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On Acceptable Levels of Safety in the Breeding Barn at Shelburne Farms

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ABSTRACT: The Breeding Barn, a National Landmark, is a monumental example of the estate architecture that appeared in North America near the end of the nineteenth century. The building features an enormous riding ring spanned by composite trusses of wood and iron. Engineers have called attention to overstresses in roof-frame members. A multidisciplinary design team conducted survey work in October 2005, employing a combination of non-destructive and quasi-nondestructive technologies, in order to determine rational design values for structural elements, reduce factors of safety to reasonable levels, and quantify overstresses through modeling and analysis. Results of resistance drilling of deteriorated wooden elements, strength testing of iron samples, and data produced by 3-D laser scanning will be used to complete the analysis

1 HISTORICAL BACKGROUND

Shelburne Farms, originally the agricultural estate of William Seward and Lila Vanderbilt Webb, is a 1400-acre National Historic Landmark District located on the eastern edge of Lake Champlain in Vermont, USA. 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.

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 land for the farm, W. Seward and Lila Webb consulted with celebrated landscape architect Frederick Law Olmsted, Sr. (1822-1903), to develop a landscape design for what would ultimately be a 3800-acre estate. In his c.1887 design, Olmsted proposed a plan dividing the property 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. Today Robertson is best known for his Park Row Building (1896-1899), which at 391 feet from curb to lantern tops was the tallest building in the world when it was constructed (Landau, 1996). The buildings at Shelburne Farms represent Robertson’s most significant estate commission. In general, the buildings combine the Queen Anne and Shingle styles and are characterized by extraordinary workmanship and design. The buildings feature gabled and hipped roofs with multiple towers, dormers, and ventilators, wide overhanging eaves supported on elaborate brackets and rafter-ends, multi-textured wall surfaces covered in shingles, clapboards, and pseudo half-timbering, and foundation stonework of estate-quarried red Monkton quartzite.

Robertson worked at Shelburne Farms for twenty years, and sixteen of his buildings survive, constructed between 1886 and 1905. The buildings are arranged on the estate in clusters or groupings according to function and consistent with Olmsted’s division of the landscape into

Figure 1 : The Breeding Barn at Shelburne Farms is approximately 418 feet long; the lantern at the center of the building springs from purlin timbers approximately 55 feet above the barn floor.

farmland, forest, and parkland. The groupings are anchored by four enormous buildings, centerpieces around which life and work on the model estate revolved. They include Shelburne House (1888, with significant renovations by 1900), a Tudor Revival mansion which served as the Webb's country residence; the Farm Barn (1888-1890), which was the agricultural headquarters of the estate; the Breeding Barn (1891), which served as the center of Dr. Webb's horse-breeding efforts; and the Coach Barn (1902), the transportation center of the estate and one of Robertson's last major efforts.

The Breeding Barn is the principal building of the Southern Acres portion of the Farm, and was built in part to fulfill Seward Webb's dream of breeding a line of strong and elegant draft horses especially suited to Vermont. The building was originally called the Ring Barn, named for the riding ring that occupies the largest interior space. Construction of the barn was begun in 1889 and completed in 1891. At the time, the barn was described in *Frank Leslie's Popular Monthly* (September 1892) as "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."

The main block of the building is approximately 32.6 m wide by 127.4 m long, with a two-story annex centered on the rear facade. The building is largely timber-framed, supported on a redstone foundation, and clad in wooden shingles. Building elevations are dominated by the complex-sloped two acre hipped roof, with multiple dormers and enormous central lantern. The walls are 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 21.9 m wide and 114.3 m long once housed the riding ring. Surrounded by stables, the ring was lit by glazing in the gables of six large dormers (arranged in pairs at the center and at each end of the ring) and the lantern, supported on wooden purlins 16.8 m above the floor. This central space is surrounded by framed aisles on all four sides that once housed stalls at ground level and loft space above. The annex 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.

To support the roof over the riding ring, Robertson designed a composite truss of timber and iron. Each truss has wooden (Southern yellow pine) top chords trussed with wrought iron tension members and struts; a raised bottom chord of wrought iron completes the truss form. At the lower end, principal rafters are captured in cast iron housings that also receive the ends of tension members. Housings are fastened to timber plates at principal post locations. Principal rafters support a deck of purlins and common rafters. Aisle roofs are comprised of a deck of common rafters on timber purlins supported by king- and queen-rod trusses. The firm of Post & McCord, one of the largest iron and steel fabricators in New York City (the firm was the prin cipal steel contractor involved in the construction of the Empire State Building), supplied the iron truss elements.

Figure 2 : The Breeding Barn interior exhibits an extraordinary level of interior finish. The use of iron rather than wood for truss elements except top chords helps to covey the impression of great volume in the riding ring space.

There have been at least two major structural interventions in the riding ring roof frame. As originally designed by Robertson, principal trusses were paired to support the lantern at the center of the ring; a single truss was installed to support inboard dormer framing for major dormer pairs located at the east and west ends of the ring. Sometime subsequent to original construction, but early in the history of the building, a second truss was added at inboard dormer locations to support dormer framing not carried on the end walls. A second intervention 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 cast iron 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.

2 CONDITIONS ASSESSMENT

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 and called attention to potential overstresses in many of the principal roof frame elements (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 historical integrity. In 1995, stabilization measures were implemented that ultimately included partial replacement of foundation stonework with foundations of poured 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. The A&E team responsible for assessment of the Breeding Barn identified several areas of deterioration unaddressed in the earlier stabilization project, and once again called attention to several potential structural deficiencies in roof frame members. Specifically, the assessment recommended repair / replacement of decayed posts and valley rafters, and design of structural reinforcement of principal rafters, wrought iron bottom chords in the principal trusses, valley rafters, and trussed purlins (Smith, 2004).

Because of the importance 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.

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. Team members accessed roof frame elements in the riding ring using 20 m lifts. This initial survey of the building was completed in three days.

The survey indicated that more detailed examination 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 the capacity of unbraced rafters in each of the major dormers and with the condition of several of the valley rafters. Valley rafters exhibited varying levels of biodeterioration, and in some cases decay had resulted in dislodging of the timbers from their original positions at rafter apexes. A metallurgist was brought in to characterize the wrought iron used in struts and tension elements. Samples were obtained from fabric that had been previously demolished. The samples are large enough for conducting tension tests (ASTM A 370-97a) of the iron, scheduled for May 2006; small portions of each sample were retained for metallographic characterization. Analysis indicated a low-carbon material; the closest SAE-AISI 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 (sometime in the 20th century) on either side of each timber prevented direct examination in most cases. Of the twelve timbers examined, four were found to have substantial section loss due to decay. Results of resistance drilling tests were expressed graphically and in tabular form, indicating the extent of section loss at each of the drill sites. By pinpointing areas of loss, 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.

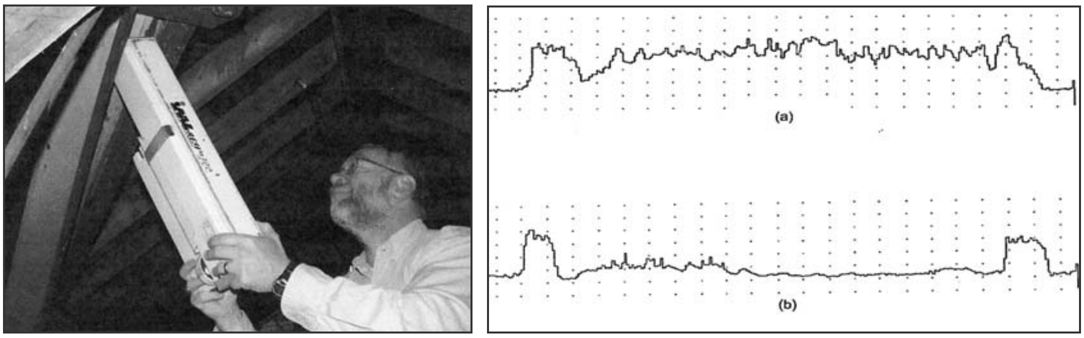

Figure 3: Resistance drilling was done to characterize the extent of deterioration in decayed frame members, left. At right, the top graph depicts sound timber (a), while the graph at bottom depicts timber with internal deterioration (Anthony 2006).

3 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 overstressing 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 determination of an "overall safe live load capacity of the structure" reveals nothing about the various components. All of the components, including trusses, rafters, purlins, sheathing, common rafters, valley and hip beams, should be tabulated with the basis for their capacity individually noted. There should be a discussion of the modifications to the basic values for timber design, such as Load Duration Factor and Size Factor. Load Duration Factor is an interesting subject which is central to timber design but largely ignored by structural engineers reviewing historic timber structures. Since wood has the ability to sustain substantially greater loads for short periods of time, allowable design values can be increased 15% for snow load, 60% for wind, and 100% for impact. This has implications for historic structures because the application of full design load of two months for snow load, and ten minutes for wind, acting on the structure is cumulative. The question becomes "what is the cumulative amount of time that this structure has been stressed to its full allowable design value for the various loading conditions, over its history?" It may be a very difficult question to answer without accurate weather data.

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 (scheduled for June 2006), will establish the original configuration of the building "as built". As soon as sufficient verification of sizes and dimensions allows, a structural analysis can proceed. A conditional analysis would lead to suggested repair strategies. Once agreement with the owner and approving agencies and grantor is received, then specific repairs can be designed and detailed.

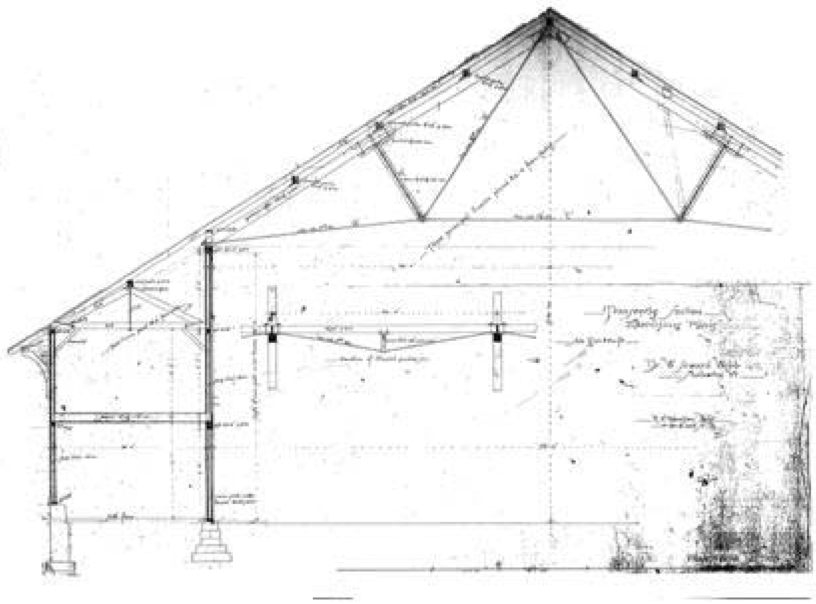

Figure 4 : A portion of the transverse section drawn by Robertson and illustrating the principal truss (Collection, Shelburne Farms Archive).

The structural elements of primary interest in the Breeding Barn are the principal trusses, purlins and valley rafters. The principal trusses known as cambered fan trusses, or trusses with raised bottom chords, are composite in configuration with timber top chords and wrought iron bottom chords. Cast iron fittings and steel pins and steel or wrought iron struts complete the assembly. The purlins, hip rafters, and dormer beams are trussed with wrought iron rods with cast iron posts in the queenpost fashion.

The designers will have to conduct a close review of 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 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 1436.1 Pa snow load and 718.1 Pa 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 25.4 cm x 30.5 cm top chord is a result of the original designer analyzing the truss using graphical means (force diagram and string polygon) first developed in the 1840's by Col. Stephen H. Long. 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, each side of the truss has reactions from purlins applied half way between panel points. Even today, with new structures, computer analyses will provide very large bending forces that can not be determined from a graphical analysis.

The 2.5-cm diameter rods are stressed to a f_T= 248669.0 KPa. This is very high when compared to a tabulated elastic limit of 172413.8 KPa and ultimate strength in tension of 344827.6 KPa. Furthermore, the rods were measured to be actually 2.2-cm in diameter in lieu of 2.5-cm diameter, as shown in the existing drawings. This would increase f_T to 324,634.5 KPa, which is well above the elastic limit for wrought iron.

There is a system of tie bar x-bracing in the horizontal plane below the bottom of the trusses. An interesting thing happens when the two 1.9-cm by 7.6-cm tie bars are asked to carry the load. The middle bottom chord truss tie consisting of a 3.8-cm diameter rod goes into compression. Since it is so slender, this member will buckle rather than transmit compression. For that reason, the program was re-run with the 3.8-cm tie rod deleted. With the tie bars included, the center rod deleted, the stresses are lower in the remaining wrought iron rods.

By using ultimate published values for clear wood specimens reduced by a factor of 4.0, the top chord of the truss actually checks out (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=22,069.0 KPa and Fc=12,289.7 KPa.

The design team is collecting metallurgical information to establish the nature of the metal elements of the composite components. The design team will have to differentiate between cast-iron, wrought iron and rolled or forged steel elements which are present, and determine through testing and research the allowable design values for each. Although the stresses for wrought iron components are high, all but one component are close or within range of the 172,413.8 KPa to 206,896.6 KPa elastic limit published in period handbooks (Hudson, 1939).

4 CONCLUSIONS

Completion of project design is scheduled for February 2007. A key issue in the structural analysis is to determine the true stresses in the components of the principal trusses and solve the apparent weakness in the truss at the dormer where the top chord is unbraced by purlins. Discarding the effects of deterioration for a moment, and ignoring connection design, we can say that as long as the stresses in the timber and wrought iron materials are within the elastic limit when reasonable design loads are applied, the Breeding Barn at Shelburne Farms is not in danger of collapsing.

The overriding questions in the evaluation of this building are as follows:

- What applied snow loads are reasonable to use in the Shelburne Farms area?
- What allowable design values should be used for the timber and wrought iron?
- How has deterioration affected the capacity of the original design shown in R.H. Robertson's drawings?
- How can observation, measurement, testing and analysis be used to expose defects and deterioration critical to the safety of the structure?
- What solutions are available to ensure the continued service of the building with a level of intervention?

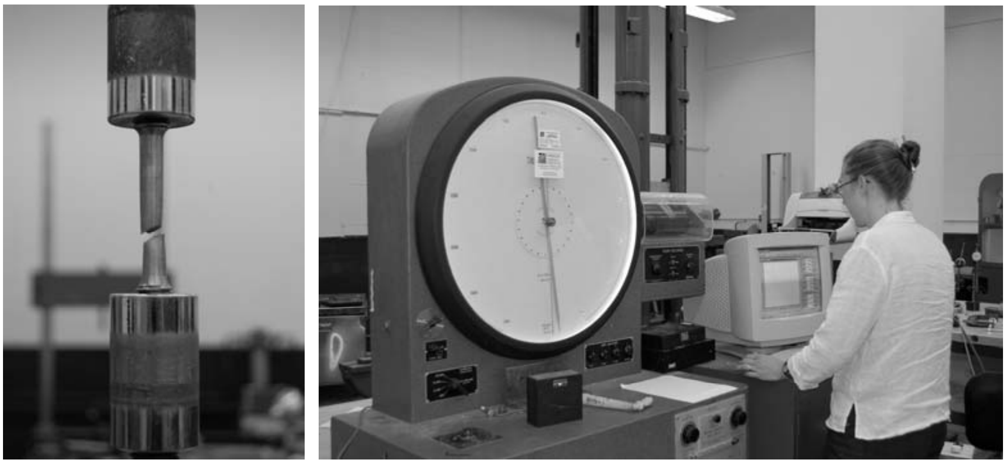

Figure 5 : Tension tests (ASTM A 370-97a) were conducted on iron samples, yielding average peak stress values of approximately 319,820.7 KPa.

3-D laser scanning of the building is scheduled for June 2006. Scanning will be conducted as a partnership between Shelburne Farms and Texas Tech University. Data recovered by scanning will be used to create a point-cloud model of the barn in its current condition, and will allow the design team to quantify deflections in structural elements. Data collected in this manner will be archived as part of project documentation, and will provide a benchmark against which future structural movements can be measured. Scans will provide detailed information concerning as-built dimensions of individual elements, and will also be used to generate a set of HABS-level drawings of the building to be used for designing repairs. Upon conclusion of the project, drawings and accompanying large-format photography will be donated to the Library of Congress.

Depending on the results of a thorough analysis, the design team has several tools at its disposal for quantifying actual stresses in frame members and minimizing interventions while achieving safety goals. They include:

- Site-specific determination of snow- and wind-loads based on historical weather data and other observations and measurements;
- Load-testing of the frame;
- Programmatic management of risks, including closure of the building during snow season, and alarms operated by instrumentation installed on structural elements and alerting stewards to weather-related overstresses.

The Shelburne Farms Breeding Barn, despite pockets of deterioration and several design flaws, has not experienced a failure or partial failure in any of the elements which constitute the vast timber framed and wrought iron structure. With an ongoing program of observation, measurement, testing, and analysis, the building will be recorded in detail and a repair strategy formulated which will ensure the retention of the maximum amount of historic fabric through the construction effort and provide an acceptable level of safety in the restored building.

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