Engineering survival and success: The contributions of historic structural features in the spire and tower of Salisbury Cathedral

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ABSTRACT: The 14th century spire of Salisbury Cathedral, when built, achieved unprecedented heights in stone masonry construction. This accomplishment was made possible through several ingenious structural systems that used iron and timber systems to supplement the traditional methods of stone masonry construction of the time. Its survival over 700 years, though, has not been without challenges and today the engineering systems of the tower and spire provide a superb example of evolved technologies that assure the structural integrity of the 123 meter high structure. The actual theoretical basis for the contributions of the structural systems in the Salisbury tower and spire will be explored in this paper with a goal of identifying the specific critical roles of individual systems based on historic structural behavior and analysis based on twentieth century structural concepts.

1 INTRODUCTION

Architects and builders have historically stretched the limits of technical knowledge in the construction of towers and spires on churches and cathedrals from medieval times onward to create some of the most impressive structures in Western Europe. This reaching beyond known limits has not come without cost, as tower and spire structures have also experienced their share of recurring problems with a constant concern that such structures may not stand up over time. Indeed, so many spires have come down that today a much smaller number of cathedrals still have spires on their towers than was the case in the past. This is a significant loss of heritage.

Structural challenges on church towers and spires have historically been addressed by taking advantage of the best known technology of the time to attempt to correct these challenges with solutions that have as long a life as possible. The lessons come from the history of towers and spires across Europe, but the history of the Salisbury Cathedral tower and spire provides a particularly rich example of structural innovation. The incremental additions to the Salisbury tower and spire of multiple buttresses, scissors arches, strainer arches, metal framework and timber scaffolding engaged as a capstone weighting system are technologies that can transfer to (and have been used at) other medieval towers and spires. The application of incrementally developed solutions is critical to the survival of the Salisbury spire and is a part of the historic tradition associated with the building. Even through the twentieth century, applications of state-of-the-art technologies at Salisbury Cathedral continued this tradition of applying current technology to more soundly address the inherent structural challenges in a masonry tower and spire of such height and delicacy.

In the twenty-first century, the spires and towers of historic church buildings will require the correction of structural problems that are minimally intrusive on the historic fabric of the building and that correct these problems with solutions that have as long a life as possible. The success of the tower and spire at Salisbury Cathedral in surviving for 700 years provides an excellent example of how to apply evolutionary technology to secure the structural integrity of what is a state-of-the-art spire structure while still maintaining the architectural fabric and beauty. Salisbury also provides an important case study of the need, when preserving sophisticated structures, to approach the duties of conservation pragmatically to find a balance between the advantages of modern technologies and the conservation goals that strive to minimize intervention. It is this pragmatism in Salisbury’s history that may indeed be the key factor in its survival while so many other medieval spires have disappeared or required complete rebuilding.
2 THE HISTORICAL CONTEXT FOR THE SALISBURY CATHEDRAL SPIRE

2.1 The historical problems

The spire and tower of Salisbury Cathedral have presented problems for builders, clerks of the works, architects and engineers through the centuries. These problems appeared from the very start when the decision was made to construct a stone tower and spire of unprecedented height on a supporting structure at the great crossing that from all available evidence was never intended to support a tower of any significant height. The consequences of this decision have impacted almost every structural component from the supporting foundations to the top of the spire. The impacts include the following:

- In the original cathedral structure, minimal foundations under the great crossing piers have visibly settled, especially at the south-west pier, resulting in an overall 'lean' to the tower and spire to the southwest.
- The crossing piers have a visible bow, a situation that is believed to have prompted the installation of the strainer arches at the great crossing.
- Buttressing, much of which appears to have been added as part of the tower construction, was probably installed in response to outward thrust from the added tower weight that caused shifting of triforium piers, cracking of walls and vaulting, and deflections of transept piers that can still be seen in the Cathedral today.
- The base of the tower up to just above the main roof ridges is a comparatively light arced structure with comparatively thin two-foot thick outer walls with multiple penetrations. Reinforcing of this level has been implemented on several occasions over the centuries and includes iron framework ties, infilled stair towers and wall openings, and stiffening walls between the arcade columns and the outer walls.
- Extended periods of neglect have resulted in failure of iron reinforcing at the base of the spire, resulting in stone damage and the need for a reworking or replacement of the iron reinforcing and major restoration of damaged masonry on at least two occasions.
- The spire itself has suffered frequent damage from storms and lightning, resulting in cracks and displaced units in the masonry and, in at least one instance, fire damage to the internal timber framing. There is also a visible bend twelve meters from the tip of the spire in the southwest direction that is of unknown origin.

The structural behavior and conditions behind these problems have been considered by caretakers of the cathedral fabric over the centuries and solutions have been implemented. For early work prior to the 17th century, there is little or no written documentation and the history must be conjectured primarily by an assessment of the surviving physical built structure. Salisbury Cathedral, though, is fortunate to have a comparatively extensive documentation of its history since the 17th century that provides insight into the conditions noted and the solutions implemented to maintain the structure through the past 350 years. Two documents in particular are landmarks in the history of English building archaeology and conservation. The first of these is Sir Christopher Wren’s assessment on the state of the Cathedral prepared for Dr. Seth Ward, Bishop of Salisbury, in 1668. This document is considered to be the first reasonably comprehensive evaluation of a historic medieval ecclesiastical building in England. The second document is titled A Series of particular and useful Observations, Made with great Diligence and Care, upon that Admira\-
ble Structure, the Cathedral Church of Salisbury, writt\-en by Francis Price, the Clerk of the Works for the Cathedral from 1738 to 1753. Not only did Price describe the building in words, but he also produced detailed drawings based on careful measurements, providing at the time a unique snapshot of the Cathedral at that specific point in time.

2.2 The structural systems supporting the base of the tower

The concerns with the foundations and supporting pillars at the great crossing of Salisbury Cathedral have been the topic of extensive discussion, conjecture and concern over the years. Some of the conjecture has been based on incomplete evidence or concern extrapolated from experience at other medieval cathedrals. Until the 1980’s, when Peter Taylor was able to make specific measurements of the pier foundations at the main crossing, the actual foundation sizes were unknown quantities that many had presumed were insufficient. Measurements taken in the 1980’s by Peter Taylor have been used to evaluate the footing situation and using soil mechanics theory developed in the twentieth century have for the first time been able to provide a theoretical basis for explaining the marginal adequacy of the footings under these piers. Taylor notes that the historic concern with the delicacy of the situation has perhaps saved the spire and tower from disaster, as this current theoretical explanation highlights the importance of maintaining the confining soils around the foundations, a contribution that would have been disrupted by any attempt to excavate and enlarge the foundations. (Taylor, 1988, p. 3)

Similarly, the bow of the pillars at the great crossing has been the topic of much discussion over the centuries. The bow and associated cracking and displacement of arcade piers at the triforium level are generally believed to have originated when the tower
and spire were added to the original tower base. Much of the engineering that can be found within the main body of the Cathedral to counteract forces imposed by the weight of the tower and spire, including scissors arches at the east crossing and 112 buttresses at the arcade and triforium levels (Price, 1753, p. 35), were believed to have been added during or shortly after construction of the tower and spire in the early 14th century. The exception to this are the east-west strainer arches at the great crossing, which appear to have been installed approximately 100 years after the spire addition. The contribution of these strainer arches, which are supposedly restraining through compression bearing, has been called into question over the years based on visible gaps between the arches and the crossing piers. (Price, 1753, p.53) Strengthening measures have been recommended as recently as the late twentieth century to stiffen the crossing pillars and increase the capability to resist buckling forces, but no specific deficiency has been identified (except the visible bow). The current approach is to monitor the situation to ascertain if the bow is a manifestation of an active condition, or an adaptation of the building structure to stresses from loads imposed in the past that have found a steady state of equilibrium.

Iron, though, does corrode and when exposed to weathering conditions will require significant restoration or replacement on more frequent intervals than stone and such replacements and restorations provide opportunities for utilizing improved technologies. Iron-based technologies have also evolved over the centuries, and thus have also been favored for added retrofits to address deficiencies that develop over the years.

3.2 The metal tension framework and gallery infill in the original lantern tower

The best evidence that a conscientious engineering effort was involved in the raising of the tower and spire at Salisbury is the elaborate medieval wrought iron framework that is located in the original lantern tower of the Cathedral. The medieval ironwork in the lantern was later supplemented by diagonal ties installed under George Gilbert Scott and his engineer, F. W. Shields in the 19th century.

The original lantern at the base of the tower – the portion from the eaves of the main roofs up to the clear horizontal parapet band – has been identified by Tatton-Brown and other sources as clearly not designed for the superimposed load of a soaring tower and spire. (Tatton-Brown, 1991, p. 328) Originally, the lantern was believed to have been designed to support only a short timber spire or pyramidal roof and was intended to be open to the space below with large wall openings to bring exterior light into the center of the building.

The load of the tower and spire carried by the lantern, estimated to be 6000 tons at this level, exerts an imposed stress of 1.724 N/mm² on the approximated effective bearing area (Reeves, Simpson & Spencer, 1992, p. 381), which is well within the minimum 16.5 N/mm² compressive strength of the Chilmark limestone of which it is built. What the iron tie system at this level does accomplish, though, is to effectively reduce the unbraced length of the wall and corner column elements, limiting the unbraced length for outward buckling at these corner stair towers to the height of the arcade, and keeping the theoretical unbraced length to thickness ratios within limits considered acceptable by twentieth century code standards. Inward buckling of the stair towers is resisted through bearing of the masonry wall construction on the four sides, while outward buckling forces are resisted by tension in the iron framework (Figure 1, Force Fm) that transfers the load into compression bearing against the depth of the walls at the adjacent corners. The lantern is thus reinforced, for purposes of buckling, so that the unbraced length is limited to the height of the arcade. The intent of this framework appears to be valid and for over five hundred years performed admirably in providing the confining hoop stress to allow the thin (by medieval standards)
lantern structure at the base of the tower to support the considerable weight above.

The original medieval ironwork although intact on the interior of the tower, appeared to have either succumbed to corrosion in places or was weakened in other ways when George Gilbert Scott conducted an assessment of the Cathedral in 1862. (Cocke & Kidson, 1993, p. 29) The diagonal cross ties installed by Scott and Shields resist the same outward buckling action in a more direct manner (refer to Figure 1, force Fss) and also further reduce the unbraced length by providing two sets of ties mid-height between the medieval framework at the top and bottom of the lantern, as well as a set between the medieval frames at the top of the lantern. These braces are each of square cross section at the interior of the lantern, dividing at corner piers of the tower to pass through the wall and connect to anchor plates at the exterior face of the corner diagonal buttresses. (Reeves, Simpson & Spencer, 1992, p. 404)

The segmental nature of the framework and the relatively thin cross section of the members has possibly been a positive factor in allowing the iron system to accommodate the differential expansion between stone and iron under thermal fluctuations. An embedded design within the stone would likely result in fracturing and spalling of the stone due to thermal stresses caused by expansion of the iron. By bringing the framework into the interior of the tower as an exposed framework, and any thermal growth can be taken by elastic buckling and/or the play in the hook and eye connections between segments without imposing excessive stress on the stone. The amount of iron in contact with the stone (at the corners) is dimensionally small, thus limiting thermal loads that may impose tensile stresses on the stone.

3.3 Tension rings and transfer structure at the base of the spire

The spire at Salisbury sits on the square crossing tower with the octagon faces in the primary directions (north-south-east-west) supported directly on the tower walls. The diagonally oriented faces are supported by ‘squinch arches’ that bridge diagonally across the corners of the tower to transfer the load from these faces to the tower walls. This arch introduces a thrust perpendicular to the plane of the four tower walls at approximately the third points of each wall. Price observes that consequently there is no ‘buttment’ for the [resulting thrust from] these arches except for that provided by the ‘iron bandages’, which are provided at the base of the octagonal spire. (Price, 1753, p. 38)

Unlike the retrofit nature of the iron framework in the lantern, the two systems of iron framework at the top of the tower and at the base of the spire are specific structural systems to contain the outward thrust resulting from the dead load weight transfer on the sloped sides of the spire. The system at the top of the tower was completely removed in 1967–68 and replaced by a Peter Taylor designed system of stainless steel bars with adjustable turnbuckles at the squinch arches that are encased in epoxy resin that is integrated into a continuous concrete ring beam in the gutter at the base of the spire. (Tatton-Brown, 1991, p. 342) Structurally, the original system (and its replacement) functions in the same manner as the lantern system described previously, although fully embedded in the masonry. The iron band at the base of the spire consisted of a single ring of iron bars joined using pegged scarf joint connections. This band is located external to the stonework, but was protected by being set in a recess that was filled with lead. This band effectively overcomes the need to relay on buttresses to resist the outward thrust (Th) from the transferred dead load of the diagonal sides of the spire by providing the tension bar to tie the arch and cancel the net effect of forces (Fr) from each side of the arch. (Fig. 2) With the great height of the Salisbury spire, this alternative approach is probably the only option, as the height of the tower dimensionally limits the amount of thrust that can be resisted by the dead weight of the tower walls and pinnacles at the corners.

It is also worth noting that the proportions and geometry of the Salisbury tower, with its straight
vertical sides, are contrary to the conventional stone masonry theory that requires increasingly deep buttresses toward the base to contain the lines of structural thrust from above – a convention that can be seen in most continental European stone spires that results in the tapered pyramidal configuration of Cologne, St. Stephen’s Vienna and others. The Freiburg Münster, with a slim upper profile and a pyramidal base structure was the prototype for the Germanic spire towers that came later. Unlike Salisbury, the octagonal plan of the spire at Freiburg is carried down through the middle portion of the tower, avoiding the concentrated thrust associated with Salisbury’s squinch arches and effecting the transition of octagon to square plan at the top of the main body of the Münster, where buttressing can be blended into the wider profile of the church building. There are, however, iron rings encased in the joints of the stone masonry at the top of the tower and the base of the spire at Freiburg. These provide a mechanism for the redistribution of unbalanced forces around the slightly uneven plan geometry of the built tower (Fritz, 1926, pp. 50 & 59) and also provide a restraint point to resist outward buckling action on the corner elements of the octagonal support tower that rise up individually from the floor of the open Oktogonhalle.

It is the ‘iron bandage’ at the base of the Salisbury spire that has been most subject to the pitfalls of using iron in exposed conditions. Price reported that the band at the base of the spire, even though protected in a recess covered with lead sheet, had been swollen due to corrosion, lost material and splintered the stone. (Price, 1753, p. 38) Price added an iron band at the base of the spire in approximately 1740 to supplement the original medieval band, both of which were replaced in 1968 when the stainless steel band and concrete ring beam system. (Tatton-Brown, 1991, p. 342) The medieval iron band, a system that is essential to the structural integrity of the spire, did however function adequately for approximately 400 years and Price’s additional ‘bandage’ provided another 200 years of service – an impressive duration for the pre-industrial wrought iron encased in lead system.

3.4 External rings on the spire

The upper iron bands around the perimeter of the spire at Salisbury were initially a recommendation of Wren’s as a reinforcement to address concerns with the perceptible bend of the spire towards the top. This bend to the southwest is in addition to the out-of-plumb alignment that Wren documented in his 1668 report. Wren specifically recommended this ‘bandage’ at the location of the bend (corresponding to the fourth and fifth rings from the top on the spire today), but also recommended that additional bands be added to provide greater ‘security’. (Wren, 1668, p. 24) Wren’s immediate recommendation appears to have been promptly implemented (c. 1670), but the additional ‘security’ rings recommendation was not forgotten and the rings below were originally installed in the late 17th or early 18th centuries. 230 years later, the iron straps were replaced with copper by R. Beaumont. (Tatton-Brown, 1991, p. 342) The longevity of these iron bands, in a fully exposed condition, similar to the iron band system at the base of the spire, is better than can be expected for the material and probably can be attributed to the low level of impurities in the pre-industrial iron that was used.

Wren’s purposes appear to be twofold. His concern with the bend in the spire appears to be with regard to this bend as a point of structural weakness and thus a point of failure in future storm events. The ‘upright bars’ on each octagon panel serve to anchor the portion of the spire above the bend to the portion below, with the top of the lower portion well-secured by the exterior hoop that compresses the stone shell at this anchor point. The additional hoops appear to be in response to Wren’s concern with settlement and observations of ‘downward cracks’. (Wren, 1668, p. 24) Although Wren’s immediate recommendation for this decay was to replace with new stone and remortar, the pattern

![Figure 2. Iron tie arrangement and force diagram at squinch arches. (Background Drawing Source: Price, 1753, Plate 8).](image-url)
Figure 3. Internal tie system to the spire, immediately above the gabled doors and openings. (Source: Taylor, 1988, p. 8, Figure 3.)

of ‘downward cracks’ also raised a concern of splitting that was most likely caused by outward buckling and would most effectively be arrested with regular tension hoops down the length of the spire. The fact that there appears not to have been any tension rings on the Salisbury spire in the first 300 years of its life can be considered as validation of the idealized conical spire developed by Heyman. (Heyman, 1995, pp. 127–29) It is likely, though that due to local stone deterioration and/or weakness, construction irregularities or lightning damage, that the integrity of the spire was compromised and outward buckling action could develop in thin slender elements created by vertical cracks in the shell.

Outward buckling was no doubt also intuitively noted in the Freiburg Münster spire in its conception, where the ribs can more readily be visualized as slender column elements. The Freiburg spire ribs do have a visible outward bow that appears to exemplify this behavior and thus to justify the need for the horizontal iron bands that are embedded at regular intervals along the height of the spire. The forces that the rings are capable of resisting are quite small, but Fritz notes that the small forces that are developed are due to the ‘swollen’ profile of the ribs and the irregular plan base on which the spire was built. (Fritz, 1926, p. 59)

A more recent 20th century addition to the series of rings along the height of the Salisbury spire is Peter Taylor’s internal tie ring, located at the level immediately above the door and light openings in the spire that is designed to consolidate the octagon structure adjacent to the zone of weakness introduced by the openings. The system (Fig. 3) is economical, simple and largely protected from the elements. It consists of twin high-tensile steel tendons that pass around steel saddles at the inner side of each of the octagon corners. These saddles are then anchored by tensioned bolts that pass through the saddles and the spire shell and are anchored by bearing plates at the exterior of the spire corners. (Taylor, 1988, p. 8) The system has the advantage of minimizing the exterior exposed components (which can be of high grade corrosion resistant materials) and placing the primary structural component in the protected interior, where the material can be selected for its superior structural properties (i.e. a very high Young’s modulus value).

3.5 The internal timber frame

Perhaps the most intriguing and ingenious aspect of the structure at Salisbury is the timber frame scaffold inside the spire. This timber frame was archaeologically evaluated and documented during the late twentieth century spire restoration. (Tatton-Brown, 1996) The scaffold is only occasionally in contact with the interior face of the stone shell and thus does not function as a supporting framework for the stone shell.

The history of this framework is unclear. Michael Drury, current Cathedral Architect at Salisbury, reports that recent dendrochronological testing appears to support an original date of around 1400, or the time of the first significant repairs following a possible lightning strike. This date, if accurate, would undermine previous theories that the framework was part of the original scaffolding and would associate the framework with scaffolding for the 15th century repairs. This may make more plausible the possibility of forethought given to the dual purpose of the scaffolding serving as dead weight anchoring of the capstone, as the total system may have been designed as a response to the damage experienced on a spire that had been a ‘first’ of its kind.

The need for an internal scaffold during the original construction is not a given, since exterior scaffolds were known to be typically used in medieval construction to build towers and spires and an exterior scaffold would have been required in any case to complete the top of the spire. Working from within the existing spire to access damaged portions of the spire in the 14th century may well have been more feasible than erecting scaffolding from the ground up.

What appears to have been the purpose of intentionally connecting the framework to a rod through the capstone was to provide a dead weight load at the top of the spire that would effectively pre-compress the stone shell to counteract tensile bending stresses induced by wind. Calculations of the stresses on the shell of the spire using approximated wind loads developed from current British Standards have found the difference in stresses with and without the weight of the timber framework represents a significant increase in the margin of safety provided for the upper portions of the spire as a result of this superimposed load. These approximate calculations indicate that the weight of
the timber scaffolding increases the factor of safety at 12 meters from the top from 1.57 to 2.29, values that represent a modification of the factor of safety from a marginally acceptable value (∼1.5) to a value that would be considered good design practice (>2.0) by current standards.

In 1738, Francis Price reported that the central piece of the timber scaffolding had become disconnected from the capstone approximately at the level of the weather door. This defect was immediately repaired, but Price surmised that this defect may have contributed to the upper bend in the spire that was of such concern to Wren in his 1668 report. (Price, 1753, p. 59) Calculations show that the spire could accommodate design wind conditions without the benefit of the additional ‘prestress’ provided by the dead weight of the scaffold. However, there is no way of knowing precisely the nature of the wind loads experienced by the spire at 123 meters above ground, an elevation where wind speed, gusts and other factors can differ radically from the conditions at ground level. Even over a limited time period exposed to less than maximum wind load conditions, fatigue behavior can cause deterioration of all structural systems, including stone. A marginally acceptable structure will be more susceptible to crack propagation at minor defects under repeated cyclical loadings. The ‘bend’ is noted to be to the southwest by Price and Wren, and this would be the side typically subject to tensile stress by the prevailing wind direction. A temporary disconnection may have begun this process of fatigue deterioration by allowing the incremental opening and closing of fine cracks on the southwest side, causing deterioration of the stone, which was fortunately arrested by the reinstatement of the weighted capstone system.

Less apparent is the damping contribution of this framework that would work to temper resonant vibrations of the spire in gusty high wind conditions—a known phenomenon in tall thin structures. Wren designed a comparable pendulum structure suspended from the capstone in the spire in Chichester in 1721. It is possible that Wren was inspired by what he saw inside the Salisbury spire during his review of the fabric in 1668. (Tatton-Brown, 1991, p. 345.) If intended, Wren’s engineering basis for the damping contribution of this suspended framework was at best instinctual. Given what is known of structural behavior under gusty wind load conditions from 20th century research, the damping contribution of the pendulum could be as considerable as the dead load prestress in reducing the magnitude of the wind-induced bending stresses and associated long term fatigue-like tensile stresses experienced by the spire during high-wind storm events.

There is one final system that was installed as part of the major restoration of the Salisbury spire in the late 1980’s/early 1990’s. Peter Taylor designed a series of steel tube frames that fit against the interior face of the spire at several elevations. These frames serve the purpose of stiffening the spire and providing a second structural system to temporarily carry loads of the spire above to allow stone replacement during restorations. In a sense, they are a permanent installation of ‘temporary shoring’. Taylor specifically designed the frames with a geometry provided by the slope of each face that prevents the structure from becoming a mechanism. The frame is redundant structurally and contains an ‘in-built limit to the amount of movement of which it is capable, thus resisting any irresponsible attempt to ‘lift’ the spire.’ (Taylor, 1988, pp. 8–9) In keeping with appropriate principles of historic building conservation, the frame installations are reversible and are of a technology that reflects the date of installation.

4 CONCLUSIONS REGARDING THE EFFECTIVENESS OF SALISBURY’S STRUCTURAL SYSTEMS

The structural systems for the tower and spire at Salisbury Cathedral fall into two distinct groups. The first group is the supporting base from the foundations up to the original lantern level on which the 85 meters of tower and spire were constructed. The problems experienced through this zone have primarily been attributable to the fact that the original construction at and over the crossing was not intended to carry such a great mass of stone. The structural systems in this area are essentially retrofit solutions of buttressing at the base to resist outward thrust at the crossing pillars and iron ties in the lantern to resist outward buckling from the high levels of compression stress on the comparatively thin supporting sections. These systems appear to be effective and necessary solutions to resist the thrusts and structural actions resulting from this large load. Less conclusively addressed, though, have been concerns about the bowing and settlement of the pillars. Numerous attempts to assess the conditions at the foundations and at the pillars have developed a tenuous explanation for the structural behavior based on advanced soil mechanics theory and that the supporting base for the spire has found a stable equilibrium.

The structural systems at Salisbury Cathedral that can be considered most applicable to other structures are the various iron bands and framework systems that tie together the tower and spire structures and resist the outward thrust forces generated on these structures. The original medieval iron frameworks in the lantern and at the base of the spire are quite elegant in their minimal mass, simple connection joints and concealed design. Successful modern replacements, most notably Taylor’s tie ring above the openings at
the base of the spire, follow similar concepts while incorporating appropriate updated materials improvements. What these tie systems accomplish is to provide the mechanism to internally counterbalance outward thrust loads and avoid the need for external buttressing or other visually intrusive modifications. Properly designed to not impose additional stresses due to differential thermal movement and with adequate protection from weather effects that cause corrosion, these metal tie reinforcements are structural solutions that minimally intrude on the historic fabric.

Metal bands along the height of the spire, such as the ten copper bands of the Salisbury spire and the iron rings embedded in the horizontal stone bands of the Freiburg Münster address less straightforward but important issues. These bands are not theoretically required due to any dead or wind load stresses on the shell of the respective spires, but they do effectively consolidate the spire cones to distribute stresses so that local irregularities do not propagate and become a major structural problem.

The other critical structural system in the Salisbury spire is the weighting of the top portion of the spire through connection of the internal scaffold system to the capstone to provide adequate dead load resistance to wind loads through the upper portion of the spire. This system supplements the metal cramp connected stones to provide a sufficiently solid structure at the top to counteract high wind load stresses and thin geometrical cross sections. Although specific historical evidence is insufficient to prove direct cause and effect, it does appear possible that the temporary loss of this connection could be a cause for the visible bend at 12 meters from the top of the spire.

REFERENCES