Design Principles for Tower and Steeple Restoration

By Robert Fulmer

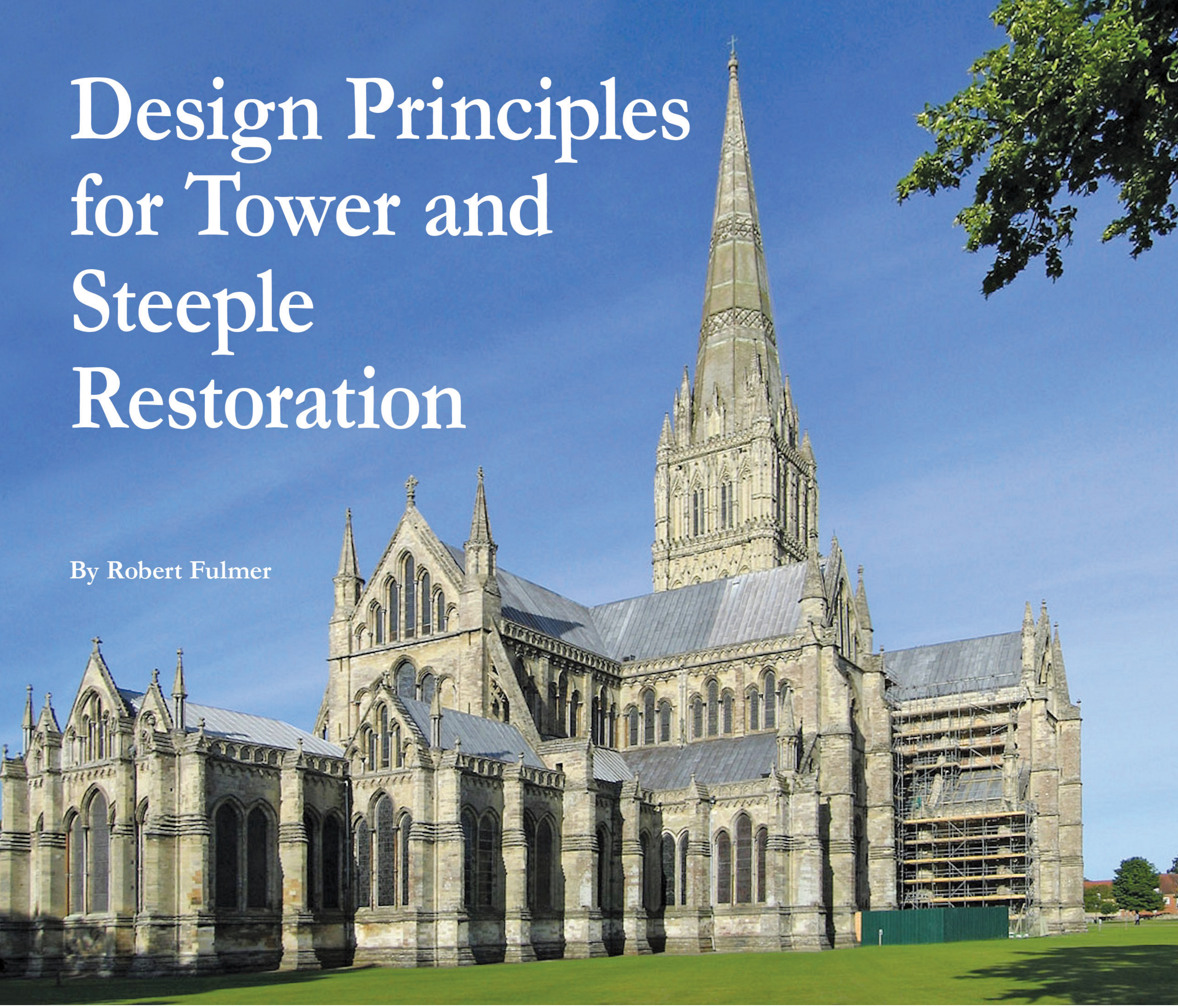

Figure 1 – Salisbury Cathedral, England, during a lead roof replacement.

INTRODUCTION

The contemporary tectonics of analyzing and designing the restoration or construction of architectural towers and steeples can both inspire and confound contemporary design professionals. The effective design of steeples, bell towers, spires, and clock towers requires a multidisciplinary synthesis of technical, aesthetic, and engineering requirements that are unique to tower architecture. While the design requirements for tower and steeple restoration can be as diverse as the structures themselves, there is a commonality and standard principles that need to be addressed within the design process for each project.

BRIEF HISTORY AND NOMENCLATURE

Throughout history, towers and steeples have been an integral part of our architectural landscape. There are numerous documented third- and fourth-century church structures with towers located principally in what is now known as the Middle East, such as Etchmiadzin Cathedral, built in 301 AD as the first cathedral in the (then) Kingdom of Armenia. The inclusion of towers on ancient religious structures was actually predated by and adapted from their original purpose as military towers as early as 3500 BC.

Clock towers were not an architectural component of Christian churches until approximately 600 AD, when their use was also adapted from military watchtowers. See *Figure 1*.

At that time, towers were fairly modest and were constructed separately from the principal church building.

Some contemporary discussions use the architectural terminology associated with towers and steeples interchangeably. For the purpose of clarification, some basic tower terminology is defined below.

Bell Tower: A tower that contains one or more bells or is designed to hold bells, even if it currently has none. A bell tower may be integrated into a church building or serve as a freestanding structure.

Campanile: An early Italian architectural term for a (usually) freestanding bell tower, derived from "campa" (meaning bell). The earliest campaniles, dating from the 6th to the 10th centuries, were plain round towers with minimal ornamentation near the top. Square campaniles began to appear at the end of the 10th century. In the 19th century, that design inspired the tower at Westminster Cathedral (by J.F. Bentley, 1897). The revival of the campanile in the 19th and 20th centuries included installations at factories, country houses, blocks of buildings, markets, and academic structures as a bell or a clock tower. (See *Figure 2*.)

Belfry: An integrated tower component designed to house bells. It is not a freestanding structure.

Steeple: A tall ornamental structure, usually surmounting a tower and ending in a spire. Common on Christian churches and cathedrals, the term generally connotes a religious structure.

Spire: A tapering conical or pyramidal structure commonly found on top of a church tower or skyscraper. The spire originated in the 12th century as a simple, four-sided pyramidal roof, capping a church tower. Nineteenth-century architects used spires prolifically, particularly during the Gothic Revival period of the mid-1800s.

Pinnacle: An architectural, vertical ornament of pyramidal or conical shape, crowning a buttress, spire, or other architectural member. A pinnacle is distinguished from a finial by its greater size and complexity, and from a tower or spire by its smaller size and subordinate architectural role. A tower may be decorated with pinnacles, each one capped by a finial.

Cupola: A secondary dome-like structure on top of a building, utilized to admit light, ventilation, or as ornamentation.

This basic glossary of architectural tower terminology will assist in clarifying the design process in subsequent sections. For the purpose of this discussion, the term "tower" shall be used generically to describe complete bell tower, clock tower, and steeple assemblies.

TOWER SCHEMATIC DESIGN PHASE

Just as in the architectural design of each building project, the schematic design phase is the first step in developing the contemporary tower design process. It is a logical sequence that differs in some respects from other building projects.

Whether the purpose for the tower restoration is a result of a discovery of water infiltration, structural damage, a planned change in use, or the expiration of the service lives of structural or envelope materials, this phase begins with preliminary client discussions to determine the proposed purpose, goals, and budget for the restoration.

The data-gathering process in this phase is essential and begins with the building conditions survey. The information obtained during the survey is then utilized to form the initial basis of design (BOD) document, early in the design development phase.

Tower Access

Once the scope and focus of the inspection have been determined, access to all levels of the tower must be planned.

Whether in the schematic design phase or construction phase, the logistics of tower access can be challenging. Unlike the construction phase, the requirements for OSHA compliance are less onerous for design inspections. However, personal safety planning is obviously essential. The need to access the full height of a tower for inspection and actual construction significantly impacts both the cost and schedule of all tower projects. The trade euphemism of "everything costs more and takes longer when working at height" is a basic design principle to be kept in mind (*Figure 3*).

Figure 2 – Campanile, Cathedral of Pordenone, Italy.

Figure 3 – Baker Tower industrial rope access inspection.

Figure 4 – Rope access enables forensic analysis and materials sampling.

While interior access is normally available to the belfry or clock level on most towers, accessing the interior space above the belfry level to evaluate cupola, spire, weathervane mast, etc., can be problematic. In certain circumstances, mechanical lifts or cranes can be utilized to access the tower exterior. Occasionally, however, "mechanical access" is not adequate or feasible.

For example, recently Dartmouth College requested a forensic building condition survey and structural evaluation of their iconic Baker Library tower as a precursor to restoration. The square-planned brick tower base is integral to the attached building on three elevations, with one tower elevation extending to grade and housing the main building entrance.

The inspection requirements of the 200-ft.-tall tower precluded the use of a crane for access due to the heavy volume of pedestrian traffic at the tower base entrance, as well as landscaping considerations. While inspection of the full tower height is important, to determine existing conditions, document load concerns, inspect weathervane substructure, etc., full tower access was essential in this case.

With no mechanical access option and the prohibitive cost of staging erection for inspection, the author used an "industrial rope access" option to access the tower (*Figure 4*).

Although the use of ropes to access structures has been employed for centuries, the older evolving techniques were encumbered by limited lateral mobility and safety issues.

The Industrial Rope Access Trade Association (IRATA) was formed in the United Kingdom in 1989 to address maintenance access problems within the offshore oil and gas industry. Today, the industrial rope access techniques developed by IRATA have been adapted for use in high-rise building surveys, maintenance, and façade inspections, as well as fulfilling wind turbine and offshore oil platform inspection and maintenance requirements. Rope access allows the operator to descend, ascend, and laterally traverse the rope system with the structure at arm's length, making it ideal for tower inspections.

The author's firm successfully completed the Dartmouth tower inspection, utilizing rope access techniques as an efficient and cost-effective alternative to mechanical or scaffold access.

If your firm does not have certified rope access capabilities, it is possible to train designated employees at one of several training centers in the U.S. The Society of Professional Rope Access Technicians (SPRAT) was formed in Pennsylvania in the mid-1990s to provide U.S.-based education and certification. If training is not an option, there are a number of domestic companies that specialize in industrial rope access inspections that can be contracted for individual projects. As some firms are reluctant to perform forensic inspections due to potential liabilities, it is important to clarify your forensic needs early in the discussion phase.

Building Conditions Survey

Forensic inspections represent the most critical function in the tower design process. Prior to the actual inspections, the designer should ideally have obtained and reviewed any existing construction documents. If construction drawings do exist, they often were produced during an earlier era when a construction document set contained less information than contemporary documents. In addition (as is most often the case with tower projects), as-built drawings are rarely available. Therefore, physical inspections of the complete tower structure are essential. The data obtained from a thorough inspection process will define the basis of design and scope of work for the project. In addition, structural evaluations during the inspections provide essential data to determine existing load conditions and define structural upgrade requirements for code compliance.

The building conditions survey process should be forensic in nature. Not only is it essential to examine all structural systems and components, but the forensic inspection also creates an opportunity to collect material samples for hazardous-materials testing. In the case of wood or timber frame structures, it is also an opportunity to collect samples from wood structural components for species identification, moisture content, and other conditions of use. These data are then utilized in timber stress grading and engineering design value calculations as described in ASTM D245 and SEI/ASCE 11-99.

The forensic tower inspection then becomes a principal design tool and should include evaluation of both the interior and exterior of each tower section, from below-grade (if applicable) to the top of the tower.

At a minimum, the building conditions survey (*Figure 5*) should include the following elements:

- Determine the applicable code bodies to be addressed as a result of initial observations and concerns.
- Diagram all existing structural components in situ; include sizes, locations, configurations, truss structure, and timber species, quality, and grade (if applicable). Document any conditions of structural component stress, deterioration, or failure.

- Note all areas of water infiltration, along with any structural distress or deterioration within those areas.
- Record any previous repairs or modifications to the structure.
- Note any areas of "change of use" or potential increase of future loads on the structure.
- Document the existing condition of all tower envelope systems and collect material samples, both inert (i.e., timber frame component samples) and potentially hazardous materials that may require abatement.
- Note immediate or potential life safety concerns and possible remediation procedures to address those concerns.

Figure 5 – Baker Tower building conditions survey.

Figure 6 – Point Cloud rendering from a laser scan.

"Scope creep" can occur on any construction project, but on tower projects, the impact to both the construction schedule and the project budget can be substantial and is multiplied by the significant logistics of working at height. Most often, project change orders are the result of conditions that weren't exposed or observed during the forensic inspection process.

Drones

Within the past 15 years, the quality and efficiency of camera-mounted drones (quad-copters or small unmanned aircraft vehicles, also known as UAVs) have developed significantly. Drones are a common inspection tool utilized by various industries, including the construction industry.

Nine U.S. cities require periodic façade inspections, and drones are an asset in that application. ASTM's task group on façade inspections is working on a "Guide for Visual Inspection of Building Façades Using Drones" (WK52572).

Within the context of tower inspections and design, however, drone use should be qualified and specific. Visual observations alone cannot provide enough data to replace a "hands-on" structural or forensic tower inspection.

As an example, while conducting a recent tower inspection, structural damage was discovered beneath flat-seam copper cornice and cupola panels by walking on them (while secured by rope access equipment). In addition, original construction documents had indicated that the ornate balustrades and finials at the clock, bell, and ringing chamber levels were fabricated in cedar. Our inspection revealed that those components were spun in 24-oz. copper and painted.

Both anecdotes are brief examples of observations that cannot be obtained from photos alone. However, during that inspection, a drone was utilized to inspect the inaccessible weathervane shaft connection to the weathervane mast. Drone use should be considered a tool in the inspection process and not the sole means of documenting existing conditions.

Currently, if you are going to fly a drone for commercial use within U.S. airspace, you must register the drone and obtain an "airworthiness certificate" from the Federal Aviation Administration (FAA). In order to fly your drone commercially under the FAA's Small UAS Rule (14 CFR Part 107), you must also obtain a Remote Pilot Certificate from the FAA by successfully completing the Part 107 exam. This certificate demonstrates that you understand all federal, state, and local regulations; FAA operating requirements; and procedures for safely flying drones. Compliance with the varied commercial FAA regulations for drone use is an owner/operator responsibility that requires frequent updates to ensure legal operation.

Basis of Design

The American Institute of Architects (AIA) defines the BOD as a document that records how the building systems meet the owner's project requirements (OPR) and why the systems were selected. The objective of the BOD is to provide information to the design team during each phase of the project and document the thought processes and approach as the design evolves.

Once completed, the inspection phase should provide sufficient data to produce the initial BOD. The preliminary information contained in this document can be used throughout the design development (DD) and construction document (CD) phases to develop the project scope, including the identification of governing code bodies, a listing of all architectural divisions to be included in the CDs, and further refinements of the project construction budget.

These data are then shared with the project design staff and owner(s) during the DD phase. The BOD document should be used as a dynamic organizational tool that is equally beneficial to the owner and the design team and is updated at regular milestones, such as the 30%, 60%, 90%, and 100% phases of construction document submissions. Misunderstanding the design intent of a tower project is one of the most common project-related challenges. The BOD should reflect a current and clear presentation of the OPR and design intent as the project evolves and is a key communication component throughout the design process.

Laser Scanning and Architectural Modeling

Existing conditions or as-built modeling has always been a principal design requirement in tower restoration. The need to accurately portray or document the exterior of a tower is essential in the creation of useful project drawings. Prior to 20 years ago, without original drawings, the documentation process was arduous and, consequently, expensive. The designer was required to access the tower in the safest manner possible and measure each exterior architectural component as accurately as possible. The accuracy of the measurements obtained was key to the tower load analysis modeling, as well as the replication of architectural details.

In the late 1990s, laser-scanning technology (*Figure 6*) began to develop, creating the possibility of an application for measurement and documentation of existing buildings. As laser technology improved, it was integrated with existing architectural modeling software. At this time, there are a number of companies that specialize in laser measurement and digital recording of existing buildings. Currently, the accuracy of laser measurement technology is cur-reup to 2 mm over a 120-m span, which exceeds most required design tolerances. Drawings and models can be quickly and accurately created in drafting software in 2-D/3-D, including 3-D BIM modeling. With full 3-D modeling, material takeoffs and envelope detailing can be generated, along with an array of component schedules. Customizable databases can be generated for area calculations, condition assessments, hazardous material reports, etc. The databases can then be exported from the building information modeling (BIM) software to be incorporated into any other existing management databases.

The advantages of utilizing the currently available technologies in tower documentation and design can be significant. However, the financial and detail requirements of individual projects vary, and a cost-benefit analysis should be performed to confirm the feasibility of modeling options required for each individual project.

DESIGN DEVELOPMENT PHASE

The AIA describes the DD phase as "the predominant production phase, expanding upon the representative work of the schematic design (SD) phase and prior to the finalization of construction documents."

Tower projects require a DD phase that is expanded beyond what is normally incorporated in traditional construction projects. Scope requirements for specifications and divisions not normally utilized (such as scaffolding and access engineering requirements), niche trade divisions (e.g., bell and clock restoration), as well as quality assurance measures requiring in-situ testing are routinely included in the DD phase of tower projects.

Due to logistical complexities of working at height, systems testing in situ and warranty obligations must be verified and "signed off" prior to staging removal. Any systems failures or water infiltration issues occurring after staging removal and project close-out can be difficult and expensive to remediate. Subsequently, these post-construction issues inevitably invoke the "whose responsibility is it?" dialogue. Consequently, these quality assurance procedures need to be carefully spelled out in the DD phase. Additionally, the design process should incorporate systems that, while currently performing, may be more cost-effectively addressed while access is in place. This comprehensive design approach reduces misunderstandings from owners who were not clear on the complete project scope.

For example, while in the DD phase of an academic tower restoration, the client was advised that the tower's lightning protection system was not UL-compliant, and the tower's exterior lighting was dated. Initially, the client declined the additional upgrades, citing budget concerns, but was eventually convinced to incorporate the work. Positive comments on the aesthetic improvements of the tower at night were received; but more importantly, the tower was struck by lightning a year later, sustaining minimal damage. It is important to effectively convey to the client during the design process the cost-effectiveness of addressing both compliance issues, as well as work that may require remediation within the near future.

ASSESSMENT STANDARDS AND RELEVANT CODE BODIES

Tower Engineering

Although the documented history of "tower" structural engineering dates back to the 27th century BC, when Imhotep first designed a step pyramid for Pharaoh Djoser, throughout most of ancient and medieval architectural history, the "engineering" and construction of towers and religious structures was performed by master tradesmen. Since no structural theory for towers existed, construction technique was based on previous construction experience, utilizing masonry (including concrete technology developed by the ancient Romans), wood timbers, and composite systems of both to form the structural support systems for towers.

Structural engineering theory was further advanced in the 1850s when mild steel structural support systems were first made possible by English inventor Sir Henry Bessemer, eventually replacing both wrought and cast iron as the structural material of choice. Although structural steel was becoming increasingly popular in Europe, in North America, many of our 19th- and early 20th-century church structures were being constructed with timber-framed structural support systems. However, engineering of the timber-framed trusses was not common until the mid to late 1800s. Prior to the 1900s, it was uncommon for designers to address considerations such as load duration, materials moisture content, and other conditions that are commonplace today.

Standardized timber stress-grading techniques and design values were not developed in the U.S. until the mid-1930s, at the time when framing and structural support components of steel (or composite steel and timber frame) became increasingly popularized. In spite of the engineering inconsistencies of that period, many of the tower structures created then still function today.

Although structural engineering didn't take shape as a profession until the Industrial Revolution, the trade has become one of the most significant components in tower design. Structural analysis (developed by Galileo in 1638), load analysis, and current code compliance are the engineering components that drive contemporary tower project scope and design.

When evaluated using contemporary engineering analyses and models, many existing towers fail to meet current structural standards.

While utilizing the observations, measurements, and data obtained during the forensic building conditions survey, relevant code bodies can be identified and referenced to help frame the engineering analysis and develop the structural remediation scope.

But what are the criteria that can trigger the initial structural assessment?

Structural assessments and upgrades may not be required unless a change to the structure alters loads and stresses or unless structural deterioration, damage, or distress is observed. However, building alterations within the recent past that were perceived as upgrades or efficiencies at the time could now trigger a structural evaluation and subsequent remediation requirements. Several of the most common examples of tower "alterations" addressed by the current I-codes are examined below.

IEBC 2015, CHAPTER 4 / IBC 2015; ALTERATIONS AND REPAIRS

a. **Energy upgrades:** In an effort to control energy costs, many churches have decreased heating (or cooling) days by adding insulation in the attic or roof system. Such an energy upgrade can increase dead loads and/or live loads by increasing snow accumulation on an existing roof and steeple support system.
b. **Reinforcements or repairs of the tower/steeple structure:** The support or "stiffening" of the structural components can alter existing load paths or create asymmetrical loading conditions. This condition applies to partial sheathing repairs as well (i.e., replacing deteriorated 1-in. horizontal sheathing with plywood). Unless full replacement of sheathing or structural components is planned, repairs should be made "in kind."
c. **Envelope material alterations:** Replacement of the roof or tower cladding with systems that can increase live loads (i.e., replacement of a copper roof system with cedar or asphalt shingles may increase the dead load but can also alter the live load by replacing the "slippery" copper system with materials that promote snow and ice retention).

Structural Distress

Some examples of damage, deterioration, or distress to structural components (documented by visual observation) that could trigger code-specified structural observation(s) and/or special inspections per IBC 2015, Sections 1704 and 1705, are:

a. Obvious deterioration, decay, or signs of water infiltration within the interior framing or exterior steeple components
b. Failed, split, or otherwise compromised structural components observable from the interior or exterior of the tower
c. The appearance of asymmetrical settling or positioning of the structure
d. Areas of excessive roof deflection, including interior areas of load transfer below the tower assembly, such as ceilings, interior walls, etc.
e. Significant structural impact on adjacent roof truss systems from steeple loading
f. Unit deterioration and suspect mortar conditions evident from signs of "bowing" or other deterioration in cavity wall construction

While structural evaluations are stipulated in the model building codes, full code upgrades are not always required for existing buildings. If a structure has a history of performance but is currently noncompliant, most model codes contain prescriptive options for repair compliance. The purpose of this subjective option is to allow consideration for basic safety.

Both the IBC and IEBC contain a "Historic Buildings" chapter, allowing potential code exceptions by the "local authority having jurisdiction" (i.e., building inspector, code enforcement officer, etc.).

While researching code bodies that are applicable to a specific project, it is helpful to begin with a review of the regional governing building codes, as they may have adopted specific editions of national building codes. Which code bodies and versions (years) are applicable depend on the location of the project. For example, when referencing IBC Chapter 34, "Existing Structures," the state of Massachusetts directs the user to the IEBC 2009.

A review of the following relevant national code bodies should be performed to ensure that the engineering analysis includes all requisite code and design considerations:

- **IBC:** Provides compliance provisions for alteration, repair, addition, and change of occupancy of existing structures. Strengthening or replacing structural elements and systems is generally required when those components are "substantially" damaged. This is further defined as "a 20% reduction of capacity, with remaining capacity less than 75% of

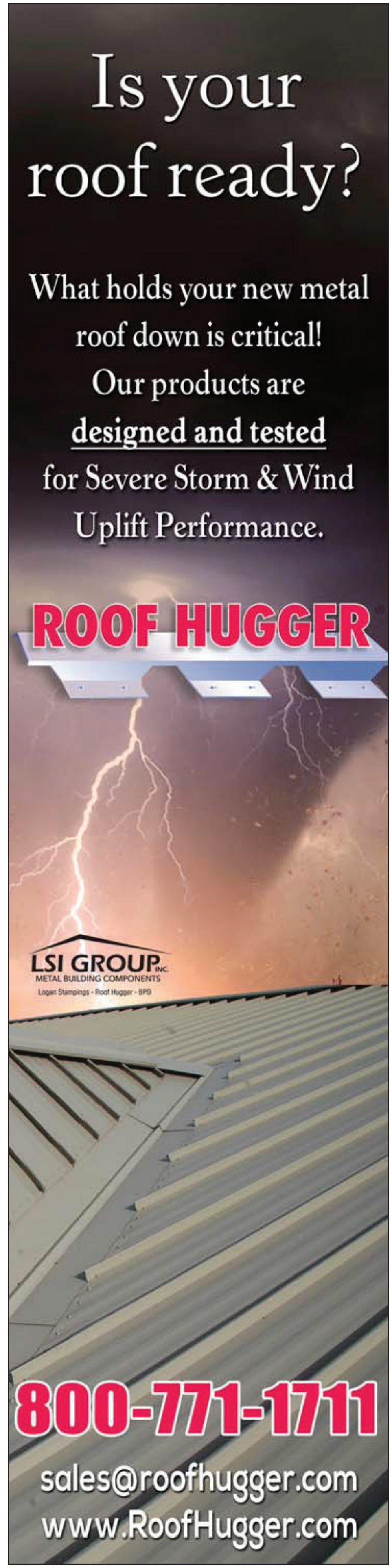

Figure 7 – Clock tower restoration, Groton School, Massachusetts.

that required for new construction. Components that are damaged less than "substantially" are permitted to be repaired or restored to their predamage condition. The IBC then prescribes "strengthening" or replacing the affected structural components if additions, alterations, and/or repairs cause more than a 5% increase in design gravity load or more than a 10% increase in the demand-capacity ratio for lateral-load combinations.

- **IEBC:** The International Existing Building Code provides three separate methods of code compliance in reference to the alteration, repair, change of occupancy, or addition to existing buildings. These include the "Prescriptive Compliance Method," "Work Area Compliance Method," and "Performance Compliance Method." It is important to note that only one method may be used for a single permit. Structural requirements are generally consistent with the IBC specifications noted previously.
- **ASCE:** Wind load analysis. Types of wind forces on towers that require calculation:
    a. Lateral load: A "pulling and pushing" (horizontal) wind pressure
    b. Uplift load: Pressures from wind flow that cause "lifting" effects
    c. Wind overturning moment
- **ASCE 7:** Seismic load calculation
- **ANSI/AISC 360:** *Specification for Structural Steel Buildings* (and other structures)
- **ANSI/AISC 341:** *Seismic Provisions for Steel Buildings*
- **ASTM D245:** *Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber*. Strength-ratio analyses to estimate mechanical properties of timbers
- **TFEC 2:** *Code of Standard Practice for Timber Frame Structures*. Utilize for timber frame repairs, joinery, in-situ augmentation, etc.
- **SEI/ASCE 11:** *Guideline for Structural Condition Assessment of Existing Buildings*

Analysis and application of all relevant building codes and standards are critical steps in the engineering process at the appropriate level for the various phases of the project. The information obtained will define the design criteria and project scope in order to produce a compliant and well-constructed tower structure.

Engineering Modeling

After recording and interpreting the structural data obtained during the forensic inspections and completing a code review and analysis, the structural design and modeling can begin. While a "hand analysis" of the data is certainly feasible for most tower projects, the design process is significantly aided and expedited by the use of 3-D structural analysis and design software.

Using a CAD-like drawing/editing environment, this software inputs dynamic synchronization between spreadsheets and graphics to produce models rapidly, while analyzing current code, gravity, and lateral load calculations (among other features). One of the principal benefits of the software is that it allows the designer to analyze a system of individual components instead of looking at each member individually. It is important to remember, however, that the model produced is only as good as the input (a nod to meticulous inspections), so precise input concerning support conditions, restraints, etc. is critical for an accurate model.

DESIGN CONSIDERATIONS, CASE STUDY #1

Groton School is a private secondary school located just outside of Boston, Massachusetts. The school retained the author's firm to design and manage the restoration of the campus clock tower *(Figure 7)*.

The tower is positioned in the center of an academic classroom building. The structure was designed in 1898 by noted Boston architects Peabody and Stearns in the Classical Revival style and built in 1899. The tower stands approximately 150 feet above grade and is supported by a timber-framed structural support system, integral to a timber-framed roof truss system.

Composite Materials

During the SD phase, the Groton School Board of Trustees expressed an interest in restoring the tower to be "low maintenance" and inquired about composite materials. The initial request was to utilize polyvinyl chloride (PVC) for all exterior details, including the ornate millwork and railing system. The original 1899 cladding and millwork were made of first-growth eastern white pine. When we began our materials research, we found very little nonpropriety information available. When PVC manufacturers were contacted, we found conflicting information and vague answers regarding replications of the millwork and "turning" of details such as the urn finials and balustrades. At this point, our due diligence led us to conduct our own research and testing. That process provided the following data:

1. PVC is an isotropic material; its volumetric thermodynamics are a response to temperature, and movement is omnidirectional (under equal pressures). Wood is an anisotropic material. Its thermodynamic movement varies between parallel and perpendicular to its grain. The expansion coefficient of isotropic materials is three times its linear coefficient.
2. PVC products have low thermal distortion (54–80°C or 129.2–176°F) and "Vicat" softening temperatures (92°C or 197.6°F). In addition, PVC can be deformed by a continuous application of an exterior force (temperature, gravity loads, etc.)
3. When field cut or routed ("turned"), PVC becomes absorptive and requires painting. Due to its low heat distortion and softening temperatures, PVC can only be painted with light-to-medium colors with a light-reflective value (LRV) greater than 55. Coatings with an LRV below 55 will void most PVC manufacturers' warranties.
4. As the clock level of the tower is a "square," the siding and millwork are mitered at each corner. Manufacturers' recommendations to accommodate material movement at the corners varied between a ½- to ¾-in. gap at the corners (subsequently filled with sealant), depending on air temperature during installation.

Based on the data collected, it was concluded that PVC is a highly dynamic material. That characteristic is exacerbated with an increase in volume (such as millwork assemblies and ornamental details). Detail assemblies of multiple layers of PVC that varied in thickness would be prone to asymmetrical material movement. It was determined that PVC would be best utilized in linear applications with limited volume differential or isolated component locations (i.e., decorative finials, etc.)

As a result of our research, we concluded that while the use of PVC is appropriate for the replication of some millwork details, the geometry and configuration of those details must be carefully considered.

Specifically, PVC was utilized to replicate the railing assembly, including balustrades, moldings, decorative urn finials, and finial boxes. The column capitols and bases were fabricated from cast fiberglass. The egg-and-dart clock bezel and leaf accents were cast in epoxy resin.

Structural Framing

During the SD process, a timber grade quality assessment inspection was conducted with removal of wood samples. While accessing the tower using the industrial rope access method, the author began to remove materials on the bell-level cupola roof and observed evidence of long-term water infiltration (*Figure 8*). Over time, water infiltration had substantially deteriorated several column support members. The author used ASTM D245 strength ratio analysis to estimate mechanical properties of the white pine timbers. Structural analysis of the steeple framing revealed overstresses under dead load alone. Extensive in-situ capacity augmentation was required throughout the steeple and adjacent scissor roof truss framing.

When two deteriorated vertical posts were replaced with full-height white oak 8 x 8s, steel tension rods were added at the cupola level, and strain gauges were used to ensure load sharing and accurate distribution of dead-load forces among reinforcement members. Structural augmentation also included the composite method of adding "sister" and "foot" plates to overstressed members in situ, after repositioning by jacking them into place.

Figure 8 – Structural deterioration of the belfry dome.

Millwork

The original 1899 cladding and millwork on the clock tower were of eastern white pine. During that era, construction timber was mostly "first growth" or naturally grown, which resulted in a dense wood product with low absorption. Today, the majority of our domestic timber is silviculturally grown or "farmed." The rapid rate of contemporary tree growth produces a less dense, more absorptive wood product with a shortened service life when compared to the same species harvested a century ago.

The original tower pine components performed well for 115 years. In order to replicate that service life, an alternative species was selected for the tower envelope. South American mahogany was chosen for all

Figure 9 – Mahogany millwork, replicating the original pine details.

Figure 10 – Structural failure of improperly erected staging, causing ten-day project delay.

cladding and millwork (*Figure 9*). Mahogany is a dense wood with low water absorption qualities and good insect resistance. Its fine grain also promotes good coating adhesion.

A millwork firm was chosen for its ability to replicate the existing configurations of the ornate exterior details, using five-axis computer numerical control (CNC) equipment. The tower laser scan was used to model all millwork details in BIM and deliver them to the millwork firm, which programmed the data into its CNC machinery. In order to ensure accuracy and document existing configurations, one tower elevation was hand measured, providing an information baseline. All individual millwork component dimensions were then entered into a spreadsheet database program.

All millwork was specified to be fully primed at the fabricator's facility after verifying acceptable wood moisture levels, and then partially assembled. The on-site coating requirements included the priming of all field cuts prior to installation and two coats of a proprietary epoxy-based coating that provided a ten-year warranty.

All wood products were compliant with either the Forest Products Society's (FPS's) International Forest Stewarding Council (FSC) or the Sustainable Forest Initiative (SFI) to confirm they were sustainably sourced and ethically harvested and purchased.

Staging

The staging component of a tower project, while essential, can at times be underspecified by the project designer. Scaffolding can have a disproportionally large effect on a tower project, as it can be expensive; and as the first trade on a project, no other work can begin until the staging has been completed, inspected, and approved.

OSHA Subpart L, Section 1926.452, Item (c) (6), states "scaffolds over 125 feet (38.0 m) in height above the base plates shall be designed by a professional registered engineer and shall be constructed and loaded in accordance with such design." As is the case with most standards, this represents a minimum requirement.

As with most large academic projects, the clock tower restoration had a brief scheduling window, to be completed when most students were not on campus during the summer months. The author had specified the configuration of the staging, including a large work platform at tower mid-level. In addition, scaffold plans from the staging contractor's engineer and mandatory pullout tests for the wall anchors were also specified, as was full netting with applicable wind load testing.

After submitting the required engineering staging plans, and anchor pullout tests were conducted, the contractor began staging erection on the project start date.

As part of the project management team, the author was inspecting the staging, when at approximately 30 ft. above grade, deflections in the upright legs of the steel frames were observed. Further inspection revealed that the staging was not being erected per the engineering design and had 50% fewer attachment points than specified at the exterior masonry wall (*Figure 10*). Work was terminated, and the staging condemned while a structural investigation began as to whether or not the noncompliant staging could be remediated. Meanwhile, monitoring devices were installed to detect movement with the existing staging assembly. Ongoing horizontal movement (away from the building) was documented, and lateral loading continued until approximately 12 steel frames became deformed and were unusable. At that point, the staging was dismantled and the contract with the original staging company was terminated. A second company was engaged and new staging erected with engineering supervision. The end result was a ten-day project delay; however, no injuries occurred.

Exterior Lighting and Lightning Protection

A tower project provides a cost-effective opportunity to upgrade the existing electrical systems, as the access logistics are in place. Significant progress has occurred in contemporary exterior tower lighting technology.

Exterior LED systems can provide flood, spot, or "strip" fixtures that are smaller and more discreet, with increased efficiencies (i.e., LED 24-watt fixtures, operating on 12V and providing 177 lumens).

The Groton clock tower and pedestrian access were previously poorly lit. By specifying LED fixtures at grade, on the roof, and on the tower itself, both public safety (at grade) and aesthetics were vastly improved (*Figures 11* and *12*). With an integrated sensor system, the lighting is programmable and provides automatic duration and intensity options.

A tower electrical scope should also include a lightning protection system evaluation by a UL-certified inspector. Any defects or upgrades required within the system can be cost-effectively mitigated during the project. A new lightning protection system was subsequently engineered and installed on this project.

Clock and Bell Restoration

The original tower clock installed in 1899 was manufactured by E. Howard and Company in Boston, Massachusetts. It is an intricate, antique, round-top timepiece with a weight-driven pendulum and was mechanically wound once every five days. After evaluation, while currently in serviceable condition, the clock was in need of restoration. Originally, the clockworks were housed on the clock level, directly behind the clock face.

Additionally, the clock mechanism rang the single bell in the belfry above on both the half hour and hour. The bell was manufactured by the Meneely Bell Co. of Troy, New York, in 1899. As the Meneely Bell Co. went out of business in 1956, a bell restoration foundry was contacted for restoration. Within the first week after staging completion, both the clock and bell were removed by crane and sent to their respective restoration firms.

Two clock scope alternatives were proposed to the school. First, an automatic (electrical) winding system was proposed and installed during restoration. Secondly, upon restoration of the clockworks, they were relocated from the tower clock level to the classroom hallway beneath the tower. The clockworks have antique value and form an attractive period timepiece. A large glass display case was built in the hallway to protect and display the clockworks. Mechanical linkage was added, connecting the instrument to its original position, and it continues to function as a timepiece while operating the bell.

DESIGN CONSIDERATIONS, CASE STUDY #2

Recently, Dartmouth College in Hanover, New Hampshire, requested a forensic building conditions survey and structural evaluation to serve as the basis for a schematic design of its iconic Baker Library tower as a precursor to restoration. The tower was designed by noted college architect Jens Frederick Larson to emulate the tower at Independence Hall in Philadelphia (*Figure 13*). The steel-framed structure was com-

Figure 11 – Roof design to minimize view of tower lighting fixtures.

Figure 12 – Tower lighting mock-up in progress.

Figure 13 – Baker Library Tower, Dartmouth College.

pleted in 1928. The square-planned brick tower base is surrounded by the attached building on three elevations, with one tower elevation extending to grade and housing the main building entrance.

The tower stands 200 ft. in height, with a weathervane mast (spire) extending 28 ft. above the weathervane cupola and supporting a weathervane that is 7 ft. tall and weighs 600 lbs. (*Figure 14*).

Bell Restoration

Bell systems are integral to many towers and, if present, should be included in the project scope of work. Bell sets are defined as either a carillon or a chime.

A carillon is a collection of 23 or more bells, which are by definition "played serially to produce a melody or sounded together to play a chord." Although contemporary carillons are frequently played by system software, traditionally, they were played mechanically with a keyboard.

A chime is defined as a carillon-like instrument composed of fewer than 23 bells. The term "change ringing" refers to the art of ringing tuned bells in a full circle, allowing the ringers to produce different striking sequences. It is an important design consideration, as the considerable weights of the bells employed in "full-circle ringing" require complete load analyses and inspection of their support structures.

Many owners are not aware that as musical instruments, bell systems require regular maintenance and should be inspected in five-year intervals as both performance and safety considerations. As a result, a conditions assessment was ordered for the Dartmouth chime and performed by

Figure 14 – Baker Tower weathervane, depicting Dartmouth's founder, Eleazar Wheelock, in 1769, teaching a Native American.

a bell restoration consultant. In addition to providing a scope of work for maintenance or possible restoration of the chime, the assessment also provided specific weights of the bell chime for a complete dynamic load analysis of the chime and belfry system.

The scope of the inspection included an acoustical analysis of each bell, as well as the belfry chamber. In addition, all bells, striking mechanisms, and associated hardware were measured to ascertain weights for dead-load data, and all components were inspected.

As a result of the consultant's inspection, it was learned that the bells were cast by the Meneely Bell Company, Troy, New York, in 1928 (*Figure 15*). Original records were located and stated the largest bell of the chime weighed 4,993 lbs. The total weight of the 17 bells (exclusive of the framing and equipment) was 23,351 lbs.

A full structural analysis was performed, based on the inspection data and revealed that while under code-prescribed loads, most of the carriage components were within allowable stress limits for a full design load. The few timber-framed bell support system components that were overstressed provided capacity for 75% of the demand. It was then determined that in-situ capacity augmentation could be utilized to remediate the issues (*Figure 16*). Specifications for the bell restoration and structural scope of work were added to the project documents. Bell restoration and casting foundries are a "niche" trade and can be difficult to locate, requiring the designer to search outside of the U.S.

The Whitechapel Bell Foundry was established in East London, England, in 1570 and has been continuously in business since that date. In the past, they have produced original bell records for several projects by the author's firm. Their UK location is generally not an issue, as they have restoration staff who work regularly in the U.S. If considered for a project, they should be contacted with as much advance notice as possible for scheduling.

Figure 15 – New tower bells prior to the 1928 installation, Baker Tower.

Security Management

Security management systems are an important component of the tower scope of work. Public safety concerns highlight the need to address and specify systems and procedures to mitigate public exposure and eliminate unauthorized public access to the tower.

For this project, a security threat assessment was performed by a security consulting firm. As a result, the current security system was upgraded to include keyless entry (card readers), a surveillance system upgrade, and a revised access control system (ACS) to comply with UL 294 and UL 864 standards. In addition, all fenestrations were alarmed. Electronic surveillance is currently maintained by campus security, as scheduled tower tours are conducted upon request. These tours provide interior access to the ringing chamber level, with exterior access provided behind railings on all elevations.

Firestopping and Suppression

A thorough analysis of existing fire suppression systems and penetration firestopping was performed within the tower. Testing or installation of penetration firestops should comply with UL 1479 and ASTM E814 requirements, and firestop con-

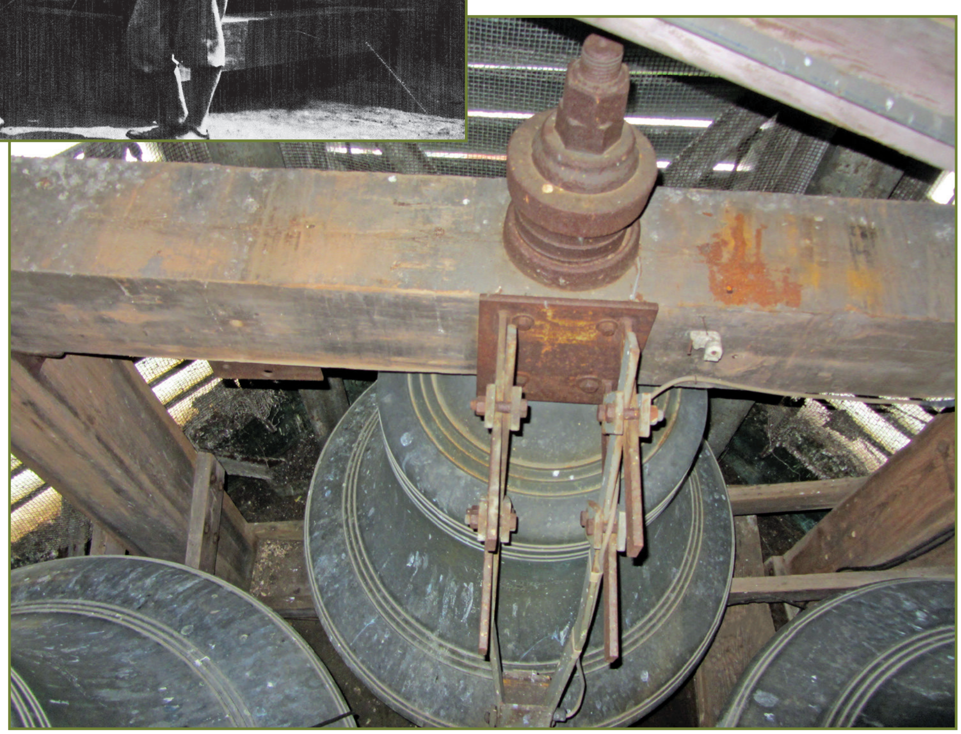

Figure 16 – Tower chime supports required in-situ capacity augmentation.

tractors should have FM 4991 approval. If an existing fire suppression system is in place, it should be fully inspected and tested during the schematic design phase.

Both firestopping and fire suppression systems are critical life safety components in tower design. In addition, if the tower is attached to a building, 2015 IBC section 1510.5 states that the fire resistance rating of the tower must be equal to that of the attached structure.

QUALITY ASSURANCE

Specifying the use of independent inspectors on a tower project could be perceived as burdening what often is an already over-stressed project budget. Nevertheless, the use of independent inspectors on tower projects can be even more beneficial than their involvement on conventional construction projects. As highlighted in former case studies, construction mistakes do occur. If installation defects or water infiltration issues are not addressed prior to project closeout and staging removal, the remediation process can be very expensive. Independent inspectors should be involved in the submittal approval process, perform materials and system testing while work is in progress, and schedule and oversee manufacturers' warranty inspections. Additionally, consideration should be given to hiring an independent safety consultant who has tower experience and is familiar with all applicable OSHA regulations.

Some conditions requiring oversight are as follows:

- Staging inspection (daily) per OSHA standards
- Roofing and wall installation (both low-slope and steep-slope), performance of in-situ water tests, and oversight of warranty inspections. Document with photos and field reports.
- Firestop system installation, per ASTM E2174 and testing per ASTM E814
- Project safety officer, supervised by the project manager

As a quality assurance measure, independent inspectors provide value-added objectivity and safety to tower and steeple projects.

SUMMARY

While there are a number of design considerations and problems unique to tower and steeple restoration, a methodical, multidisciplinary approach to project scope development and code compliance as described will guide the designer. Although some of the trades and systems in tower design are uncommon, engaging in a thorough evaluation of all project systems, engineering, and code requirements will produce an effective and comprehensive project design.

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UAVs May Soon Be Roofers

An unmanned autonomous vehicle (UAV) equipped with a nail gun has been developed that may be the precursor to models that will keep some roofers on the ground while the drone does the dirty work.

Ella Atkins, a professor of aerospace engineering at the University of Michigan in Ann Arbor, designed the system after repairing her own roof. She and colleagues modified a DJI S1000 octocopter by attaching an off-the-shelf nail gun. Using tracking information from a ground-based motion-sensing system, they maneuvered the AV over a mocked-up roof and nailed down a series of asphalt shingles.

The firing mechanism is only unlocked by pressing on the gun's tooltip on a surface. To view the mock-up demonstration, visit https://youtu.be/GA445FIxkjo.