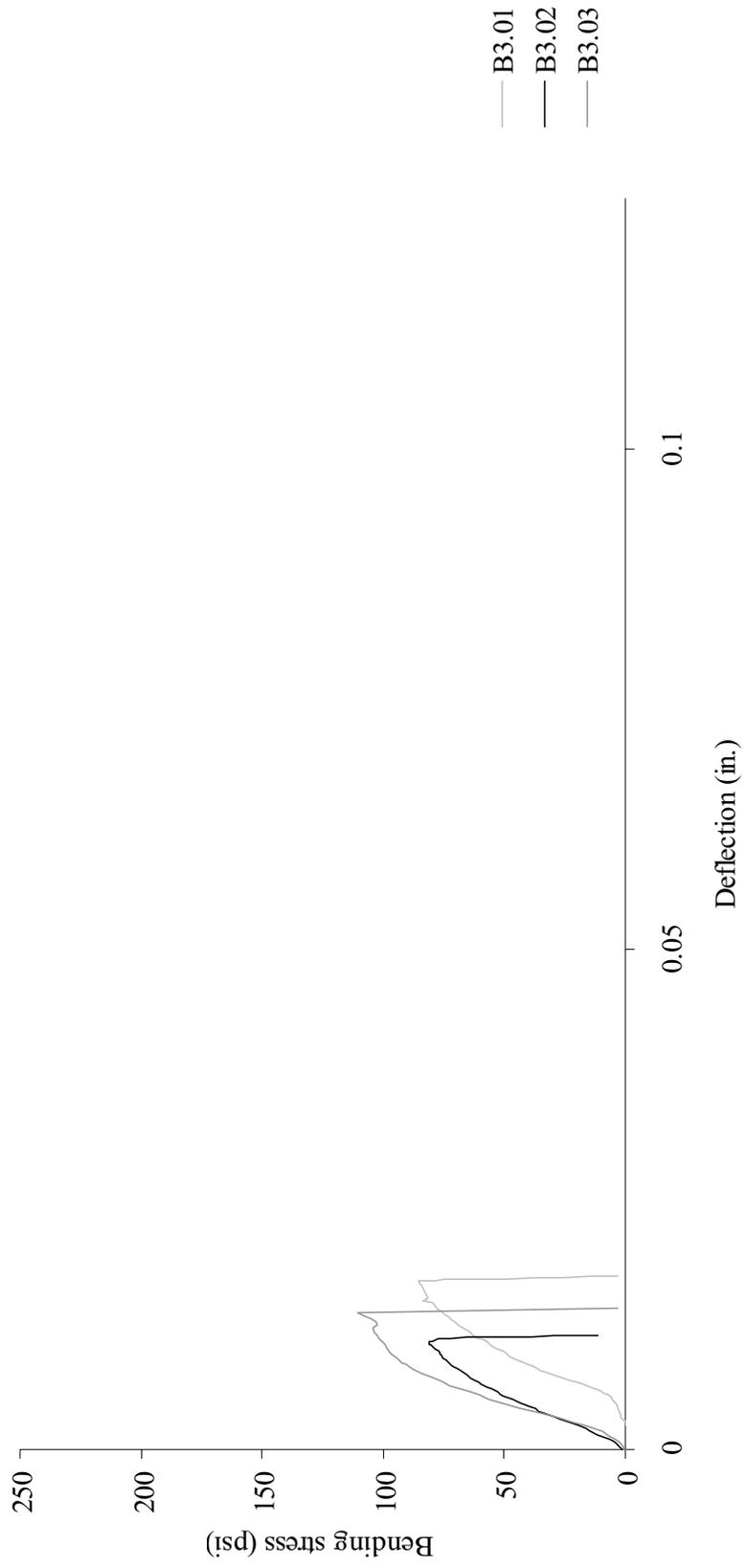
### Bending Test Assembly B1



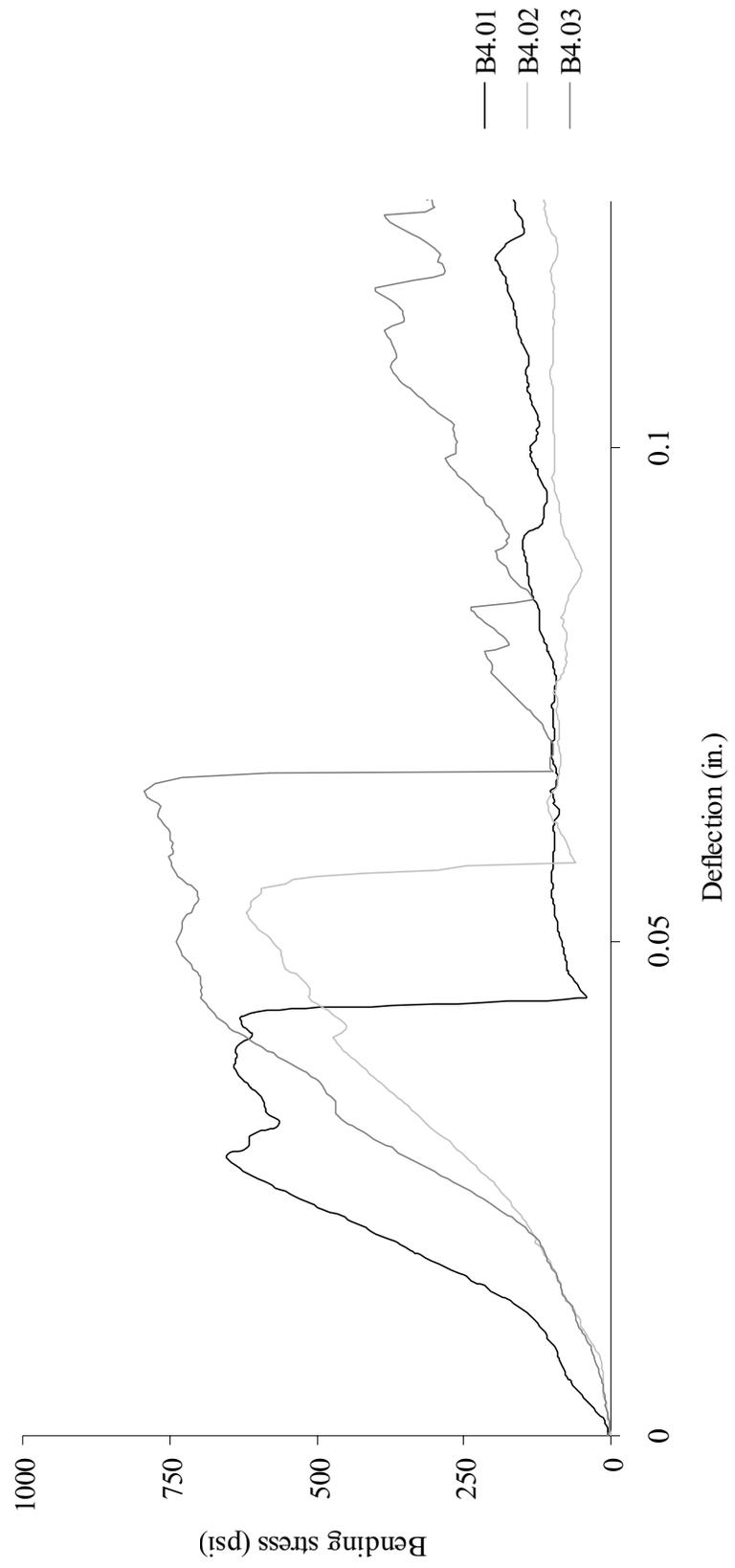
Bending Test Assembly B2



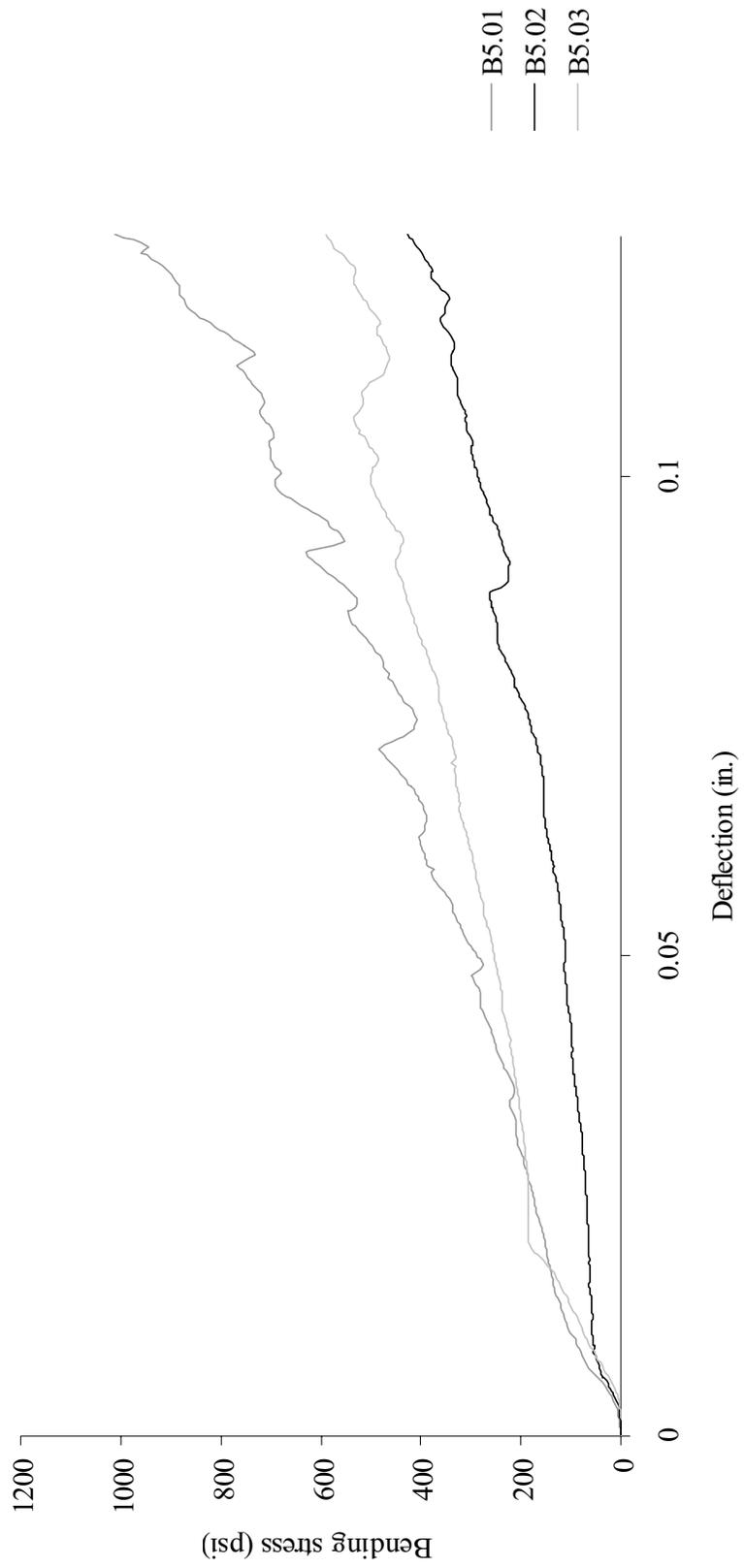
### Bending Test Assembly B3



### Bending Test Assembly B4



### Bending Test Assembly B5



## **APPENDIX D:**

### **TENSILE STRENGTH OF COLUMBUS OHIO LIMESTONE**

#### ***Standard Test***

ASTM D 3967-95a, Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens

#### ***Purpose***

This test provides an indirect means of determining the tensile strength of stone. At maximum load failure initiates at the center of the disc and propagates outward along the loading direction. Calculation is used to determine the tensile stress perpendicular to the loaded diameter at the time of failure.

#### ***Apparatus***

Instron 4206 electromechanical testing machine. Load cell capacity of 5000 lbs.

Testing was conducted at the Mechanical Testing Facility, LRSM, University of Pennsylvania by Dr. Alex Radin. March 8, 2004.

#### ***Procedure***

The samples used for testing were circular discs, 5 in total, with diameters of 2.75" and thickness of 1". Prior to testing the stone discs were washed with deionized water and a nylon bristle brush, and then allowed to air dry for 24 hours. A compressive load was applied diametrically at a rate of 0.005 inches/minute.



Figure D.1 Testing setup for splitting tensile strength

**Calculation and Results**

The splitting tensile strength of the samples was calculated as follows:

$$\sigma = 2P / \pi LD$$

where,

$\sigma$  = splitting tensile strength, psi

P = maximum applied load, lbf

L = thickness of disc, in.

D = diameter of disc, in.

**Table D.1 Tensile strength of samples**

sample	tensile strength (psi)
T.01	807
T.02	733
T.03	898
T.04	651
T.05	718
<i>mean</i>	<i>761</i>

Standard deviation = 94.4

Standard error = 42.2

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