Assessment and Analysis of the Breeding Barn at Shelburne Farms

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History and construction chronology

Shelburne Farms, originally the agricultural estate of William Seward and Lila Vanderbilt Webb, is a 566-hectare National Historic Landmark District located on the eastern edge of Lake Champlain just south of Burlington, Vermont. The property is owned and operated by a nonprofit organization devoted to the cultivation of a conservation ethic through education and the stewardship of natural and agricultural resources.

Figure 1. The Breeding Barn at Shelburne Farms

The Webbs developed the estate between 1886 and 1902, as part of a grand experiment to develop innovative new approaches to land use and farming. Early in the process of acquiring the land, Webb consulted with celebrated landscape architect Frederick Law Olmsted, Sr. (1822-1903), to develop a landscape design for the growing estate. In his c.1887 design, Olmsted proposed a plan dividing the estate into farmland, forest, and parkland, combining the pastoral and picturesque in the tradition of the great “ornamental farms” of nineteenth-century Europe.

The estate architecture was designed by New York architect Robert Henderson Robertson (1849-1919), a prominent nineteenth-century designer of monumental architecture. Robertson was an early designer of skyscrapers and today he is best known for his Park Row Building (1896-1899), which at 27 stories was the tallest building in New York at the time of its construction. The buildings at Shelburne Farms represent Robertson's most significant estate commission. The Breeding Barn is the principal building of the Southern Acres portion of the Farm, and construction was begun in 1889 and completed in 1891 (Figure 2). At the time, the barn was said to be "probably the largest and best-appointed building of the kind, not only in the United States, but in the world. Those who have seen it call it one of the wonders of America". (Frank Leslie's Popular Monthly, September 1892).

The main block of the building is approximately 32.6 meters wide by 127.4 meters long, with a two-story annex centered on the rear facade. The building is timber-framed, supported on foundation stonework of Monkton quartzite, and clad in wooden shingles.

Figure 2. The barn under construction, c1890. Shelburne Farms Archives.

Building elevations are dominated by the complex-sloped 0.8-hectare hipped roof, with multiple dormers and enormous central tower. The walls are clad in wood shingles punctuated by scores of multi-pane windows that admit light and ventilate the interior space. A gable-roofed arched entry is centered on the front façade.

At the center of the building, an unbroken cathedral-like space measuring approximately 22 meters wide and 110 meters long once housed the riding ring. Surrounded by stables, the ring was lit by gable windows of eight large dormers and lantern glazing in the tower, supported on timber purlins 16.8 meters above the floor. The riding ring is surrounded by framed aisles on all four sides that once housed stalls at ground level and loft space above. The annex, added sometime after initial construction of the main block, originally housed grooming operations, a tack room, and machinery for processing oats. The level of interior finish is very high throughout most of the building (with the exception of the loft space), with wood-paneled walls, cased window and door openings, and neat chamfers on exposed frame elements.

The framing of the aisles and annex is fairly typical of heavy timber framing of the day, but Robertson borrowed from contemporary railroad construction in iron in designing the beautiful and highly efficient roof structure over the riding ring (Unwin, 1869). Here, a series of fourteen principal trusses of timber and iron were designed to support the roof expanse. Bay width was apparently determined by spacing of the stalls at ground level. Each truss has timber (southern pine) top chords trussed with wrought iron tension members and struts; a raised center element of wrought iron completes the truss form. At the lower end, principal rafters are captured in cast iron shoes that also receive the ends of the tension members. Shoes are seated on timber plates at principal post locations. With the ironwork painted white and receding from view in the limewashed riding ring, Robertson was able to convey the impression of a classically-framed timber building with an enormous open volume below the heavy timber rafters. Principal rafters support a roof of purlins and common rafters. Originally, purlins and valley rafters at each of the large dormers were trussed with wrought iron tension members and iron pipe struts.

There have been several major structural interventions in the Riding Ring roof frame; their chronology is only partially understood. As originally designed by Robertson, fourteen principal trusses divided the Riding Ring into fifteen bays, and the earliest set of drawings included no provision for cross-bracing of the long walls (Figure 3). At some point it was realized that lower chord elements as specified were too small to prevent deflection of the trusses and bending of side wall columns, and Robertson's office issued a new framing plan calling for installation of cross-brace ties between every principal rafter pair. These ties were to terminate in cast iron connections fastened to plate timbers behind truss heel connections. At the same time, trusses were doubled under the tower to support additional loads associated with that structure.

The dimensions of iron tensile elements in the tower trusses were increased and additional struts were added to support top chords at tower purlins. At the doubled trusses, cross-brace ties terminate at "double-wide" cast shoes spiked to the timber plates.

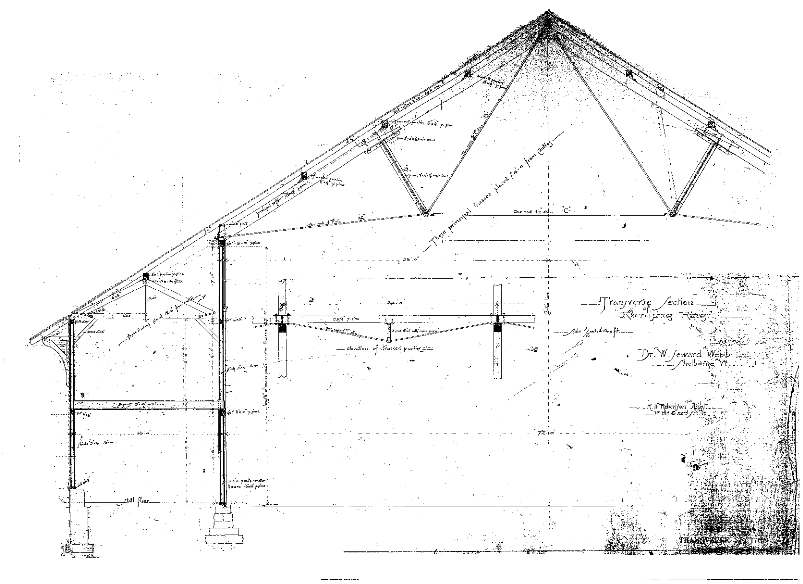

Figure 3. Robertson's earliest drawings of the roof frame omitted the ironcross-tie braces at plate level. Shelburne Farms Archives. All rights reserved. May not be reproduced without permission.

Sometime subsequent to original construction but early in the history of the building, additional trusses were installed to support inboard dormer framing for major dormer pairs located at the east and west ends of the ring. Top-bottom chord connections are still made at cast-iron housings, though these differ in design from the original elements. In the newer trusses, the raised center elements of the lower chords are equipped with turnbuckles, unlike their counterparts in the original trusses. Because of the proximity of cross-brace ties to the original trusses, the newer trusses were installed between columns and required additional bracing in riding ring walls. The level of craft displayed by these new trusses is roughly equivalent to that of the original construction.

An intervention which probably took place several decades later resulted in alteration of many of the valley rafters associated with the major dormer pairs. Originally, valley rafters at each of the large dormers were trussed with wrought iron tension members and paired iron pipe struts. Sometime in the twentieth century trusses on many of the valley rafters were removed and replaced with steel channels bolted on either side of the timbers. Addition of the steel channels necessitated cutting of purlins terminating at the valley rafters. In most cases, cutting appears to have been done crudely, with hatchets and chisels. Following installation of the steel channels most of the purlins were tied to valley rafters using bolted bent plates, except at dormer locations. Here purlins were never replaced, leaving trusses located at the centers of each major dormer pair unbraced.

Preservation planning

After decades of disuse and deferred maintenance, the Breeding Barn was in an advanced state of deterioration. An engineering assessment of the building in 1990 identified several areas requiring repair, including decay in all of the valley rafters in the large dormers at the tower and either end of the riding ring, jack rafters and plate timbers in their vicinity, and ridge timbers in the smaller dormers (CEA, 1990). The assessment called for repairs of deteriorated elements but stopped short of recommending augmentation of overstressed elements because of the impacts augmentation would have on historic integrity. Beginning in 1995, repairs were implemented that ultimately included stabilization of some of the foundation stonework with reinforced concrete, repair and/or replacement of some of the deteriorated structural timbers, replacement of the roof covering with standing seam copper, and installation of a fire-suppression system.

With the help of a Getty Planning Grant, Shelburne Farms was able to complete a conservation assessment for the Southern Acres buildings and landscape in 2004. A project team was assembled to conduct detailed structural assessment of the building and prepare plans for its augmentation and repair. Because of the significance and integrity of the resource, it was determined that any intervention should be as conservative of historic fabric as possible, that the historic structural system should be preserved to the fullest extent possible, and that traditional repairs are preferable to introducing new technologies so long as public safety goals are met. In order to design an intervention program that meets structural goals and guarantees public safety while having the smallest possible impact on surviving fabric, the multi-disciplinary design team determined that the focus of their work would be:

- Accurate and painstaking examination of surviving fabric to discover the nature and condition of materials and connections;
- Characterization of timber and metal elements, using non-destructive and quasi non-destructive testing techniques to the fullest extent possible;
- Rational selection of design values based on the conditions survey, materials testing, and review of the original construction documents and original design methodologies;
- Reduction of factors of safety through exhaustive knowledge of the building;
- Identification of overstresses through careful modeling and analysis.
- Development of a HABS-level documentation package, to be contributed to the Library of Congress upon completion of the project.

Figure 4. Barn interior.c1900 showing the roof frame of the riding ring, including iron cross-brace ties. Shelburne Farms Archives.

The Breeding Barn is in a jurisdiction subject to the *2005 Vermont Fire and Building Code* which has adopted the *ICC International Building Code, 2003 Edition.* This code allows for performance-based compliance exceptions in the case of historic buildings. The code has been used in establishing required live loads for the building. In managing the historic landscape and buildings of the estate and adapting them to new uses, Shelburne Farms is broadly guided by the *Secretary of the Interior's Standards for Rehabilitation*. Because of the significance and integrity of the Breeding Barn, and its importance in the history of the development of structural form, the project team has been additionally guided by the *ICOMOS Principles for the Preservation of Historic Timber Structures*, and the *ISCARSAH Principles* and *Guidelines*.

Conditions assessment and material testing

Initial examination of the building was organized as a training workshop in partnership with the University of Vermont. Professional team members included an architectural conservator, a structural engineer specialized in the analysis of historic timber buildings, and three timber framers associated with the truss research group of the Timber Framers Guild. Student trainees were selected from the Civil Engineering and Historic Preservation programs at the University. Trainees were paired with professional team members to form sub-teams. Each sub-team was assigned a portion of the building to survey. Survey data, including information about element dimensions, species, quality, and condition, was recorded on survey forms; survey forms included drawings of each of the principal structural elements so that deterioration and damage could be graphically represented.

The survey indicated that more detailed examination of the principal roof frame members was necessary to determine the quality and condition of several of the iron structural elements, and to determine the extent of the deterioration in several of the timber elements. The team was most concerned with unbraced rafters in each of the major dormers, with the condition and surviving capacity of several of the valley rafters, with the absence of a positive connection between valley rafters and other timber elements at the apex of the roof, and with the capacity of iron tension elements.

The wrought iron used in struts and tension elements was characterized with respect to metallurgical and mechanical properties. Samples were obtained from fabric that had been previously demolished. Strength-in-tension tests (ASTM E8) indicated an average yield strength of about 227,527 kPa and a MOE of 206,842,710 kPa. Small portions of each sample were retained for metallographic characterization. Analysis indicated a low-carbon material; the closest SAE-AISI alloy designation is 1005.

In order to quantify the extent of deterioration in decayed timber elements, a wood scientist assisted with a detailed evaluation of decayed timbers identified by the survey team. Quantification entailed resistance drilling of decayed timbers, using the IML-RESI System. Resistance drilling is a quasi-nondestructive technique for determining the relative density of wood, identifying discontinuities and quantifying the extent of section loss in the process. The process was exceptionally useful in evaluating valley rafter timbers, where installation of reinforcing steel channels on either side of each timber prevented direct examination in most cases.

Prior to this investigation, the extent of deterioration in the valley rafters at the Barn was not known. The wood investigation focused on resistance drilling, but included a combination of visual observations, moisture content measurements and probing to identify and quantify deterioration of the timbers in the 12 valley rafters. The likely causes of deterioration were identified for the purpose of establishing effective remedial treatments and repairs, and addressing long-term maintenance needs.

The timbers that make up the valley rafters were found to be generally in good to excellent condition. There were some exceptions. Each of the rafters was subjected to resistance drilling along its length to generate a schematic of the location and approximate extent of deterioration. Some of the rafters have deterioration on the upper face of the timber that penetrates to various depths, a condition called channelizing. Two of the valley rafters have severe deterioration of the heel where they bear on the interior wall.

Using the grid numbering system implemented by the survey team, the resistance drilling results were summarized graphically to illustrate the location and extent of deterioration in each rafter. Schematics of each valley rafter are color-coded to provide the reader with a visualization of the deterioration found. Conditions identified in red were priorities for further engineering analysis and possible repair. Areas colored green indicate no deterioration found. Areas in yellow exhibited minor channelizing (approximate depth of two inches or less) at the top of the rafter or minor deterioration elsewhere in the cross section. Orange areas indicate either local failure or deeper channelizing.

An example of one of the valley rafters is shown in Figure 5 and the corresponding resistance drilling findings are shown in Figure 6. Approximate resistance drilling test locations are marked by the drilling number on the schematic. As shown in Figure 6, this rafter has a varying extent of channelizing along the lower length of the rafter. Resistance drilling and probing revealed minor channelizing between the queen posts that progressively increased to the heel of the rafter. The upper length of the timber was found to be in good condition and is indicated as such by the green color.

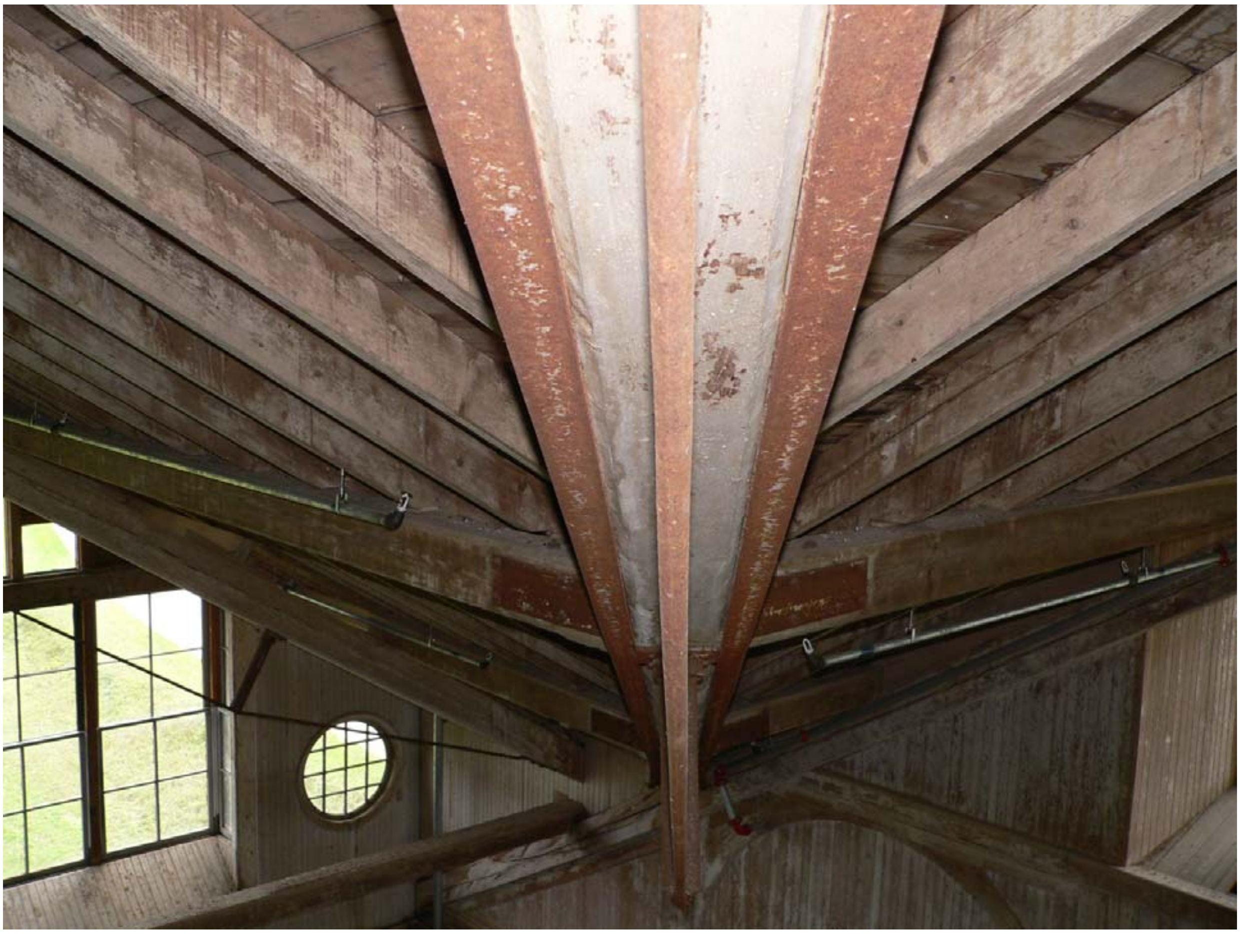

Figure 5. Valley Rafter 17 South viewed from the apex.

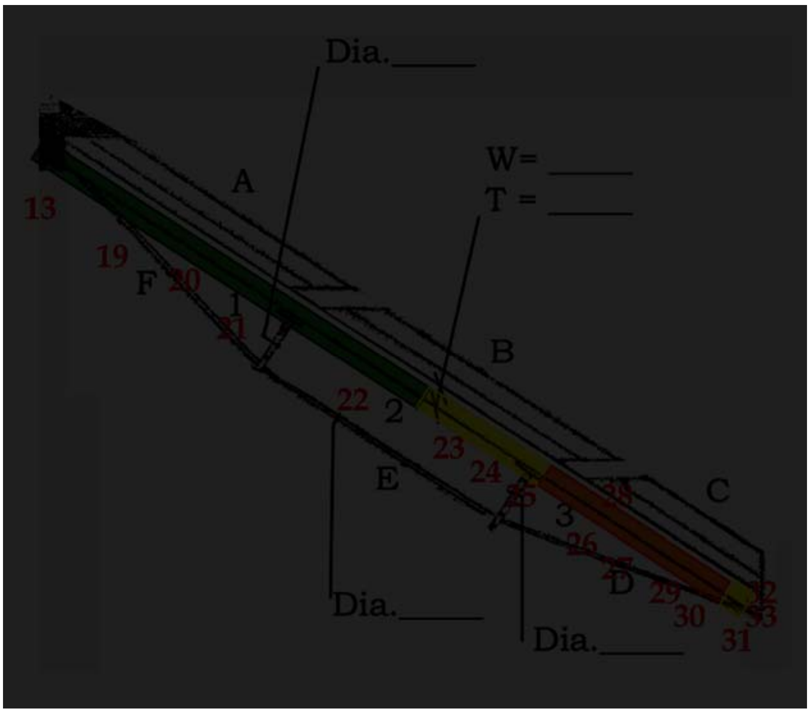

Figure 6. Resistance drilling results for Valley Rafter 17 South. Numbers in red indicate drilling locations.

Figure 7 is a diagram of the drilling results from drillings 31, 32, and 33 (which are shown on the schematic in Figure 6). The diagram is an approximation of the width and depth of the channel due to decay as indicated by the three drillings. A decay pocket of this depth was referred to as deep channelization.

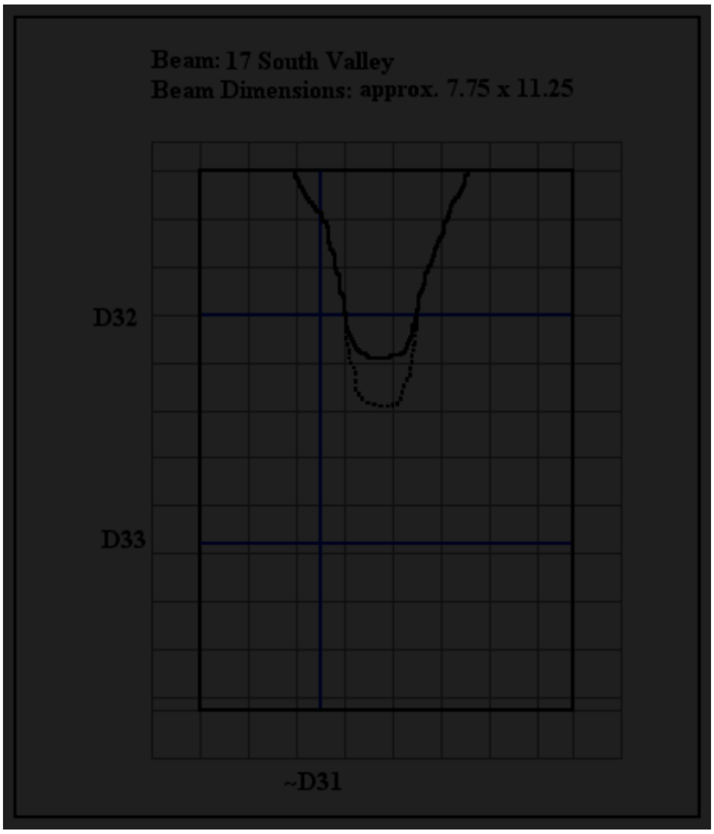

Figure 7. Diagram showing channelization pattern in Valley Rafter 17 South.
Dotted line indicates likely pattern of the decay pocket, since only three drillings were conducted.

Of the twelve timbers examined, four were found to have substantial section loss due to decay. Because the results of resistance drilling tests were expressed graphically and in tabular form, indicating the extent of section loss at each of the drill sites, this pinpointed areas of loss. Characterization of section loss based on resistance drilling will permit detailed design of timber repairs prior to dismantling the affected portions of the building, helping to reduce the number of inappropriate decisions made in the field.

Structural analysis

The procedure for evaluating a building such as this is to apply today's code mandated snow, live, and wind loads to various component systems, assuming that no deterioration has occurred. In this way, the original structure can be tested with specific design load criteria, against reasonable allowable design values with the amount of overstress tabulated for various elements.

By performing a plane frame computer analysis, the stiffness in the various components can be included, resulting in accurate theoretical deflections. The computed dead and live load deflections can then be compared to today's code mandated limits for roof structures. Once this process is completed, then a review of the amount of overstress in particular elements can be compared against reasonable values which could be expected from dense clear growth southern pine harvested in the late 1880s. After the structural analysis is complete, then a condition analysis can be made on the basis of field observation, measurement, and testing. Through analysis and engineering judgment, the capacity of the various components can be tabulated accounting for deterioration.

The production of a set of measured drawings of the structural elements, based on the original R.H. Robertson drawings and data collected by 3-D laser scanning of the building established the original configuration of the building "as built". The structural elements of primary interest in the Breeding Barn are the principal trusses, purlins and valley rafters. The team reviewed the original plans to determine the impact on the analysis of various elements. For example, the struts in the principal trusses in the R.H. Robertson drawings are called out as "four 3" x 3" x 3/8" angle irons." The survey indicated that the sizes of actual members are different from those shown in the plans. Although there is a wealth of information in the partial set of original drawings which remain, the effort to obtain a complete set of documents from other sources should continue. As Historic American Building Survey (HABS)-level drawings are developed,

differences between the actual building "as built" and the original drawings will be documented.
The preliminary analysis of the primary truss was performed with a 146.5 kg/m² snow load and 73.2 kg/m² dead load. The analysis indicated that there are overstresses in the top chord as well as the rods which extend from the heel supports to the queenpost struts. It is possible that the overstress in the 0.254 m x 0.305 m top chord is a result of the original designer analyzing the truss using graphical means (force diagram and string polygon) first developed in the United States by Col. Stephen H. Long in the 1840's.

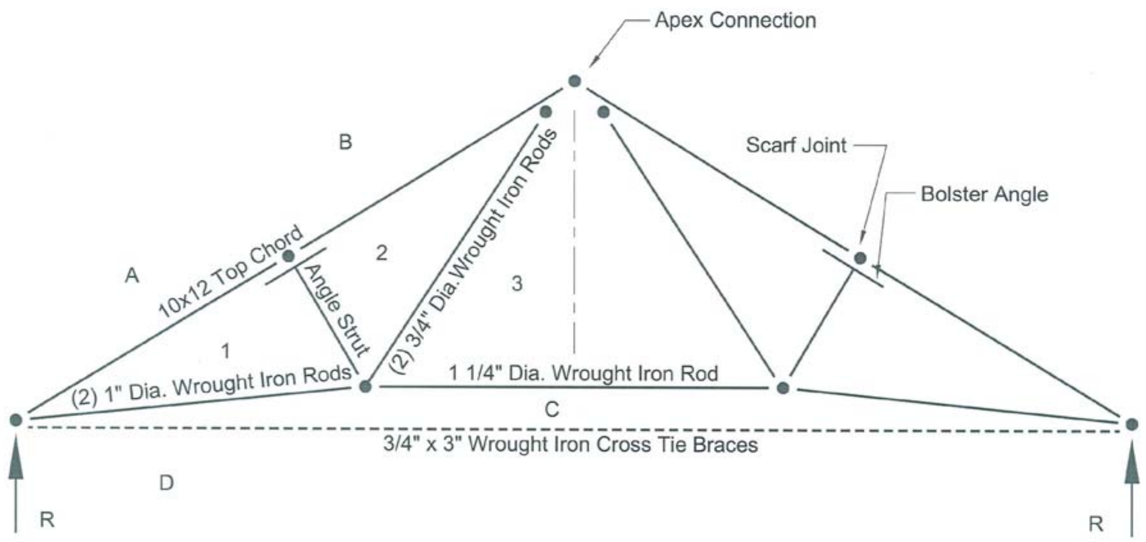

Figure 8. This image shows the location of the bolster angels and the connection arrangement at the apex.

This method of analysis provides only axial member forces. It is fairly accurate for trusses where purlin loads are applied to panel points. In this case, the top chord on each side of the truss has reactions from purlins applied midway between panel points. Even today, with new structures, computer analyses will provide often critical bending forces that can not be determined from a graphical analysis.

To analyze the truss as component in its simplest form, certain assumptions are required for graphical analysis, the method of joints, and the methods of moments and shears. Primary axial stresses are obtained on the basis of simplifying assumptions, producing an ideal truss with members having only axial forces. The following assumptions are made to allow the truss to be analyzed:

1. The truss members are connected together with frictionless pins.
2. Truss members are straight and the axis of the members intersect at joints.
3. Deformations under load do not excessively change the basic truss geometry.
4. Loads and reactions are applied only at joints (Figure 9).
5.

Apparently, the truss in the riding ring evolved from a simple truss analyzed by graphical means, to one with purlins located between joints (Figure 10), to a system combining a truss with a horizontal tie (Figure 11). The wrought iron angles used to bolster the spliced top chord is an interesting detail. These may have been added as an afterthought, sometime during design, to reinforce the top chord acting as a two-span beam supporting purlins at the midpoint of both spans. Although it certainly was possible to obtain southern pine in 12.19-meter lengths to produce a two-span continuous top chord, the designers chose to splice the top chord directly above the bolster angles.

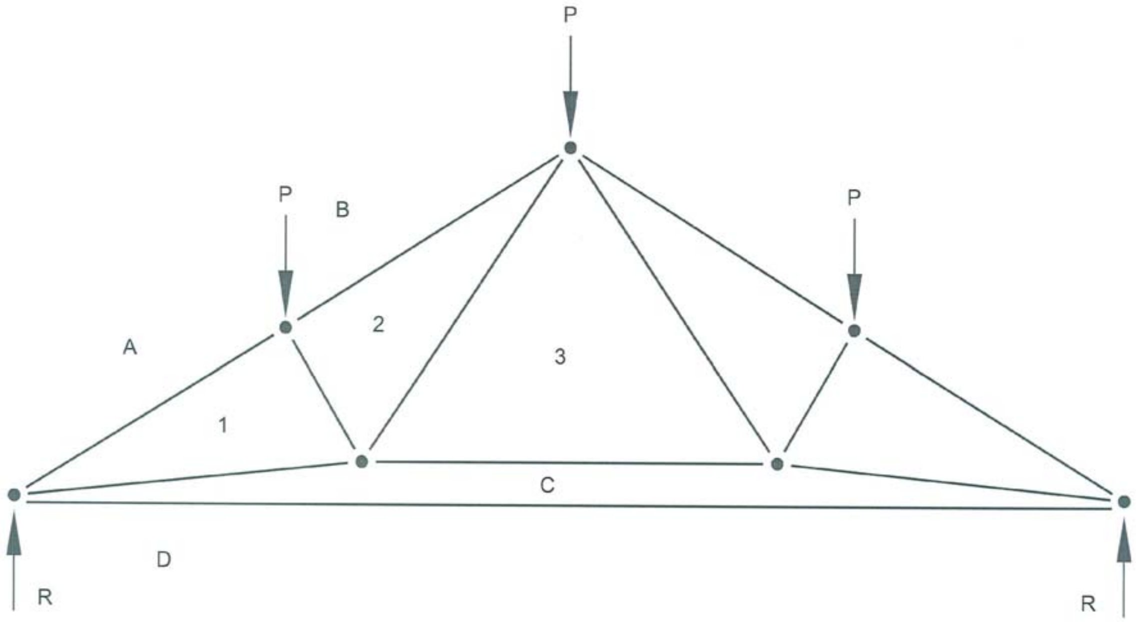

Figure 9. This shows the placement of the unit loads for the load test with the loads located at joints.

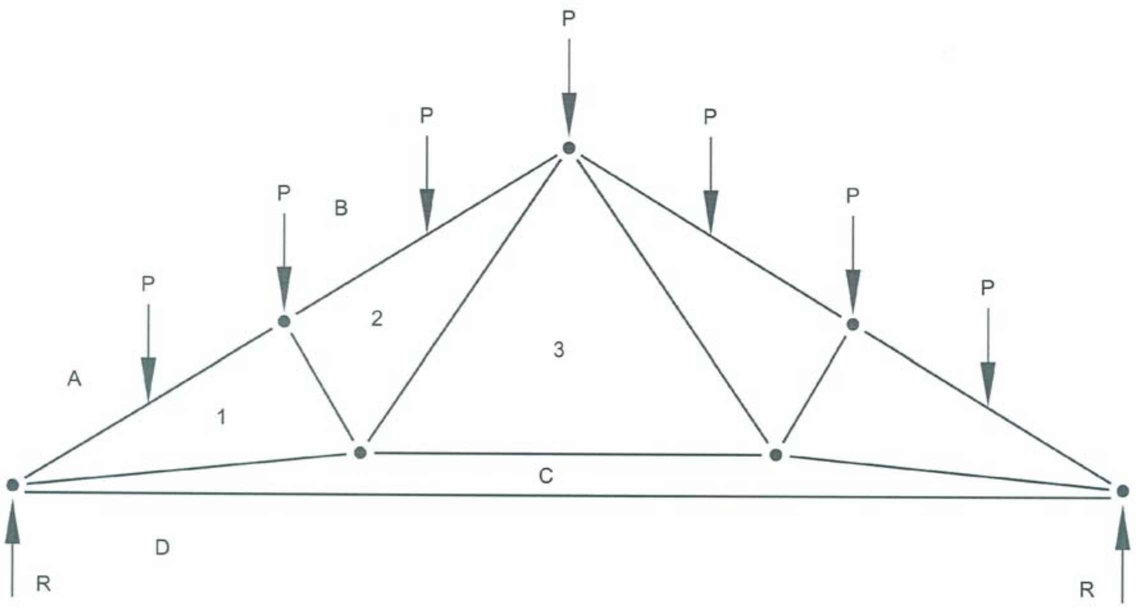

Figure 10. This shows the placement of the unit loads for the load test with the loads located at purlins.

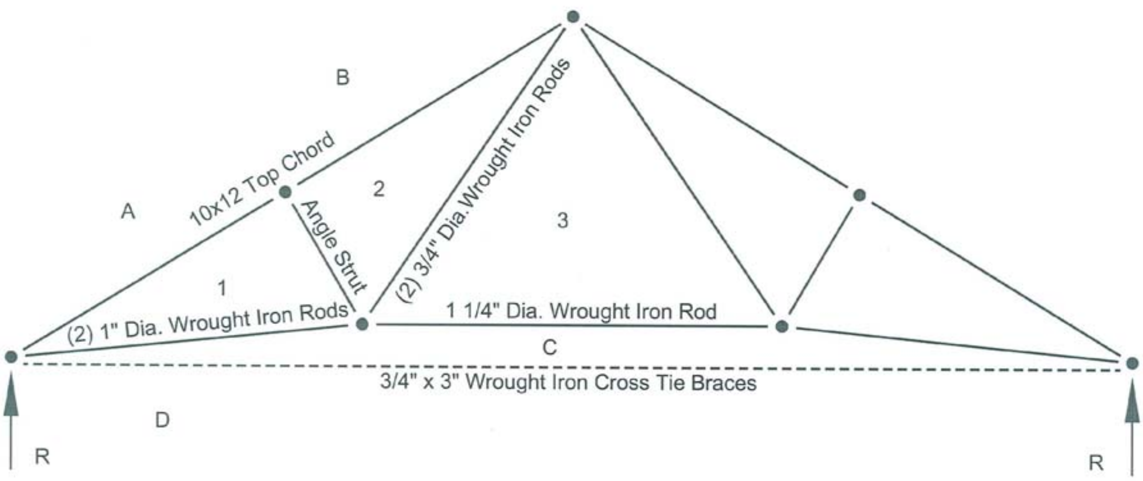

Figure 11. Analysis of the truss with the cross braces included, causes member C3 to revert to compression.

The computer analysis has tremendous advantages over traditional methods of analysis. Stiffness and continuity of various truss members can be accounted for as well as slight variations in truss geometry where the centroids of members do not converge at a single joint.

In simple plane frame analysis of the truss only, the 2.54 cm diameter rods are stressed to a f_T= 248,604 kPa. This is very high when compared to a tabulated elastic limit of 172,369 kPa and ultimate strength in tension of 344,738 kPa. Furthermore, the rods were measured to be actually 2.22 cm in diameter in lieu of 2.54 cm diameter, as shown in the existing drawings. This would increase f_T to 324,550 kPa which is well above the elastic limit for wrought iron.

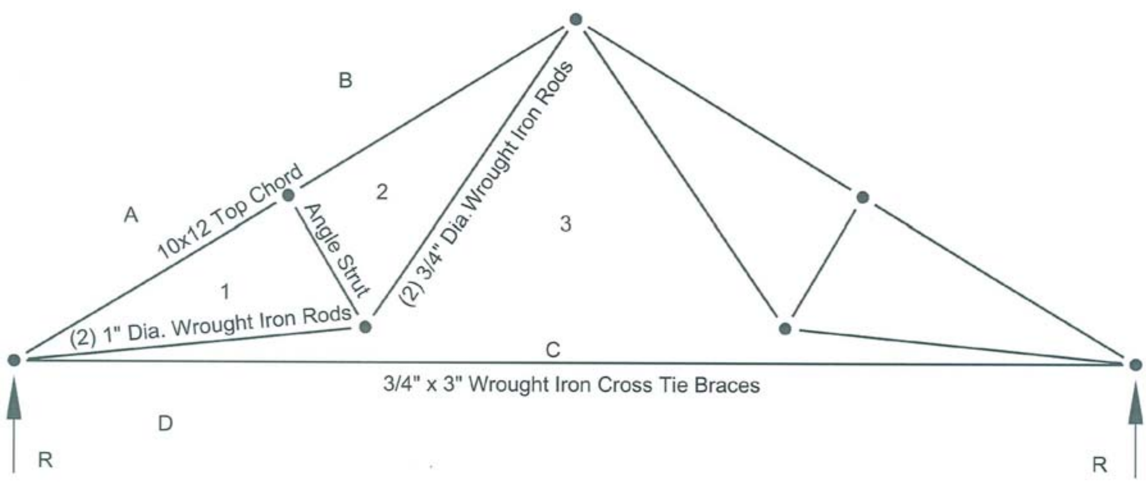

Figure 12. Testing and analysis indicates that the roof system acts as an A-frame with trussed rafters.

By using ultimate published values for clear wood specimens reduced by a factor of 4.0, the top chord of the truss almost checks out with 6% overstress. The static bending modulus of rupture and the maximum crushing strength in compression parallel to grain for clear straight-grained specimens of loblolly pine, divided by a factor of safety of 4.0 will yield values of Fb=22,063 kPa and Fc=12,286 kPa.

The design team has characterized the metal truss elements and has determined the allowable design values for each element through testing. Although the stresses for wrought iron components are high, all but one component are close or within range of the 172,369 kPa to 206,843 kPa elastic limit published in period handbooks (Hudson, 1939).

The primary issue in analyzing the trusses of the Breeding Barn is to determine the path of the horizontal tensile force in the trusses. This was also the goal of load tests. Member forces derived from analyses using the same unit load tests were compared to the results of the load tests.

Load tests consisting of 4448 N and 8896 N (force) unit loads suspended from purlins and panel points generally matched the results of the computer analysis and added credence to the thesis that R. H. Robertson added the cross-brace tie rods to the basic truss configuration sometime during construction, thus reducing horizontal and vertical deflection and reducing the stresses in both the original wrought iron elements and timber top chord.

The addition of 1.91cm thick by 7.62cm high cross-brace tie rods to the building, apparently during construction, provides another path for the tensile force to be resisted. By including the tie rods in the analysis of the building cross section, the center tie bar of the truss becomes a zero force member (Figure 11). Analysis of the roof truss by the computer using the appropriate section properties and material stiffness shows that immediate horizontal deflection under dead load only would have been a total of five centimeters. This deflection of the trusses would have manifested itself in bending of the 25.4cm x 25.4cm post from a point at the horizontal chord of the roof trussed above the side aisle to the 20.32cm x 25.4cm girt (sill) at the heel of the truss, a distance of almost two and a half meters. Certainly, a horizontal movement of two and a half centimeters would have been observed in the post for a distance of only two and a half meters in height. If the annex had already been built or partially framed, it would have provided some restraint, pushing most of the deflection towards the posts along the north side of the building which certainly would have been observed by workmen.

The answer was to provide additional ties to limit the movement which is natural to a truss with a raised bottom chord. In providing these ties R. H. Robertson transformed the building cross section into a tied A-frame with trussed rafters (Figure 12).

Bibliographical References

- Anthony & Associates, Inc.,2006, *Wood Investigation of the Breeding Barn*, Shelburne Farms, Shelburne, Vermont. Shelburne Farms: Unpublished report.
- Beardslee, Commander L. A., 1879, *Experiments on the Strength of Wrought-Iron and of Chain-Cables*, New York: John Wiley and Sons.
- Burr, William H.,1894, *Stresses in Bridge and Roof Trusses*, New York: John Wiley & Sons.
- Cambria Steel, 1903, *A Handbook of Useful Information relating to Structural Steel*, Philadelphia: Cambria Steel.
- Civil Engineering Associates. February 5, 1990, *Structural Evaluation*, Shelburne Farms: Unpublished report.
- DCF Engineering, July 22, 2005, *Shelburne Farms Breeding Barn*, Shelburne Farms: Unpublished report.
- Dumville, J., Donnis, E., O'Donnell, P., Quinn, C., Campbell, M., Wadhams, E., 2000, *National Historic Landmark Nomination: Shelburne Farms,* Washington DC: US Department of the Interior, National Park Service.

- Ferris, Herbert W. (ed.), 1953, *Iron and Steel Beams 1873 to 1952*, New York: American Institute of Steel Construction
- Greene, Charles E., 1910, *Graphical Analysis of Roof Trusses*, New York: John Wiley & Sons
- Hudson, Ralph G., 1939, *The Engineer's Manual*, New York: John Wiley & Sons, Inc.
- Landau, Sarah Bradford and Condit, Carl W., 1996, *Rise of the New York Skyscraper 1865-1913*, New Haven, CT: Yale University Press
- Phoenix Iron Company, 1885, *Useful Information for Architects, Engineers, and Workers in Wrought Iron*, Philadelphia: Phoenix Iron Company
- Schuyler, Montgomery, 1896, *The Works of R. H. Richardson*, In Architectural Record vol. 6, Oct-Dec 1896
- No author. n/d. *Shelburne Farms Information Manual*, Shelburne Farms: Unpublished report.
- Smith · Alvarez · Sienkiewycz, Architects, et al. , 2004, *Shelburne Farms Breeding Barn Complex Conservation Plan*, Shelburne Farms: Unpublished report.
- Tierney, Martin, 1994, *The Breeding Barn Stabilization and Rehabilitation*, Shelburne Farms: Unpublished report
- Tredgold, Thomas, 1860-1, *Practical Essay on the Strength of Cast Iron and other Metals*, London: John Weale
- Tuaranac, John, 1995, *The Empire State Building: The making of a landmark*, New York: Scribner
- Unwin, W. Cawthorne, 1869, *Wrought Iron Bridges and Roofs*, London: E. & F. N. Spon.