STRUCTURAL ANALYSIS OF WOOD TRUSSES OF SAN PAOLO FUORI LE MURA, ROME, ITALY

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ABSTRACT
The Roman double trusses of San Paolo fuori le Mura (FLM) are the oldest long-span Roman trusses for which sufficient information exists to perform a structural analysis. Span, spacing, and scantlings of members were recorded previous to the loss of the trusses due to a catastrophic fire in 1823. Wood species type can be inferred from comments by Pliny the Elder regarding other long-span trusses in ancient Rome. While the quality of the wood cannot be determined, the analysis results can be bracketed using allowable stresses from different wood visual grading standards. Dead and live loads can be estimated using loadings developed for current engineering practice. Quantifying the levels of stresses in the trusses of San Paolo FLM indicates a relatively conservative design. Stresses in the rafters, or upper chords, were reduced by the insertion of a collar strut providing an intermediate support to the upper chords. Even if it is assumed that timbers matching visual grade DF/L No. 2 were used, the combined flexural and axial stresses in the upper chords are well within those permitted by modern design standards.
Keywords: Roman double truss, Early Christian basilica, San Paolo fuori le Mura, wood truss design.

1 INTRODUCTION

The Emperor Constantine's shift to Christianity in the 4th century changed both the culture and architectural traditions of Rome. However, the architectural changes were not as radical as the cultural changes. Builders in Rome still apprenticed in their craft with masters of the previous generation, and building materials such as brick, stone, and timber did not change. Although Early Christian basilicas departed from the architectural tradition of Imperial Rome, they did not break from that tradition – their form represents an evolution or adaptation of the earlier Imperial Roman basilicas.

Choisy observed in 1873 that "the modern trusses of Italy… resemble those of the Christian basilicas, and those, constructed in a time where architecture had no other basis than memories, more or less altered from Roman practice, which are evidently nothing but copies of the originals that are lost to us" [1]. This study concurs with Choisy's observation that Imperial Roman buildings destroyed centuries ago are echoed in the form of Early Christian basilicas. These Early Christian basilicas consistently used the simple double truss, which was later used by Roman builders in the Medieval era.

Constantine's building program, and that of his successors, included several basilicas with wood truss roofs and substantial clear spans in the nave. Curiously, it was not the cathedral of Rome, San Giovanni in Laterano, that was the largest of these Early Christian basilicas. Rather, it was the funerary basilicas that had the largest clear spans. The traditional religious faith of Imperial Rome included ancestry worship, and the early Christian church absorbed this practice and constructed large basilicas with significant covered areas to accommodate both the burials and the feasts held to honour the dead. The two largest of these funerary basilicas, Old St Peter's and San Paolo fuori le Mura (FLM), were built in the same century with similar truss types and spans.

Old St Peter's was demolished stepwise beginning in 1506 to make way for Bramante's redesign of the basilica. Although Bramante's St Peter's covers an area similar to that of the demolished 4th century funerary basilica, its masonry vaults and massive piers are radically

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different from the original wood-truss form. Drawings and paintings of the Old St Peter's interior confirm that its form was similar to that of San Paolo FLM. However, the scantlings of the timbers were not recorded in any document that has survived, so an accurate assessment of the capacity of these long span trusses has not been possible.

In contrast, significant details of the trusses of San Paolo FLM were recorded prior to the fire that necessitated its rebuilding. Also, the intent of the rebuilding process was to restore the lost church, and not to create a new and different monument. The trusses of San Paolo FLM are the earliest wood trusses in the Roman tradition for which sufficient information survives to permit numerical analysis.

2 HISTORIC BACKGROUND

The funerary basilica of San Paolo FLM was begun in 384 and finished in about six to eight years [2]. Sited over the traditional grave of St Paul, it was a five-aisled basilica with a timber truss roof. Early in its existence it had a coffered, gilded ceiling [2]. San Paolo FLM survived largely intact until 15 July 1823 when repairs to the lead roofing coincided with a disastrous fire which burned out all of the roof trusses and collapsed many of the walls. Following the fire the basilica was rebuilt, reusing the surviving walls and columns and replacing the roof trusses and roofing (Fig. 1). In this way the many burial sites in the funerary basilica were maintained, and we are able to experience the same building volume and spatial quality of the lost original.

Jean Rondolet measured the trusses in 1784, 39 years before the fire [3]. Rondolet had worked as an assistant to Jacques-Germain Soufflot in the construction of the church of Ste. Geneviève in Paris. Soufflot's work at Ste. Geneviève is significant not only for its architectural merits, but also for the extensive materials testing program which he developed, seeking to select the highest quality stone and better understand the structural behaviour of the dome he designed. Steeped in this tradition of scientific inquiry at the work site for Ste.

Figure 1: A view of the interior of San Paolo FLM from a side aisle.

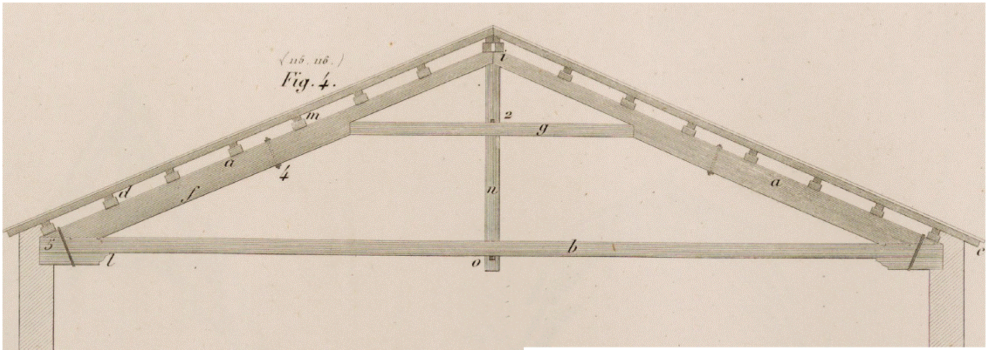

Figure 2: Rondelet’s drawing of the trusses of San Paolo FLM. *(Source: Traité théorique et pratique de l’art de bâtir, Pl. 105.)*

Geneviève, it is no surprise that Rondolet eventually would author and publish the encyclopaedic *Traité théorique et pratique de l’art de bâtir* which would go through many editions and form the basis for engineering and construction science for decades.

Rondolet was not impressed with the architecture of San Paolo FLM, but he was sufficiently interested in the engineering of the building to record the sizes of the members and form of the truss. Rondolet later published an engraving of the truss form in his *Traité théorique*
(Fig. 2). The elevation drawing shows the upper chords or rafters, a tie beam at the base of the triangle, a vertical kingpost, and a collar beam supported by independent props. Rondolet shows iron straps holding a short corbel up against the bottom of the tie beam. It is assumed that the forces between the upper chord and tie beam were transferred with a dap connection. Since the trusses were about 1,400 years old when Rondolet observed them, it is likely that dirt and dust would have obscured the dap.

Depending upon the proportions of the truss, a collar beam can serve different functions (Note that Ochshorn’s term “compressive brace” equals “collar strut” as used in this paper) [4]. Visual inspection shows that the collar beam in the truss of San Paolo FLM is a compressive brace, providing supplemental support to the upper chords. For that reason, these will be referred to as collar struts to more accurately describe their function. Also, it is noted that the English language term “kingpost” is misleading. It is not a post providing vertical support. Rather, it is a tension member, providing mid-span support to the tie beam. The German term, *hängesäule,* more accurately describes its function [5], as the German language separates roof timberwork into general classifications of *Hängewerk* and *Sprengewerk.* However, to maintain continuity with traditional terms, this vertical member will be referred to as a kingpost.

Rondolet’s drawing was redrawn and published by both Auguste Choisy in *L’art de batir chez les romains* and Friedrich Ostendorf in *Die Geschichte des Dachwerks.* Ostendorf redrew the truss elevation as a perspective drawing, probably to emphasise the fact that it was a double truss. However, in the re-engraving process the pitch of the upper chords was steepened. Rondolet’s drawing, therefore, is used exclusively to determine the form and proportion of the trusses.

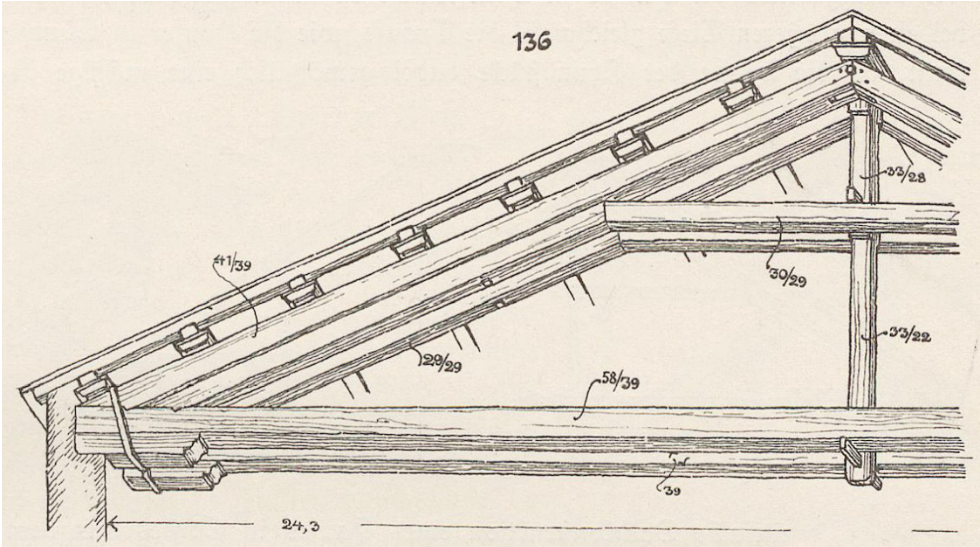

Figure 3: Ostendorf's illustration of the trusses of San Paolo FLM. *(Source: Ostendorf, Figure 136.)*

3 STRUCTURAL ANALYSIS

The structural analysis of the wood trusses of San Paolo FLM was conducted using simple hand calculations using customary units. While a computer solution using a structure stiffness matrix method is possible, it was concluded that due to the magnitude of the unknowns in some of the data, there was little value in the greater precision. The analysis considered the truss system with pinned connections and a roller support where the collar strut intersects the upper chord. It is acknowledged that there will be some transfer of axial loads at the collar strut due to friction, but this is judged to be relatively small. It is also assumed that thermal movements, volume change due to humidity, and wind loads will tend to cause slippage and reduce any restraint due to friction over time.

For simplicity, the roof load was assumed to be distributed, rather than applying point loads from each of the purlins. The moment distribution method was used to calculate the bending moment at the roller support. The simplified moment distribution procedure for pinned end elements, as outlined by Crawley and Dillon [6], resulted in a rapid convergence on a solution for the intermediate bending moment. Any support that might be given to the upper chords by the rafter props was neglected, with the assumption that such support would be insignificant. The axial load from the weight of the tie beam and coffered ceiling was then calculated, and the combined stresses of axial load due to roof loading and the axial load from the tie beam and ceiling were summed. The total bending stress and axial stress were then divided by their respective allowable stresses in an interaction equation to determine the percent capacity of the trusses under the assumed loads.

Since the purpose of the analysis is only to gain an understanding of the design practice of the Early Christian builders, and due to the degree of uncertainty introduced by the necessary assumptions, this analysis only considered gravity loads. It is recognized that wind loads can significantly change the stress levels in truss members, especially when there is a positive pressure on the windward side of the gable and a negative suction on the lee side.

However, given the relatively low pitch of the upper rafters, about 22 degrees, wind loads will only result in negative pressures or an upward suction on the roof for both the windward and leeward sides of the roof. Therefore, wind loads will only result in a reduction of the downward load on the trusses [7]. In addition, the capacity of wood members is greater when subjected to loads of short duration – in the case of wind loads the duration factor provides for a 60% increase in allowable stresses [8]. The timber corbel at the truss support would decrease the functional clear span of the truss by the depth of the corbel if the iron strap held it tightly. However, since the condition of the corbel and iron strap is not known, this was not considered in the analysis.

The upper chords are subjected to both axial and bending stresses, and modern codes require the calculation of a column reduction factor to account for potential buckling under compressive loads. It was assumed that the purlins were spiked into and/or notched around the upper chords, bracing them laterally. It was also assumed that the inclined strut that supports the collar beam provided support to counter buckling on the bottom face of the upper chord. Therefore, the tendency to buckle was only considered in the section of upper chord from the collar strut support to the peak, and then only in the vertical plane. However, the scantling of the upper chords is robust and, assuming a "k" factor of 0.8, the column reduction factor was determined to be 0.98. Since the reduction from the column factor was so small and the uncertainty of some of the assumptions was relatively high, this column reduction factor was neglected.

Rondolet also published a second form of the trusses of San Paolo FLM with a scarf joint in the tie beam and the addition of two hangers at the intersections of the collar strut with the upper chords. The change in configuration of the tie beam has little effect on the levels of stress within the upper chords, and so only Rondolet's first version was analysed.

3.1 Determination of loads

Loads on the trusses were determined by the plan dimensions, analogous contemporary practice, and modern codes. In 1554 Giovanni Colonna da Tivoli measured the center-to-center distance between nave columns as 85 *piedi romani* [9], or approximately 81.8 feet (25.2 m). Subtracting a column diameter leaves an estimated clear span of 79.7 feet (24.3 m). The nave length reported by Colonna da Tivoli is 297 *piedi romani*, or 285.7 feet (87.9 m). Engraved views of the interior of San Paolo FLM prior to the fire show double trusses spanning across the nave centered above each nave column and at the mid-span of the architrave between nave columns. Trusses were spaced at approximately 13.5 feet (4.12 m). However, since these were double trusses, each triangular assembly of rafters, tie beam, and collar strut supported a tributary area of roof approximately 6.75 feet wide (2.06 m).

Scantling dimensions recorded by Rondelet tend to group themselves around modules of one Roman foot, one and a half Roman feet, and two Roman feet; respectively about 11 1/2 inches (29.2 cm), 17 inches (43.2 cm), and 23 inches (58.4 cm). The weight of the timber framing was estimated using a density of 40 pcf (640 kg/m^3). Purlins and sheathing were assumed to weigh 7.5 psf (360 Pa) and the load of the clay tile roofing was estimated to be 12 psf (575 Pa). The live load on the roof was estimated using the Eurocode minimum roof live load for Rome (zone 3) of 600 Pa, or 12.5 psf. The dead load of the rafters was estimated to be 70 plf, or 1,000 N/m. A summary of the loads is contained in Table 1.

The loads from Table 1 were multiplied by the tributary width of each half truss, 6.8 feet (2.04 m). The beam weight, 70 plf (1.0 kNm), was added to the sum for a total load on each upper chord of approximately 290 plf (4.20 kNm).

Table 1: Assumed distributed loads on the upper chords in psf (Pa).

Dead and live loads on the upper chords in psf (Pa)			
Dead loads		Live loads	
Roof tiles	12 (575)	Eurocode min. roof load	12.5 (600)
Sheathing and purlins	7.5 (360)		
Totals	19.5 (935)		12.5 (600)

Estimating the weight of the coffered ceiling was more difficult, since there are no drawings showing its appearance and the only descriptor given in chronicles is that it was gilded. A wooden ceiling can weigh as little as 2 psf (96 Pa), or it may have deeply built up coffers with multiple layers of wood planks weighing many times more. Since historic descriptions of the ceiling state that it was gilded, it was likely relatively elaborate and ornate. A ceiling weight of 10 psf (480 Pa) was estimated, resulting in an approximate 70 plf (1,000 N/m) load on each tie beam of the double truss.

3.2 Determination of material properties

Rondolet did not note the wood species when he observed and drew the trusses of San Paolo FLM. Due to the fire, that information is lost to us. However, ancient authors mention fir and larch as the wood species of choice for long-span applications. Pliny the Elder stated, "Fir and larch are strong weight-carriers, even when placed horizontally…" [10]. Larch is also suggested as the wood species of choice because in imperial times long specimens of substantial scantling were available. Pliny the Elder noted, "What is believed to have been the largest tree ever seen at Rome down to the present time was one that Tiberius Caesar caused to be exhibited as a marvel on the deck of the Naval Sham Fight before mentioned; it had been brought to Rome with the rest of the timber used, and it lasted till the amphitheater of the emperor Nero. It was a log of larchwood, 120 feet long and of a uniform thickness of two feet, from which could be inferred the almost incredible height of the rest of the tree by calculating its length to the top. Within our own memory there was also an equally marvellous tree left by Marcus Agrippa in the porticos of the Voting-booths, left over from the timber used for the ballot office; this was twenty feet shorter than the one previously mentioned, and 18 inches in thickness" [10]. Based on the use by ancient Romans, it is concluded that larch is the most likely wood species used by the 4th century builders in Rome.

The National Design Standard [11] groups wood species of similar properties. While the stresses for European Douglas Fir/Larch are listed for dimensional lumber 2–4 inches thick, there is no listing for European Douglas Fir/Larch for timbers of larger scantling. Instead, the similar North American Douglas Fir/Larch category was used in this analysis to determine the allowable bending stresses. However, it is noted that not only is there variation in properties between North American Douglas Fir/Larch and Douglas Fir from France and Germany (DF-FG), there is an even greater difference between the DF-FG and the Douglas Fir/Larch from the Czech Republic and Bavaria (DF/L-CB). For example, comparing the values of the No. 2 grading standard, there is an 8% drop in the reference design value of the Douglas Fir from France and Germany (DF-FG) relative to the North American category (DF/L-NA). On the other hand, when sourcing the wood species from the Czech and Bavarian forests (DF/L-CB), there is a 50% higher reference design value to the North American species (DF/L-NA). While 8% is a relatively small value when considering the fact that most allowable stress safety factors are about 40%, a 50% difference is extremely significant.

Table 2: A comparison of reference design values in pounds per square inch for selected wood species from Table 4A, Reference Design Values for Visually-Graded Dimension Lumber (2–4” thick) and Table 4F, Reference Design Values for Non-North American Visually-Graded Dimension Lumber (2–4” thick). *(Source: NDS Supplement.)*

Reference design values from the 2018 NDS Supplement Lumber 2–4 inches thick			
Standard	N. American Douglas Fir/Larch (DF/L-NA)	Douglas Fir, France, Germany (DF-FG)	Douglas Fir/Larch, Czech Rep. and Bavaria (DF/L-CB)
Select structural	1500	1500	1900
No. 1	1200	975	1400
No. 2	900	825	1350

While we have some evidence that the wood used for the trusses of San Paolo FLM was a Douglas Fir or Larch species, there is little possibility that we can identify the source for the lumber. Therefore, when results from the structural analysis are considered, the variation in potential wood sources and their respective strengths must be kept in mind.

No mention was made by Rondolet of the quality of the wood used in the trusses of San Paolo FLM. Visual grading standards currently used to determine material properties include factors such as knot size, knot spacing, inclination of grain, wane, checks, and other physical properties of timbers. Given the combination of length and scantling, it is probable that wane was present on many of the timbers.

In addition, some disruption of timber supplies was likely to have occurred in the 4th century. Constantine abandoned Rome as his capital, shifting the primary capital to the former city of Byzantium. While we have no records on the disposition of imperial forests and timber sources during these years of change, it is unlikely that 4th century Rome could match both the quality and quantity of timbers produced during the imperial era. Accordingly, the No. 2 grade for Douglas Fir/Larch is concluded to most likely match the quality of the 4th century timbers used in San Paolo FLM.

3.3 Accuracy

The use of historic data to perform a structural analysis for a no-longer-extant structure poses unique challenges. One uses data collected by others, relying on their attention, precision, and thoroughness. Mainstone’s invective against the application of structural analysis to buildings which are no longer extant [12] makes several points that are of value. The author agrees with Mainstone that engineering analysis alone is of little value, and that engineering analysis should always be understood within the historic context that considers the materials, techniques, and understanding of the time. Similarly, structural analyses are problematic when performed by individuals without sufficient experience to form a basis for judgement and understanding. However, Mainstone’s general criticism of assumptions is not accepted by the author. Rather, what is important is to understand the maximum and minimum values associated with the assumptions, and frame one’s conclusions within the context of those limits.

Mainstone also declares that modern calculations are not of value in “entering the mind of the designer centuries ago…” Such a statement ignores the development of modern engineering practice. Just as in ancient times, acceptable engineering practice is defined by the avoidance of failure. Our modern codes are based in part on structures that have survived and remained serviceable in contrast to those which have collapsed. While numeric theory and extensive testing permit us to have more accurate data regarding material strengths and provide more consistent factors of safety in our designs, we must understand that historic builders went through the same process of observing successes and failures and developing a set of rules or standards to increase their probability of success. Roman builders of the 4th century had the benefit of nearly a millennium of experience throughout the empire, and previous building masters would have developed rules of thumb, proportioning standards, and other design aids to direct their apprentices. While modern codes are far more sophisticated and accurate, this does not invalidate the usefulness of modern codes in evaluating pre-modern structures. Indeed, modern codes provide a framework within which historic structures can be better understood.

In the case of San Paolo FLM, the plan dimensions and spacings remain in the rebuilt church, so there is strong confidence in those parameters. Rondolet's measurements cannot be checked, but it is a reasonable assumption that a building professional would be able to reliably record typical or average scantlings for timbers. Likewise, environmental loads will be similar to those experienced by buildings in the 4th century.

Some variation is expected in the loads between modern and antique roofing and finish systems. Clay roofing tiles may vary somewhat in weight, but it is a technology with a long use and typical roofing tiles used currently vary little from those of 4th century Rome. It is far more difficult to determine the loads from the gilded ceiling. However, since the ceiling is supported by the kingpost, variation in the ceiling weight will cause variation only in the axial load in the upper chords. It will have no effect on the magnitude of the bending stresses in the upper chords.

By far the largest potential variation in the interpretation of the results is the quality of the timbers and their source(s). It is known that old-growth timbers have a tighter grain and greater resistance to abrasion. However, the more closely-spaced growth rings resulting from slowly growing trees do not necessarily mean greater strength in compression and bending. Modern testing has been conducted on samples with a wide variation of wood quality. Higher quality samples will match the properties of old-growth timbers, and little variation is expected if the appropriate visual grading standard is selected. The challenge is selecting the appropriate grading standard.

As was noted in the previous discussion on the selection of wood species, the sourcing of Douglas Fir/Larch wood can result in 50% differences in reference design values. Even greater variation is present when comparing a No. 2 visually graded timber relative to a Select Structural visually graded timber. These potential differences must be kept in mind when interpreting the analysis results.

3.4 Analysis results

The horizontal and vertical forces at the truss supports were initially found by considering the system without the collar strut. Moments were calculated at the toe of the upper chords, solving for the horizontal force at the peak of the truss. The vertical force at the toe of the upper chord was calculated by summing the dead and live loads on the rafters.

The moment in the upper chords at the collar strut support was calculated by using the component of force normal to the axis of the upper chord and solving for the moment at the support of the collar beam through moment distribution. The distribution factors were calculated from the inverse ratio of their lengths, as both sections have the same physical

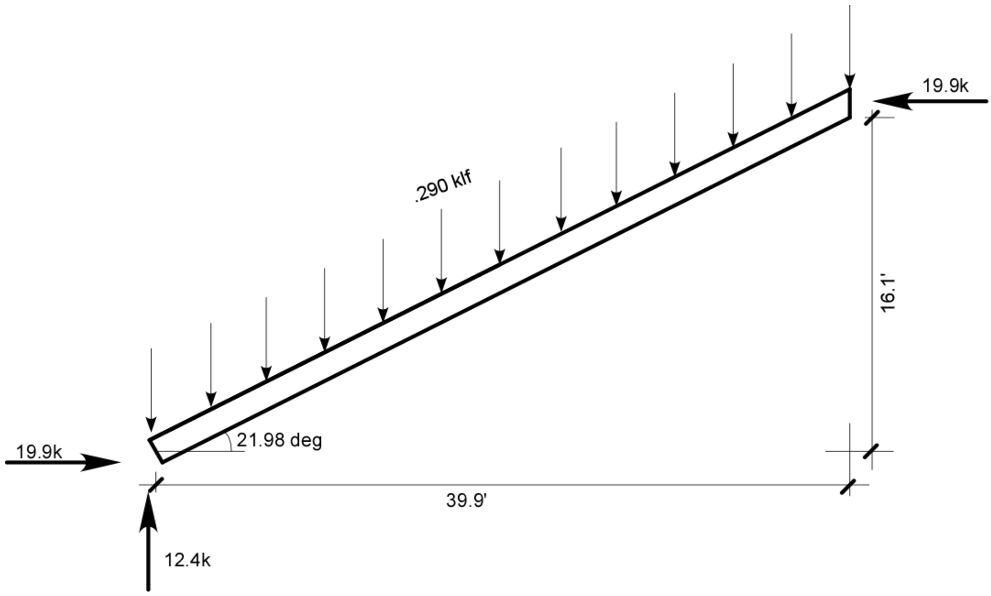

Figure 4: A diagram showing the analysis of the horizontal and vertical forces at the truss supports. Forces are shown in kips (1,000 pounds) or kips per lineal foot.

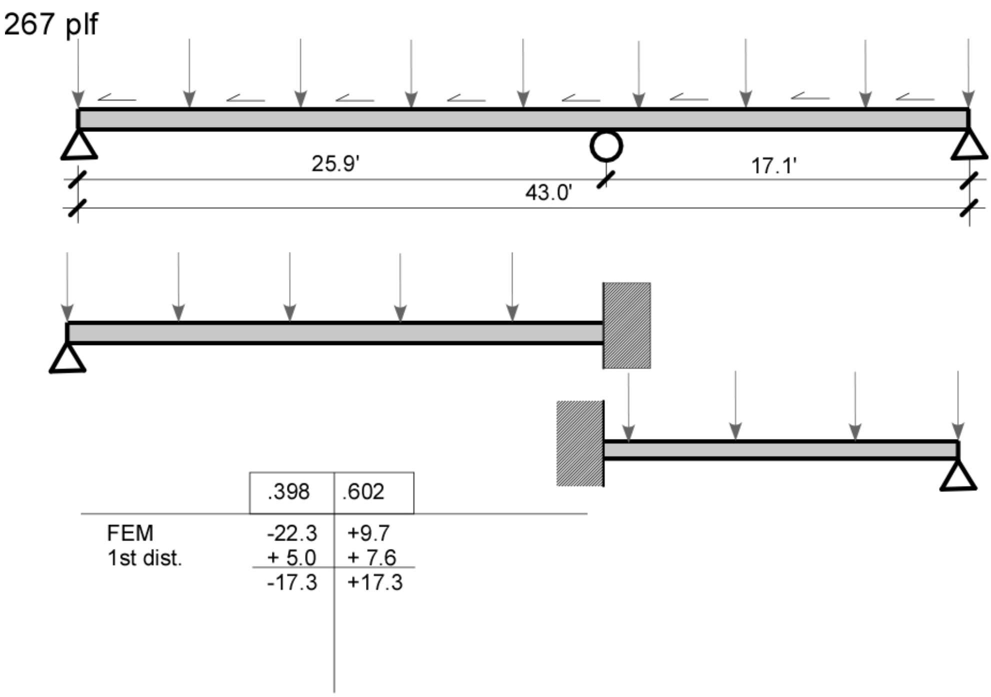

Figure 5: A diagram showing the moment distribution calculation of the moment in the upper chords at the point of intersection with the collar strut.

scantlings and both sections are pin-ended away from the support. Fixed-end moments were calculated based on a fixed-pinned beam. Because both sections of the beam are pinned away from the joint, there is no carry-over to add to the accumulated moments. Therefore, the calculation converges on the solution after only a single iteration. The moment was calculated to be 17.3 kip ft (23.4 kN m).

Since the upper chords have a section modulus of 666 in^3 (10,900 cm^3), this results in a bending stress in the upper chords of the trusses of 380 psi (2,600 kPa). The axial force in the upper chords from the tie beam restraint and the axial force resulting from the kingpost load results in total axial force in the upper chords of approximately 30 kips (130 kN). Dividing by the area of the upper chord results in an axial stress of 120 psi (830 kPa).

The capacity of the upper chords was determined by solving the interaction equation involving both axial stresses and bending stresses:

$$(f_a/F_a) + (f_b/F_b) \leq 1.0.$$

Inserting the calculated axial and bending stresses and allowable stresses given in the NDS for Doug Fir/Larch wood No. 2 visual grade into the interaction equation gives the following result:

$$(120 \text{ psi}/600 \text{ psi}) + (380 \text{ psi}/875 \text{ psi}) \approx 0.60.$$

The interaction equation shows that, based on the above assumptions, the trusses are only loaded up to approximately 60% of their capacity under modern allowable stress provisions. Even if lower quality timbers were used, the calculated levels of stress would be well within the capacity of the truss members. This explains why the trusses survived from the 4th to the 18th century. Even if partly compromised by fungus or insects, there was substantial excess capacity in the trusses. Likewise, unusual wind events or a rare snow fall would not push the trusses past their maximum capacity.

The role of the collar strut is clear from the analysis. If the simple triangular form of the two inclined upper chords, tie beam, and kingpost are considered without the collar strut, the upper chords would be subjected to a bending stress of about 1,100 psi (7,600 kPa) with full dead and live loads due to gravity. This is a high level of stress for most wood species, and for the assumed Doug Fir/Larch No. 2 species would result in a combined interaction equation result of 1.46, or a 46% overstress based on modern codes. The Roman innovation of inserting a collar strut with two inclined props made possible the long span trusses which lasted many hundreds of years.

It is noted that the kingpost does not increase the capacity of the trusses. Instead, its function is the control the deflection in the tie beam. If there were no kingpost to support the tie beam at its mid-span, the dead weight of the tie beam alone would result in a deflection of 5 inches (13 cm), with potentially higher deflections due to the addition of a coffered ceiling. This also explains why the beam is such a deep member. Such a large scantling is not required to handle the tensile force generated by the two upper chords. Under full gravity loads, the force in the tie beam is approximately 28 kips (120 kN). However, because of the scantling of the tie beam, roughly 1–1/2 by 2 Roman feet, the actual tensile stress is about 90 psi (620 kPa), only 20% of its capacity. The use of the kingpost as a hanger and the depth of the tie beam likely were chosen to control the downward bowing of the ceiling.

4 CONCLUSIONS

Analysis suggests that the trusses of San Paolo FLM had significant excess capacity, and would have performed well with timbers of relatively poor quality. Such a construction suggests that the design of the trusses was developed over the course of centuries, with successive building masters observing successful structures and passing that knowledge on to apprentices.

The scantling sizes, based on modules of Roman feet, suggest that the trusses may have been adapted from a standard Roman truss design using standard-sized elements. The Roman propensity for standardization is well established, as Romans created standard cart sizes and used standardized column dimensions in quarries and stone yards [13]. Pliny the Elder's citation of unusually long beams gives their scantlings as 18 and 24 inches, modules of Roman feet. Asilis has noted that Imperial Roman basilicas tend to have wider intercolumnations between nave columns than those of Early Christian basilicas [14]. The intercolumnation of the nave columns is related to the spacing of the trusses. This presents the possibility that Early Christian builders learned from existing Imperial Roman truss designs, but elected to reduce the spacing of the trusses to compensate for greater variation in timber quality.

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