USE OF PROPORTIONS AS A STRUCTURAL DESIGN TOOL IN EARLY CHRISTIAN AND EARLY MEDIEVAL CHURCHES

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by
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This study explores whether early builders, who did not have sophisticated structural analysis tools available to them, based their design and construction methods on a proportional system, i.e., intentional geometrical relationships between building elements. Where the use of proportional systems has been observed, such systems can help define the architecture of a particular period.

The city of Rome contains early Christian and early Medieval churches, buildings used as houses of worship in the early centuries of the Christian religion (0-1200 CE). During this time period, there were really no established rules for structural design, Vitruvius being the only written source for architectural design. Many of the early Christian churches bear the stamp of improvised architecture, in the randomness of the layout, and in the use of spolia, material ransacked from Roman monuments.

Primarily based on domestic Roman architecture, but in part due to the builders' limited understanding of the classical Roman orders, early Christian churches represent early experiments in the adaptation of the basilical form to the Christian liturgy. Their empirical approach suggests that a posteriori, builders followed certain guidelines based on geometrical proportions to achieve a stable construction. The aim of this research is to explore the spatial and proportional relationships between structural elements in Imperial Roman basilicas, early Christian churches, and early Medieval churches in Rome.

This study tests the idea of resemblance in proportionality from one church to another of the intercolumniation ratio, i.e. a ratio of intercolumniation to column diameter, in the colonnade dividing the nave from the aisles. Site measurements, existing scale drawings, and written descriptions have been used to gather data twenty four Christian churches in Rome and three basilicas, one Republican, and two Imperial, none of which have been significantly modified or
have measurements that are available to us. A linear trend line is used to establish the geometric relationships between intercolumniation and column diameter for three types of architectural elements used in these churches: arcades, architraves, and flat arches. The results are used to identify and quantify any patterns or guidelines that might have existed to allow early Christian Roman builders to construct successful and complex buildings using simple tools and resources.

Arcades found to be used the most for intercolumniation ratios of approximately 4, architraves for smaller ratios close to 2.6, and relieving arches, as an intermediate solution, for ratios close to 3. Vitruvius’ favored intercolumniation ratio for entablatures is 2.25, which is slightly lower than those observed in this study. Also there appears to be a consistency through the construction periods. Ratios persist from the observed civil Imperial basilicas through the later churches of the same system, although the civil basilicas are designed in majestic scales. Relieving arches are used in porticoes added in later centuries, with higher intercolumniation ratios, but carrying less loading. Finally, even when a guideline is not as apparent, it is evident that some buildings follow their own logic. Some cases suggest that builders, while following a rule, were testing it and experimenting with the limits of that rule.
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Chapter 1

Introduction

Since ancient times, architects have applied theories of proportions with the enduring desire to accomplish order, symmetry, beauty, and manipulation of human senses, within the space or on the exterior of a building. Proportions are universally given as one of the major elements in architectural design. Euclid defines a ratio as the quantitative comparison of two similar objects, and proportion, as the equality of the ratios, as a relationship between two elements (Joyce, 1996); the most logical idea is that this relationship was used for the basis of design rules. As a matter of fact, due to the absence of scaled drawings and measuring instruments, the application of proportions, rather than an absolute measure, could make the process of construction easier and provide accuracy.

Authors such as the ancient Roman architect Vitruvius and the Italian Renaissance architect Palladio establish a guide for building design, often referring to proportions as the underlying principle. In his Ten Books on Architecture, Vitruvius synthesizes what he believes is the key to architectural activity. He describes the human figure as the principal source of proportion and provides rules for the design of various objects including temple fronts, lifting machines, water works, and weapons, based on the idea of designing by proportion. In his text, there is no extended argument that presents any reason these particular rules are the ones that should be used or why they have the special status given by the author. However, they appear to be grounded in experience and intended to create objects that fulfill a desired function.

A specific example is Vitruvius’ anthropomorphic association of the classical orders. He suggests the Doric order is analogous to the male figure, based on the idea that a man’s height is
six times the dimension of his foot. This same ratio applies to the height of the Doric column to its diameter. In contrast, the Ionic order imitates a woman’s slenderness, the column’s diameter being one eighth the height, taken from the relationship between a woman’s footprints and her height. The Corinthian is related to a maiden, as it is more slender with a column height ten times the thickness.

Another example of proportion used as a building rule can be found in medieval construction, the use of quadrature by masons described by the German architect Roriczer as “to take the elevation from a ground plan” (Frankl, 1945). This technique was used to translate sketches without scale into an absolute size. In his booklet, Roriczer explains how to make a pinnacle using orthogonal projection to draw the plan, and the elevation in geometrical relation from a square as modular unit. Again, proportion was used as a practical device to compensate for the absence of a standard unit of measurement.

Clearly, the only structural system Ancient Roman and Medieval builders could rely on was a variety of rules that originated from empirical knowledge, achieved only by using built works as a laboratory for further analysis. Their empirical approach suggested that builders followed guidelines based on geometrical proportions to achieve a construction that followed previous work and therefore offered some assurance of safety.

In this thesis, the author intends to demonstrate that proportions were used by builders for structural reasons, not solely for an aesthetic purpose. In particular, the aim is to explore the spatial relationship between specific structural elements in Roman early Christianity and early Middle Ages (0-1300 CE). In addition, the author will further explore the application of a structural design system based on a simple rule of ratios.

The city of Rome contains a significant population of early Christian and early medieval churches, buildings used as houses of worship in the early centuries of the Christian religion. Although the designation ‘early Christian’ generally refers to the period dating from 0-1000 CE,
the construction of early Christian churches started in the IV century after the legalization of Christianity as a religion by Constantine. Many of these buildings date from the time of general decline in Roman civilization (early V century) or from after the occupation of Rome by other races, i.e. Germanic migration and invasions (until VI century). During this time period there were no established conventions for building construction and many of the early Christian and early medieval buildings are characterized both by the apparent randomness of the layout and by the use of ‘spolia’, material ransacked from Roman monuments. Largely based on domestic Roman architecture and in part based on the builders’ limited understanding of the classical Roman orders, these buildings represent experiments of the use of intercolumniation ratios to column diameter to make structural decisions.

Unconsciously or consciously, these builders may have imitated Vitruvius’ statement in his Third book. He classifies temples according to the ratios of intercolumnar spacing and the column diameter. Vitruvius uses the term ‘araeostyle’ to describe columns that stand further apart than is desirable and ‘eustyle’ to note when their placement is right. He states that the strength of the architrave above depends on the spacing of the column and further that the ‘diastyle’ and ‘araeostyle’ are not appropriate for stone architraves.

1.1 Thesis Objective

The main idea the author intends to demonstrate in this thesis is that early builders based their structural design process on a commonly agreed upon set of guidelines based on proportions.

We are specifically investigating whether the intercolumniation as a ratio of column diameter is a significant determinant of the type of structure employed in Churches of Rome from 0 to 1300 CE. This time spans three important construction periods: Imperial Rome, early
Christian, and early medieval. The consistent use of the rules may help to understand how ideas about construction from one age appear in the succeeding age, whether by observation, oral transmission of ideas, or by the way in which the rules reflect necessities of building.

1.2 Thesis Scope

This thesis focuses on twenty-four churches and three civil basilicas constructed from I century to XIII century, for which the original structure is still apparent and measured scale drawings of the original building are available. The purpose of this study has led to the selection of churches that consist of single or double aisles separated from the nave by a colonnade. We obtain measurements extracted from scale drawings and/or written descriptions from different sources, mainly by the architectural historian Richard Krautheimer. Also, to the greatest possible extent, direct measurements were taken with a laser measurement device to obtain closer accuracy of obtained dimensions, as well as dimensions not found in the sources mentioned. Consequently, we have collected, documented, and tabulated the dimensions of the interior elements, drawings and photographs of these churches in a database. With the intention of analyzing the geometry of each building we determined ratios of all dimensions taken. With the data organized, it is possible to compare the results between the structural support types. Accordingly, we created and examined a scatter plot of the intercolumniation at the vertical axis and column diameter at the horizontal axis, to obtain a visual representation of the dimensions. We further investigated the trend line in an attempt to infer a stable ratio. Also we performed stress calculations on selected architraves to verify certain hypotheses about the system adopted for various intercolumniation ratios.
1.3 Literature Review

The following literature review describes the concepts of ancient and medieval building design. This review contains a brief summary of engineering studies of empirical structural design, masonry arch analysis, and stone strength. Most of the sources on these topics consider the construction and analysis theories of rules based on empirical design, not directly the early Christian or early medieval Churches. However, the findings of these sources can be applied to these periods. Also described in this section is a previous study on proportions of Imperial Roman basilicas and early Christian churches.

1.3.1 Proportions in architecture

Vitruvius’ Third Book provides a definition for proportion: “consists in taking a fixed module, in each case, both for the parts of a building and for the whole, by which the method of symmetry is put into practice. For without symmetry or proportion no temple can have a regular plan; that is, it must have exact proportion worked out after the fashion of the members of a finely-shaped human body” (Vitruvius, 1998)

Vitruvius discusses five column elevations on temples based on proportion: ‘pycnostyle’, when the dimension between columns is one and a half the dimension of the column diameter; ‘systyle’ when it is double; ‘diastyle’ when triple; ‘araceostyle’ when it is more than triple; and ‘eustyle’ when the intercolumnar spacing is two and a quarter of the column diameter (wider at the central intercolumniation). He elaborates on the ‘araceostyle’, stating that if the intercolumniation is greater than they should be, and that the entablature must be wood rather than stone or marble. In regard to ‘eustyle’, he acknowledges that it has “proportions set out for convenience, beauty and strength” (Vitruvius, 1931).
Based on Vitruvius’ written sources and those of Villard de Honnecourt, Heyman affirms that builders of the classical period through the Middle Ages used rules of proportion to design structures. He states that their geometrical approach allowed them to have a correct understanding of the design and behavior of masonry (Heyman, 1995).

Heyman argues that even though ancient and medieval builders are mostly successful, the limit state of the structure was never considered until Galileo in 1638, who exemplified his ideas on a cantilever beam. Galileo was looking for the magnitude of the breaking load while pursuing to find the strength of the transversely load as a function of its depth and length. In this investigation he found that the geometrical rules of proportions did not apply; if the dimensions of the beam were doubled, the strength was increased by significantly more than double (Heyman, 1995).

1.3.2 Engineering analysis of masonry buildings

Masonry arches in historic buildings have been the object of study for several engineers. Authors such as Heyman and Ochsendorf have developed methods to understand the behavior of masonry arches.

The anagram of Robert Hooke has been discussed by many authors due to his statement “as hangs the flexible line, so but inverted will stand the rigid arch” (Heyman, 1995). In his book, Heyman argues that in order to determine the thrust line of the arch, the properties of the material are of importance and must be considered. Equally important is the geometrical boundary conditions. He states that the equilibrium equations are not enough to obtain the thrust line and it is not possible to do it solely by Hooke’s hanging chain.

Ochsendorf analyzes the phenomenon of a circular arch of constant thickness over leaning buttresses. Through rigid-plastic analysis, he shows that when the supports spread a
certain distance apart the vertical load is constant, opposite to the horizontal force which increases. At the same time, this modifies the geometry of the arch, causing the hinge location to move closer to the keystone further increasing the thrust before a collapse. The theoretical maximum distance that the supports separate is almost linearly proportional to the thickness ratio of the arch. Generally, previous to collapse, the arches support up to five times the initial minimum thrust, although this could be less due to imperfect corners of the voussoirs, which are not exactly hinges as assumed during the analysis. Additionally, the lack of precision in the construction of voussoirs can also alter the geometry, triggering a sudden change of the hinges location, while a failure of one of the buttresses could cause a collapse, since is possible with only four hinges (Ochsendorf, 2006).

1.3.3 Proportions in Imperial Roman basilicas

In his fifth book, Vitruvius explains the rules to establish the dimensions of the basilicas in the forum. He states that the width must be equal or less than half of the length, but never smaller than a third. The width of the aisles should be a third of the central nave width, and the height of the columns should be equal to the aisle width. For the design of the architrave, friezes and cornices in a basilica, he refers to his third book where he explains the “right” intercolumniation spacing for the species of temples, which he calls ‘eustyle’. This consists in an ideal intercolumniation spacing of 2.25 times the diameter of the column, and the height 9.5 times the shaft diameter (Howe, Dewar, & Rowland, 1999).

Recent studies on the proportions of early Roman basilicas from II century BC until II century AD have been done by Walthew. His purpose is to advance the hypothesis that the column diameter played a role in the layouts of the Roman basilicas that the interaxial dimension was the base for the whole design, representing predetermined modules. “It is, of course, possible
that both interaxial measurements and lower column diameters operated in conjunction as part of a single modular system” (Walthew, 2002). Earlier, he started with the idea of searching for a pattern and module that could suggest a standard unit of measurement (Walthew, 1995). According to Walthew, the nave colonnade was the first part designed, meaning that it is the most important to determine the length, width, and height of the building.

To accomplish this analysis, Walthew gathers the measurements of thirteen Roman basilicas, mainly in Italy and Spain. This material is presented by the author with written description, scaled drawing of the layouts, tables of dimensions of each Imperial basilica, comparative tables of certain relations between of them, and last a table comparing the proportions. He compares: length to width, nave length to nave width, total length to nave length, and nave width to aisle width. His conclusions are that the dimensions of length plus width of nave equal the total length, the aisles are half dimension of the nave, and at last the sums of the aedes equal the axial length of the nave (Walthew, 2002).

In a previous article, he mentions briefly that the great early Christian basilicas (Santa Maria Maggiore, San Paolo fuori le mura, and San Clemente) are at the end of the long line tradition of the civil Roman buildings (Walthew, 1995).

1.3.4 Design in early Christian architecture

The idea of a consistent design system in the early Christian churches, the notion that there is a concordance in dimensions of spoliated elements from different churches and its resemblance with imperial Roman basilicas is introduced by Barresi et al.

These authors analyze how the spoliated columns of the naves are used as the base to define the proportions and measurements of the churches. They analyzed the relationship between
various dimensions of the column, such as the diameter, the height of the shaft, the intercolumniation, and the total height of the columns, including capital and base.

The study is based on churches dated from the IV and V centuries: San Giovanni in Laterano, San Pietro in Vaticano, San Paolo fuori le mura, Santa Maria Maggiore, San Sisto Vecchio, San Vitale, Santi Giovanni e Paolo, Santa Sabina, San Pietro in Vincoli and San Clemente.

The development of their work includes the creation of a database (unfortunately unpublished), tables outlining the dimensions of each church, a table of comparison, and a scale elevation of the columns. Also included is a description of the features of each church, as well as all the dimensions related to the colonnades.

The findings are summarized by stating that a ratio of total height to the shaft of 1.2 is common among most churches. This supports the idea that the rules from Roman construction apply similarly to the adaptation of spolia elements on churches built in IV and V centuries. Additionally, the similarities between San Vitale, San Sisto Vecchio and Santi Giovanni e Paolo, with equal intercolumniation and very close proportions in plan and elevation, suggesting that they followed a standard pattern (Barresi, Pensabene, & Trucchi, 2000).

Unfortunately, this analysis is limited to early Christian churches through two centuries. If this study could be extended to a longer time period increasing the number of cases studied would yield better results and possibly verify the continuity in the design process of churches in the period.
1.3.5 Spolia in early Christian architecture

The term “spolia” is used to designate architectural elements or parts of a sculpture taken from one site and reused in another location. In Latin it refers to the plural of ‘spolium’, spoils of war (Hansen, 2015, p. 9).

It is important to note that Roman churches built in the first centuries of the Common Era possess reused elements, evident in the inconsistency of the features within the same assembly. In the interior of these churches among a series of repeated elements, there is incongruity of colors, materials, and style. This condition is mainly seen in the columns, capitals, and moldings.

According to Hansen, recycling has always been used. However, in this particular period the reuse of materials is not only exposed, but prominent and intentional part of design. She states that this is a creative and unconventional combination of architectural elements from ancient buildings reused in new contexts, a “juxtaposition of contrasting architectural elements” (Hansen, 2015, p. 14).

Hansen believes that the recycling of architectural elements in the first years is an effect of the economic crisis and the shortfall in manufacturing and productivity induced by this depression (Hansen, 2015, p. 26). To this, Kinney agrees. She explains that the columns once represented the empire’s technological and reliable infrastructure, but during the economic decline, Roman builders where forced to seize materials and turn to stockpiles. She insists that the use of spolia begun in the time of Constantine and continued to the Middle Ages and the Carolingian period, and died with the Renaissance (Kinney, 2001, pp. 139,143).

In Hansen’s opinion, the use of spolia had a conceptual significance for designer of the churches. She sees it as a metaphor for Christian doctrines, for instance the change of material and style within the rows of column, paired with the other side, could represent the path to salvation towards the altar. Other notions include the color attribution to divinity and the use of
various styles to mark the separation of clergy and laymen (Hansen, 2015). On the other hand, Kinney finds the purpose ambiguous. She discusses two alternative ideas, that it was mere reaction of necessity or a desired decision (Kinney, 2001, p. 145).

Looking at the older Roman basilicas, where the order, symmetry, uniformity, repetition, and congruence are distinguished, the reuse of architectural elements on the churches was a radical idea. Variation in materials and styles represented a break from the classical, predictable uniformity and its roots in certain rules of proportion. Another antagonistic idea is the use of arcades over columns. In classic Rome, the arcade is used for an opening on a wall and underpinned by piers, rather than columns (Hansen, 2015).

It is obvious, that one of the main characteristic of early Christian and early medieval churches in Rome was in fact the use of spolia. Ignoring the reasons or circumstances under which the builders ransacked and reused architectural elements, the starting point appears to be the availability of defined elements. Neither Hansen nor Kinney explored the configuration of the elements or the thoughts that builders considered in order to combine the elements. Decisions such as spacing between columns, total length, and nave width according to the elements found have not been examined by them.

1.3.6 Krautheimer drawings

The German architectural historian Richard Krautheimer spent a great part of his career studying early Christian, Carolingian, Medieval, Byzantine and Roman architecture.

In his collection, Corpus Basilicarum Christianarum Romae, he documents a detailed survey on the early Christian basilicas from IV century to the IX century. In it, he makes an extended description of each church, reproduces drawings, compares features with each other and argues some conjectural restorations.
For this study, the majority of measurements are taken from Krautheimer’s drawings or written references. As such, this work relies on his authority to present accurate dimensions. His extensive discussion of early Christian architecture, the comprehensive description of the Roman architecture and history, and his thorough studies of each church has been essential to develop this study.

Krautheimer sees the early Christian architecture as the “final expression of the architectural expression of the architectural concepts which were dominant in Western and Eastern Mediterranean areas of the Late Roman World” (Krautheimer, 1965).
Chapter 2

Early Christian and early Medieval architecture

To comprehend the context of the churches, it is important to describe the origin and early development of Christianity and the political-economic conditions of the time, together with the later transition to Carolingian and to Early Medieval.

2.1 Background

The beginning of the Christian religion is marked by the domination of the Roman Empire, the most extensive political and social structure in Western civilization. This Empire began in 31 BCE with Augustus Caesar as the first emperor of Rome, and ended, in the west, when the last Roman emperor, Romulus Augustulus was deposed by the Germanic Kingdom (476 AD). In the east, it continued as the Byzantine Empire until the death of Constantine XI and the fall of Constantinople to the Ottoman Turks in 1453 AD (Mark, 2011).

The central figure of Christianity is Jesus, a Jewish leader considered a prophet and by many, the Messiah—the Son of God. During his lifetime, he acted as a charismatic leader, teaching with direct sermons and performing miracles. He was executed by the Roman authorities, who believed him as a threat to their power.

After Jesus’ death and, according to Christian doctrine, his resurrection, his closest disciples dispersed from Jerusalem and started the missionary activity of kerygma -preaching- the word of Jesus to cities throughout the Hellenistic world (Krautheimer, 1965).

The first manifestations of Christianity as a religion consisted in small congregations that held regular stealthy gatherings in private houses. Commonly, the meeting would be held in the
dining room of ordinary lower and middle class houses, as the main purpose of the service was to share a meal to commemorate the Last Supper of Jesus and his disciples. The elder, host, and a guest speaker would sit in a couch opposite to the entrance followed by a center table and two more couches for the crowd. In Rome, where tenement houses with horizontal apartments were the norm, not necessarily including a dining-room, any large chamber may have served for these gatherings (Krautheimer, 1965).

As the Christian community grew, houses that were rented, purchased or donated to the Church served as centers of worship, baptism, instruction, funeral banquets, and living spaces for the clergy. These houses were identified as *domus ecclesiae* or in Roman vocabulary by the name of the original holder of the title to the building preceded by the word *titulus* (Krautheimer, 1980). At this point, between 150 and 250 AD, the meetings evolved into a more complex religious rite. Hence replacing the dining room with the assembly, a larger and more accessible space, which was divided by a wood railing into the altar and the general area the former corresponded exclusively to the clergy. In addition, three other rooms were needed: a *vestibulum*, for catechumen and members that could hear but not see the second part of the meeting; the *consignatorium* for confirmation, and the Baptistry for the Baptism.

The early Christian believers were persecuted by the state and local authorities until the year 313 AD, when Constantine the Great, the first Christian emperor, legalized the Christian religion through a series of laws such as the Edict of Milan. This event radically changed the position of Christianity, as the Church gained major political and economic force. By this time, one third of Rome’s population followed this religion. In his insistence on turning the Roman Empire into a Christian Empire, Constantine donated large landholdings to the Christian Church, later used for the construction of churches.

By the IV century, the Christian community had increased significantly and the Mass was further elaborated upon, gathering hundreds and thousands of members at once, which required
large and divided church buildings. In search of an architecture that could adapt, combining religious connotation with the criteria of an official building, the basilica was selected as the ideal type, i.e. a civil building typology originally used for meetings, markets and courts of law (Krautheimer, 1965). This was well-suited for use as a meeting house from a practical point of view and well adapted to Christian liturgy.

![Figure 2-1. Map of Rome, with churches and secular buildings, ca. 500 (Krautheimer, 1980)](image)

### 2.2 The basilica type

Although there are several varieties of the basilica form, the civil building typology can be identified as the common plan for Christian churches. In the adaptation to Christian liturgy, the basilica layout is mostly of rectangular morphology. In its simplest form it is a hall. Often, it
consists of a nave with one or more aisles on each side. The division between nave and aisle could accommodate a gallery that consists of an additional arcade above the aisle, and sometimes a clerestory with windows in the upper wall. The entrance is generally in the short side, although originally for civil activities could be located on the short side or on both sides. A rectangular or semi-circular apse, often opposite the entrance, held the seat of the presbyter. The apse could be extended to two or three in number. Open timber roofs or flat ceilings were used (Krautheimer, 1965). An example of the basilica layout is Santa Maria Maggiore (Figure 2-2). It consists of a central nave, two lateral aisles, a narthex, a colonnade with architraves, clerestory with windows, and a transept and a semicircular apse of medieval addition.

Figure 2-2. Santa Maria Maggiore, Rome. Floor Plan (Dehio & von Bezold, 1887)

2.3 Structural Features

For this study, it is of particular interest to investigate the three common types of structural solutions for the support that divides the main nave from the aisles in a general basilical layout. These solutions are divided for the purpose of this study into three configurations:
arcades, relieving arches and architraves, and an explanation is sought for the choice of one configuration over another.

2.3.1 Arcades

Generally, arcades are present in churches as a succession of masonry semi-circular arches without reinforcement.

![Architectural Illustration]

Figure 2-3. Santa Maria in Domnica, North colonnade

2.3.2 Architraves

An architrave is a horizontal member constructed of a single piece of stone without reinforcement. Most of the architraves used are spolia, such as seen in San Lorenzo fuori le mura.
(see Figure 2-4), and come from Imperial Roman monuments, evident in the details that often differ from one to another in the same building.

Figure 2-4. San Lorenzo fuori le mura, East basilica
2.3.3 Relieving Arches

A relieving arch, also called a discharging arch, is an arch built over a lintel or architrave to spread the weight of the overlying material to the supports and to minimize the weight bearing directly on the architrave below. (Chisholm, 1911).

Figure 2-5. San Stefano Rotondo, inner-ring (ca 470)
2.3.4 Intercolumniation

The term intercolumniation defined as the dimension measured from the base of the column shafts in a colonnade surface to surface. In contrast, the pier spacing is the interaxial dimension between columns.

In this study, the intercolumniation ratio is considered to be the dimension of the spacing divided by the diameter of the column, $s/d$ from Figure 2-6, as measured in the colonnade that divides the nave from the aisle.

![Intercolumniation ratio scheme](image)

Figure 2-6. Intercolumniation ratio scheme
Intercolumniation as a term was applied by later writers to describe the writings of Vitruvius concerning the spacing between columns in a row. In his Third book, he classifies temples according to the ratios of intercolumnar spacing and the column diameter, as shown in the Figure 2-7. A further description is available in Section 1.3.1.

Figure 2-7. Species of Temples according to Vitruvius (Howe, Dewar, & Rowland, 1999)
2.3.5 Use of Spolia

A structural system in a building is expected to be uniform so that the elements and materials used are the same for similar elements. For instance, in a modern steel structure building the logical idea is that the designs of all columns are the same size, shape and material. This contributes to the harmony, order, clarity, and economy.

However, in early Christian churches this principle does not hold, as columns within the same church differ in material, style, size, and color. For example, in the East colonnade in San Giorgio in Velabro, Figure 2-8, the four columns closest to the apse are grey granite and of Ionic order, the next two are fluted Corinthian columns of white marble, and the last two are fluted Ionic columns of *pavonazzetto* (Hansen, 2015).

This variety occurs as a result of the recycling of architectural elements in order to build these churches. The phenomenon of using the elements removed from a building or ruin in another location is often referred as spoliation, and the products are called spolia. This term is described in Section 1.3.5.
Generally, the columns across the nave are very similar in size and equal in style and material; it is possible that both come from the same building. This is evident in San Giovanni a Porta Latina (Figure 3-20), where the two columns nearest the apse are fluted Ionic, the next two are also Ionic but of grey granite, and the other two look like grey marble, both of Ionic order. The diameters of each pair are the same dimension or do vary not more than 0.05 m.
2.4 Roman basilicas

“Basilicae” is the name given to the civil buildings in the forum used as meeting halls in the Roman Empire times. This typology was later adapted to the Christian churches, as described above in Section 2.2.

2.4.1 Basilica Aemilia, Julia and Ulpia

Basilica Aemilia was built in 179 BCE, Julia in 54-45 BCE and Ulpia in 106-113 CE. The basilica of Ulpia consisted of an architrave over the interior colonnade, while the other two were arcaded. All of these buildings have been destroyed.

Figure 2-9. Basilica Ulpia (Guadet, 1867)

It is worth mentioning the difference in the layout of these Roman basilicas and the later Roman churches: the colonnade in the Roman basilicas surrounded the entire perimeter, while in the churches, this feature was eliminated to adapt to the Christian liturgy. Similarly, the location of the apse was at the center of the longer side in the Roman basilicas, but it was changed to the shorter side in the Christian structures.
Chapter 3
Description of Churches in Study

3.1 Roman Churches

Considered in this study are twenty-five Roman churches from 0 to 1300 CE, for which the original structure is still apparent or which measured, archaeological, or conjectural drawings of the original building are available. This study considers only aisled churches with a colonnade between the nave and aisles. This criterion excludes some churches that present a different layout, for instance San Silvestro in Capite, although an early Christian church, consists of a one barrel vaulted nave with four arcaded chapels by each side. See Figure 3-1.

![Figure 3-1. San Silvestro in Capite layout (Letarouilly, 1874)](image)

The locations of the churches in this study are shown in an aerial view of Rome in Figure 3-2.
Figure 3-2. Aerial view of churches in study in Rome
3.1.1 San Pietro

San Pietro was built on the site of a Roman necropolis dated to Imperial times in the location of the Circus of Nero (Hansen, 2015). The early Christian basilica was built in the IV century and demolished in the XVI century to be replaced by the present church, which is the current Papal basilica inside the Vatican. The old basilica consisted of a central nave, double aisles, a semi-circular apse, lateral chapels, and an atrium. A trabeated colonnade separated the central nave from the aisles and an arcaded colonnade separated one aisle from the next.

The nave was wide and very high with clerestory walls pierced by windows. The second clerestory had openings above each intercolumniation. The original church contained spolia columns that are part of the balconies of the present church.

Figure 3-3. Old Saint Peter’s (Alfarano, XVI c)
3.1.2 Santa Constanza

Santa Constanza was built in 350 as an imperial mausoleum for Constantine’s daughter. It was constructed in a cylindrical shape, out of unadorned brick. The church consists of a barrel-vaulted ambulatory separated from the central space by an arcaded colonnade with double spolia columns. The central inner-ring rises higher than the ambulatory with a clerestory containing twelve arcaded windows, originally topped by a dome.

The arches in the main and longitudinal axis of the center room are imperceptibly wider and higher than the others (Krautheimer, 1965). Also, the inner-ring seems to represent a transition between the traditional approaches of a horizontal trabeation to arches. While viewed from the side, the pair of columns seems to be carrying an architrave, although the arcade is clear from the front view.

The outer circle wall consists of a very thick brick wall (almost 3 meters) with arcaded niches and brick masonry arcaded chapels and absence of columns. When first built, the mausoleum was encircled by an external colonnade and included a small narthex connected to the old basilica; the latter was originally a large covered cemetery for the martyr Sant’Agnese.

![Figure 3-4. Santa Constanza (OP, 2010)](image-url)
3.1.3 Sant’Agne fuori le mura

Sant’Agnese was erected on the site of a cemetery and a martyr church in the IV century. It has a central nave with two aisles separated by arcades over spolia columns, a gallery and a clerestory. The upper floor gallery, used to view the saint’s tomb, has no direct access from the ground floor; the entrance is at the street level. The church has a semi-circular apse preceded by a triumphal arch. In the VIII century, the church was renovated, hence a number of chapels and side aisles have been added; the open view to the trusses was replaced with a ceiling in 1606. The existing vaults over gallery are from the XIX century. An inside stairway to connect the two floors was added later.

Figure 3-5. Sant’Agnese
3.1.4 San Paolo fuori le mura

San Paolo fuori le mura is a double aisle church built between 314 and 340. It was destroyed by a fire in 1823 and rebuilt from 1825 to 1854, apparently following the old foundations (Krautheimer, Corbett, & Frazer, 1977). Both colonnades are supported above by arcades. A continuous cornice extends above the peak of the nave arches, raising the wall and the windows that are at every intercolumnar span on the clerestory wall. Windows of the same spacing rise above the colonnade separating the two aisles. A triumphal arch divides the nave from the transept and the semicircular apse.

Figure 3-6. San Paolo fuori le mura (Dnalor, 2014)
3.1.5 Santa Balbina

Santa Balbina was built in IV century as a *titulus* (see Section 2.1). The layout consists of one nave with several arcaded chapels on the periphery and semi-circular apse. It has large clerestory windows located above every column spacing.

Figure 3-7. Santa Balbina (Kelley, 2012)
3.1.6 Sant’ Anastasia

Sant’ Anastasia was built in the IV century above a group of Roman houses. Its present appearance is from the reconstruction of the XVII century; it originally had a structure of architraves above. Currently, it has an arcaded colonnade. The spolia columns remain from the early Christian church.

Figure 3-8. Santa Anastasia (Lalupa, 2007)
3.1.7 Santi Giovanni e Paolo

The church of Santi Giovanni e Paolo is a very complicated combination of Roman streets, *insulae*, and a titular church, converted to a more permanent house of worship, and a new church built above between IV century and IX century with a two-phased construction. The columns were converted to piers in XVIII century.

Drawings of the original plan show arcades divided into three parts with intermediate piers. The rhythm of the arcade is repeated in the upper nave walls.

Figure 3-9. Santi Giovanni e Paolo
3.1.8 San Stefano Rotondo

San Stefano Rotondo was built between 468 and 483 over a *mithraeum* but its original function is unknown. The original design consisted of three concentric circles; the outer wall was demolished and filled with masonry during the papacy of Nicholas V (1227-1455). Currently, the building consists of a great cylindrical nave resting on discharging arches over columns with Ionic capitals. The high walls of the nave, originally faced with marble plaques, are located below the twenty-two windows of a clerestory. The central area is encircled by an ambulatory which opens into groups of five and six colonnaded arcades that differ in dimension. Originally, the shape of a cross was superimposed on each of the four arms ending in a large chamber onto the outer circle. The church could be entered through the outer ring leading to the chambers and further to the middle ambulatory, or directly through the ambulatory around the central ring (See Figure 3-10).

Figure 3-10. Reproduced drawing of San Stefano Rotondo (according to Hugo Brandenburg)
By the XII century, the tall drum-shaped wall of the central chamber was dangerously close to collapsing. Three transverse arches were added, supported in the center by two colossal Corinthian columns and in the ends by piers. The wall was strengthened by bricking up fourteen clerestory windows (Hansen, 2015).

Figure 3-11. San Stefano Rotondo (Duryee-Browner, 2012)
3.1.9 Santa Sabina

Santa Sabina was a *titulus* replaced by a church during 422-440. It is a simple three nave early Christian church with an arcaded colonnade, clerestory windows, and semi-circular apse. It has identical partially fluted columns, atypical for the time period, with Corinthian capitals and bases, apparently spolia ted from a II century building (Krautheimer, 1965). The nave is very high, long, and narrow. It has large windows in the clerestory above every intercolumniation, as well as three more in the apse and five in the façade, allowing for an abundant brightness in the nave. In contrast, the aisles are windowless and dark.

Figure 3-12. Santa Sabina (Bonjoch, 2007)
3.1.10 Sant’ Agata dei Goti

Sant’ Agata dei Goti was built in 462 as a martyr church. It is arcaded with clerestory windows and two vaulted lateral aisles. It has window openings in the clerestory wall and a semi-circular apse; the layout of Sant’Agata dei Goti represents a typical early Christian basilica. Krautheimer considers this a Byzantine church based on modules of a byzantine foot (0.308 meters) compared to a Roman foot (0.295 meters), and by the nave proportions with it being wider than twice the aisle width.

Figure 3-13. Sant’ Agata dei Goti (Andronico, Wikimedia Commons, 2015)
3.1.11 Santa Maria in Cosmedin

Santa Maria in Cosmedin is a two aisle church with a slightly irregular nave shape. The left aisle is wider than the other and both aisles become perceptibly narrower towards the altar. The nave is separated from the aisles by a row of three columns and a pier sequentially. It has been renovated multiple times but the original church consisted of a small hall. In VIII century, a colonnade was added, which is thought to have supported architraves at that time period (Krautheimer, 1965). The architraves were replaced by arches in the XII c (Hansen, 2015). Its present appearance is a restoration from the XIX century, by Giovenale, who restored the church to its form in 772-795 (by Pope Hadrian I), removing Baroque ornamentation.

Figure 3-14. Santa Maria in Cosmedin
3.1.12 San Giorgio in Velabro

This church was erected on the remains of an older building. It is a three nave basilica with an irregular and slightly trapezoidal layout. Two rows of spoliated Roman columns form an almost regular arcade that divide the nave from the aisles. The right aisle is wider than the left. The irregularity of this church is not only visible in the measurements, but in the columns as well, differing in material used across the longitudinal axis of the nave, not following the traditional practice of matching paired columns seen in other churches from the same period. Along the nave the columns vary from Ionic order to Corinthian, three diverse materials, and either fluted or smooth shafts.

The current portico, rebuilt in the XIII century, consists of four columns in the front interior bays and pillars in the corner, all with flat arches above. The campanile was added in the XI century with a clear appearance of being attached, interrupted by the façade. On the exterior, salient buttresses are visible over the left aisle.

Figure 3-15. Layout of San Giorgio in Velabro as XIII century. (Sibeaster, 2009)
3.1.13 Santa Maria in Domnica

Santa Maria in Domnica was built in the VII century. This Carolingian church has nine pairs of spoliated Corinthian columns supporting an arcade. In the upper wall, clerestory windows appear in alternating column spaces. The two lateral aisles have groin vaults which are currently reinforced with tie rods. In 820, two apses were added to the church (Krautheimer, 1980). This church is famous for having a navicella, i.e. a Renaissance sculpture of a small boat, facing the building.
3.1.14 San Saba

San Saba was originally the oratory of a monastery in the VII century. It was converted to a basilica around XII century and its current appearance is similar to this time period. It consists of an arcaded spolia colonnade. The nave is quite high in relation to the width.

Figure 3-17. San Saba (Pincio, 2009)
3.1.15 San Clemente

The present church was built in 1108-1123, although underneath the present church remain archeological ruins from the early Christian church built in the IV century, which are accessible since the XIX century excavation (Barclay Lloyd, 1989).

Barcaly, Junyent and Krautheimer have written about the relationship between the medieval upper church and its early Christian predecessor. They state that both have almost the same length, the south aisle wall remains below, and that the south columns are built on top of the IV century ones. The north wall is on top of the north aisle colonnade and a new foundation built on the earlier nave supports the recent north aisle colonnade (Barclay Lloyd, 1989).

The upper church (most recent) has a nave with two aisles, which differ in width. A colonnade with arches and a pillar in the center, divide the nave from aisles. It follows a similar configuration as the early Christian.

Figure 3-18. Drawing of San Clemente (Consentino, 1989). The top is representing the level of the church of XII c, at center the basilica of IV c and at bottom the building of I century.
3.1.16 Santi Nereo e Achilleo

The original church was built in late IV century on top of a cemetery. It collapsed in the IX century and was rebuilt in the 1870’s from the ruins found (Hansen, 2015). The current building is partially underground, a three aisles church, arcaded with a clerestory pierced by windows, and a semi-circular apse. The original columns were replaced by octagonal pillars in the XV century.

Figure 3-19. Santi Nereo ed Achilleo (Andronico, 2015)
3.1.17 San Giovanni a Porta Latina

This church is a simple three-naved church of spoliated columns with arcade above. It possesses a polygonal apse, a small additional bay between the end of the nave and the apse. The nave is elevated slightly above aisles, to provide space for windows, the terminal wall in nave provided with buttress. Most visible parts were constructed in XII century generally in conformance with VI century plan. According to Krautheimer, the configuration of this church reflects Byzantine influence.

Figure 3-20. San Giovanni a Porta Latina, Central Nave
3.1.18 Santa Maria Maggiore

The basilica of Santa Maria Maggiore is one of the seven Roman pilgrimage churches. It was built in 432-440, by Sixtus III. It has been restored several times; the last significant renovation was by Ferdinando Fuga in the 1740’s, who built the current façade and modify the interior. It has a wide nave and two aisles separated by an extensive row of columns with Ionic capitals and crowned by architraves, designed in majestic proportions. The central nave ends on a triumphal arch above the apse. Originally, it had an atrium and the apse was provided with deambulatory and not semi-circular as its present form. During the XVI century renovation several chapels were added on each side, two sacristies, a baptistery and a transept. The architrave is surmounted by clerestory windows at every other intercolumniation and paintings alternately, with mosaics below divided by pilasters.

Figure 3-21. San Maria Maggiore, Central Nave (Tango, 2010)
3.1.19 San Martino ai Monti

San Martino ai Monti was a titular church replaced by a church in the early IX century. It was ornamented in a baroque style in the VII century, which is its current appearance; although the original Carolingian layout has been preserved. It presents a colonnade supporting architraves dividing a central nave and two aisles. The columns, clearly spoliated, are of dark and pale marble, each one is elevated using a grey marble block below the base.

Figure 3-22. San Martino ai Monti (Karelj, 2011)
3.1.20 Santa Francesca Romana

Originally, Santa Francesca Romana was called Santa Maria Nuova, to distinguish it from Santa Maria Antiqua, since both were located in the Roman Forum. It was erected over the atrium of Temple of Venus in the X century. In the XV century Santa Francesca Romana was buried in the church, and since then the church is named after her.

The church has been restored several times. The visible parts of Santa Francesca Romana are a XVII century reconstruction, decorated in baroque style. Currently, parts of the exterior walls remain from the original church.

A conjectural reconstruction of the early Medieval church suggests that it was of rectangular shape, with a semicircular apse, with two aisles but of different length, North aisle being longer with a larger number of columns than the South aisle, and an L shape portico surrounding the entrance and part of the South.

Figure 3-23. Santa Francesca Romana, Central Nave from Apse
3.1.21 Santa Maria in Trastevere

From the IV to the VI century *titulus* Juli preceded the church of Santa Maria in Trastevere on this site (Kinney, 1975). The present church was built around 1140-1148. It is a basilical church and its aspect is predominantly late medieval. Relieving arches over a colonnade divide the central nave from two lateral barrel-vaulted aisles. The church also has a transept and double triumphal arch. It was renovated in the XVIII century, when a portico was added.

Kinney, in her doctoral dissertation, often compares Santa Maria in Trastevere to Santa Maria Maggiore. She states that both have a raised platform in the apse, no crypt, the clergy sits behind the altar, that both have a trabeated pergola (Kinney, 1975). It is apparent that both churches have similarities, such as the Ionic columns, the architraves and the windows of the clerestory. Although, Santa Maria Maggiore is larger in all dimensions, height, width and length, both maintain similar intercolumniation ratio close to 2.40.

Figure 3-24. Santa Maria in Trastevere, North Aisle
3.1.22 San Lorenzo fuori le mura

San Lorenzo fuori le mura is one of the seven main pilgrimage churches of Rome. The current church is built adjacent to the ruins of the basilica Maior dated to Constantine, pulled down between VI and VII centuries. The old plan consisted of a double aisled nave. The current layout consists of a nave joining two basilicas.

The East basilica, or Pelagius basilica, was built around the VI century. A colonnade with spolia architraves, an arcaded gallery and a clerestory with openings divides the nave from aisles. The nave floor is elevated allowing an entrance to a crypt underneath. The West basilica, known as the Honorius basilica, was erected in 1200, may have used columns and architraves from original basilica. It has visible relieving arches between nave and aisles.
A triumphal arch that spans over the border between the East and West basilicas indicates the earlier location of the apse for the Pelagius basilica, reverted when the newer West basilica was built to allow the East nave as the altar.
3.1.23 Santa Prassede

Santa Prassede was originally a *titulus*. It dates back to early Christian times, renovated in 772-795 and rebuilt in 814-824 (Hansen, 2015). Its current aspect is Carolingian, with a nave and aisles. Three diaphragm arches across the nave with supporting pillars on each side added in the High Middle Ages. Two trabeated columns support the clerestory wall between each pillar. Relieving arches on clerestory wall besides the windows are visible from the exterior.

Figure 3-28. Santa Prassede, view towards entrance
Chapter 4

Analysis

This chapter contains a discussion of the relationship between intercolumniation and column diameter. The intention of this section is to compare the three types of structure used in the early Christian and early medieval Roman churches and to examine the conditions under which each system is used. Furthermore, possible explanations for the patterns observed in particular cases will be discussed.

It is important to note that some churches present irregularities in the dimensions of the columns and the spacing; hence, for this study, the author used judgement to select either the average value or the modal value according to every individual case. This applies similarly to discrepancies found from drawings, direct measurements, and other sources.

4.1 Findings

4.1.1 Arcades

Arches are the most frequently used structural system in the colonnades dividing the nave and aisles in the Roman churches studied. Plotting the column diameter adjacent to the intercolumnar spacing against the column diameter it is possible to investigate the intercolumniation ratio. Both variables are measured from the lower part of the column at the base of the shaft as described in Section 2.3.4.
Figure 4-1 shows that there is a roughly linear correlation between the intercolumniation and the column diameter. Thus, the larger the column diameter, the greater the span.

In order to express this as a simple ratio of intercolumniation to column diameter, the trend line is constrained to a y-intercept of 0. The resulting trend line slope is an intercolumniation ratio of 3.65. Additionally, the column diameter of 0.60 m (two Roman feet) seems to be common; the spacing is from 1.70 m up to 2.73 m. The second trend line, not constrained to pass through the origin, indicates a trend of intercolumniations of 2.6 meters.
It is relevant to note there are two slight outliers in Figure 4-1. One is the church of Santi Nereo e Achilleo (column diameter of 0.60 m and intercolumniation of 3.60 m), with an intercolumniation ratio of 6. This ratio probably does not represent the original configuration of the church, since the interior columns were substituted for octagonal piers in the 1500’s. The other is the nave of San Paolo fuori le mura, to the left of the graph, with a 1.15 m as column diameter and a 2.5 m intercolumnar spacing, resulting in a low intercolumniation ratio for an arcade.

4.1.2 Architraves

Spolia architraves were often used in early Christian churches. A number of types and designs are sometimes seen within the same row. As is done with the arcades, a plot of intercolumniation to column diameter is used to observe intercolumniation ratios in the architraves of the churches colonnades.
Figure 4-2. Intercolumniation to column diameter in architraves

Once again, in order to express the data as a simple ratio of intercolumniation to column diameter, the trend line is constrained to a y-intercept of 0. The resulting trend line slope represents an intercolumniation ratio of 2.6. The second trend line, not constrained to pass through the origin, confirms a visual impression that the intercolumniation is predictably within the range of 1.5 m to 2.5 m for this construction type.
An obvious outlier in the graph is the church of Santa Francesca Romana, with a column diameter of 0.40 m and an intercolumniation of 2.85 m. The reason for this peculiarity is further explored in Section 4.2.3.

4.1.3 Relieving Arches

Relieving arches are the least used as structure in the interior of churches. These features may be intermediate between an architrave and an arcade. A relieving arch, especially a flat arch, can span farther than an architrave, but its span is still limited by the depth available to build the arch.
Figure 4-3 indicates a positive linear association between intercolumniation and column diameter. The slope for the trend line constrained to pass through the origin is approximately 3. However, the inference of an intercolumniation to diameter relation appears to be very tenuous for this building type. On the other hand, based on the available evidence, the intercolumniation for this type of construction is nearly constant 2.4 m.
4.1.4 Comparison of Construction Types

To appreciate the differences among the three systems, it is necessary to combine the data from each construction type into a single graph as shown in Figure 4-4.

![Churches Column Diameter vs. Intercolumniation: All systems](image)

Figure 4-4. Intercolumniation to column diameter in arcades, architraves and relieving arches, including linearization

Figure 4-4 indicates that architraves used in interior colonnades tend towards lower intercolumniation ratios, while arcades tend to show the greatest intercolumniations ratios and that relieving arches appear to have intermediate values. The slope of the trend line for column
diameter to intercolumnar spacing for arcades is 3.65, for architraves 2.60, and for relieving arches the relation is 2.97. The significance of these findings is investigated in the following section. If the trend lines are not constrained to pass through the origin, three different, relatively flat curves result, suggesting some role of absolute intercolumniation in determining the construction type.

The column diameters appear to be very consistent; the dimensions generally vary within a range from 0.4 m to 1 m. Moreover, for arcades and architraves, the median is 0.6 m and 0.65 m respectively, and the mode is 0.6 m for both. These findings are suggestive of the influence of fixing the column diameter. Perhaps, when the column diameter is fixed and greater spacing is desired, there is a tendency to change from an architrave to an arch. The flat and relieving arches appear to be a solution that stands in between arches and architraves.

4.1.5 Statistical Investigations

To verify that there is a significant difference between the calculated intercolumniation values for the different construction types, paired t-tests and ANOVA test, were applied to this data using the analysis tool supplied by MiniTab. The results were checked manually to ensure that the program was working properly.

When comparing the intercolumniation ratio values, the mean intercolumniation of naves built with arcades and architraves did not present a significant difference, with a p-value of 20%. The same comparison was made while excluding the architrave outlier Santa Francesca Romana, with an abnormal intercolumniation ratio of 7.12. The difference was strongly significant resulting in a p-value of 1%. The results are tabulated in Appendix D.
In contrast, architraves and flat arches showed no significance difference between their mean intercolumniations. For this reason, architraves and flat arches are believed to have similar behavior and can be considered as having the same intercolumniation ratios.

4.2 Continuity of construction practice

It is important to place the intercolumniation ratio in time, understand the sequence of events and transitions to different periods. The time periods considered in this study are Roman (200 BCE-200 CE), early Christian (200 CE – 700 CE), Carolingian (700 CE-900 CE) and early medieval (900 CE-1200 CE).

Figure 4-5 shows the relationship between the date of construction, the intercolumniation ratio, and the type of support. It indicates that in addition to conserving a building layout, there is an element of continuity in intercolumniation ratios throughout the periods. From the Roman basilicas in the second century, architraves have been used in similar types of layout, through early Christian and Carolingian periods and later.

The intercolumniation ratio used in the early Roman basilicas is similar to later buildings, as indicated in Figure 4-5. Most of the churches were built between the 350 CE and 550 CE, corresponding to the early Christian period. Other group of churches was built in the VII century and IX century, when the Carolingian style arose. During these two periods of frequent construction, arcades and architraves were used simultaneously. However, relieving arches appear sporadically throughout these periods, but are used more frequent in later periods.
Figure 4-5. Intercolumniation ratio-Date
4.2.1 Christian Churches and early Roman basilicas

To explore the continuity in design throughout the construction periods under discussion, intercolumniation values of the early Roman basilicas are added to the intercolumniation plots of the early Christian and Carolingian churches shown previously (Figures 4-1 and 4-3).

Figure 4-6. Intercolumniation to column diameter in Churches and Roman basilicas. Achitraves
Figure 4-6 demonstrates the continuity of the architrave design in basilicas throughout these periods. It shows that Roman basilicas were built to a larger scale than most of the other churches investigated, as observed in basilica Ulpia (the highest point on the right of Figure 4-6), with a column diameter of 1.5 m and intercolumnar span of 3.5 m. Nevertheless, the slope of the trend line including the Roman basilicas is 2.52, and without them, the slope is 2.60 (See Figure 4-2); that is, the intercolumniation ratio remains almost the same.

Figure 4-7. Intercolumniation to column diameter in Churches and Roman basilicas. Arcades
In considering the continuity of intercolumniation ratios for arcades, again it appears the Roman basilicas are designed to a greater scale than churches. In Figure 4-7, the slope of the trend line including the Imperial basilicas is 2.87, lower than the slope excluding early Roman basilicas, which is 3.62. Although it may be related to progress in building arches, the difference is not enough for any definitive conclusions.

It would make sense to say the design of Christian basilicas follow a similar pattern than the Imperial civil basilicas, considering they adopted the typology layout and have a strong presence of structural elements reused from those same buildings.

### 4.2.2 Flat Arches in Porticoes

Most of the early Christian and medieval basilicas have been restored throughout time and few were subjected to heavy baroque interior modifications, such as Sant’ Anastasia (See Figure 3-6). During these restorations, flat arches were adopted in newly added porticoes from the XVII century, XIII century and XVIII century; as seen in Figure 4-5 (intercolumniation vs date). An example is the XIII century portico of San Giorgio in Velabro, see Figure 4-8.
The porticoes present a higher intercolumniation ratio compared to the relieving arches inside the churches. Figure 4-9 gives a trend line of the intercolumniation ratio on porticoes supporting flat arches of 4.8, while at the interior of churches the trend tends to be 3. Again, this may represent progress in building flat arches, although it is also noted that the load on the flat arches over porticoes is less.
Figure 4-9. Intercolumniation to column diameter of flat arches, in churches and porticoes
4.3 Comparison with Vitruvius principles

In Figure 4-10, the trend line for the ratio established by Vitruvius as the ideal configuration of column spacing in architraves is generally lower than all types previously studied; however, it is closest to the trend of architraves in the churches.
Vitruvius writes about exceptions in his Sixth Book when discussing the design of theaters and basilicas as civil buildings. He states that architects may adjust according to the nature of the site or the magnitude of the project; the dimensions to obtain correct proportions. Hence, Vitruvius’ rules ought to be adapted considering special characteristics of the building.

4.4 Uses of the Present Method

As always, there are exceptions to every rule and there are unanswered questions that need to be addressed. In this section, three cases which do not appear to fit the general pattern are further explored and some of the methods developed in the earlier parts of this thesis are employed in their analysis.

4.4.1 San Pietro and San Stefano Rotondo

The original church of San Pietro, built in IV century and later demolished, represents one of the first examples of early Christian construction. It had two aisles on each side, architraves over the nave colonnade, and arcades on the aisle-aisle division. This change of superstructure is an interesting subject of study. It is noteworthy that there is constant pier spacing so the column axes are the same center to center in the two colonnades, although the columns supporting the architraves of the nave were of larger diameter than those with arches. Therefore, the intercolumniation ratio in the arcades (3.4) was greater than this ratio in the trabeation of the nave (1.92).
Figure 4-11. San Pietro Reconstruction (Worldwide Building and Landscape Pictures)

Figure 4-12. San Pietro Aisle and Nave Elevation
San Pietro is a good example of structural decision making. In the same building, the change in the column diameter from one colonnade to another, resulting from a different roof height, leads to a modification of the overlying structure. As the column diameter decreases, leading to a larger intercolumniation ratio, this leads to an adjustment from architrave to arcade.

A similar phenomenon occurs in Santo Stefano Rotondo, built in mid V century. The building has two circular rings so that the column axes are radiated from the center (refer to Figure 3-10). The outer ring column diameter is 0.5 m with an intercolumniation of 2.4 m, resulting in an intercolumniation ratio of 4.8, suggesting for an arcade. The inner ring columns are 0.78 m in diameter and spanning 2.50 m, with a ratio of 3.21. Where circular arches over an architrave are employed, i.e. relieving arches.

To summarize both of these cases within a building where there are two types of overlying structure, arcades are employed for higher intercolumniation ratios than architraves or relieving arches.
4.4.2 Santa Francesca Romana

The church of Santa Francesca Romana is a peculiar case. It has been greatly renovated and its current appearance dates back to the XVII century.

Krautheimer determined the possible dimensions of the original layout from archeological evidence and located the remains of an architrave. The general construction scheme is evident in a fresco from the XV c (Figure 4-14).

The column diameter of the older church according to Krautheimer is reconstruction, was 0.4 m with a spacing of 2.85 m, which results in a ratio of 7. While considering the regular range of intercolumniation ratios in other buildings with architraves, generally ratios from 2 to 3, Santa Francesca Romana certainly appears to be an outlier.

Structural analysis with hand calculation shows a flexural tensile stress in the bottom of the architrave, measured by Krautheimer to be 4.04 MPa (See Appendix E). According to Cardani et al (Cardani & Meda, 2004) the maximum stress before failure within virgin marble is 5 MPa and less for aged marble, 3 MPa approximately.
Figure 4-14. Santa Francesca Romana, fresco at the Tor de’ Specchi Monastery (1468)

Figure 4-15. Santa Francesca Romana, Stress
It is doubtful that an architrave of these proportions could remain intact. It is fair to assume that some other structural element must have been present. It is possible that the architraves in Santa Francesca Romana were accompanied by relieving arches.

Figure 4-16. Santa Francesca Romana, elevation
4.4.3 Santa Prassede

Santa Prassede is one of earliest Carolingian churches built. At first glance the intercolumniation ratio in the interior is unusually high for an architrave, 4.46, and is quite unexpected on these grounds. However, upon leaving the church and looking at the clerestory wall, from the North-East wall, masonry arches are visible. These arches used to be part of the original windows at every intercolumniation, but were filled with bricks. At every three spans, a new system of windows was added. In the interior, the third, sixth, and ninth column (from the altar) have been replaced by piers that support a transversal arch across the nave. These are located at the midpoint between clerestory windows.

Evidently some weakness in the structure became apparent, possibly resulting from cutting into the relieving arches, or possibly due to an insufficiency of the architrave. This allows this structure to be placed in the category of a relieving arch.

![Santa Prassede North-East wall, Arches](image)
It is important to note, that early builders in following the principals of proportions were also testing them simultaneously. That being said, the anomalies found in the cases previously discussed are a result of the rules intentionally being pushed to the limit.
Chapter 5

Conclusions

As discussed since classical times by authors such as Vitruvius, proportions have been used in architecture, mainly with the purpose of establishing beauty and order. However, there is no separate written evidence of established structural design guidelines. In this work, we have examined how the principles of proportionality may also be applied to design for structural stability.

The first Christian churches ever built as houses of worship started in the IV century in Rome after the legalization of the Christian religion. These buildings followed the layout of the civil Imperial Roman basilicas. These churches are denominated as early Christian churches. One of the features of these churches is the use of spolia. Builders ransacked columns and architraves from earlier buildings to use these in new constructions.

The nave to aisle division of the early Christian and early Medieval Roman churches features three structural systems: arcades, architraves and relieving arches. Arcades were the most used of the three systems, and relieving arches the least. In the analysis of the intercolumniation ratio, i.e. the intercolumniation as a ratio of column diameter, it is possible to encounter a linear positive correlation and a qualitative trend in the use of each type of structure. The greater the intercolumniation ratio, the greater the tendency to use arches, with a normative intercolumniation ratio of 3.65 for these features. Architraves are more common for the smallest ratios close to 2.6, and the use of relieving arches stands between both solutions, with an approximate intercolumniation ratio of 3.
In churches from 200 BCE to 1300 CE, the design of interior colonnades is consistent with very similar ratios. Additionally, the relationship of each system from earlier Imperial Roman basilicas and churches shows approximately the same ratios applied at very different sizes.

Moreover, later additions to five churches, dating to the XII century, XIII century and XVIII century, adopted flat relieving arches in the porticoes preceding the entrance. The porticoes have a higher intercolumniation ratio than those previously built in the interiors.

Overall, early builders based their structural design process on ideas of proportionality. It is important to note that builders, by following the principles they are testing them simultaneously. This could be a reason for cases where the ratios are an anomaly, because there is the possibility that the ratios are being intentionally modified. The differences in the mean values and trends of the three types corroborate to the idea that the intercolumniation as a ratio of column diameter is a significant determinant of the type of structure employed in basilicas of Rome from 0 to 1300 CE. As a simple rule of thumb, an intercolumniation ratio of about 4 was used or arcades, 2.6 for architraves and 3 for relieving arches.

A similar methodology may prove useful to studies of ancient and medieval architecture. For example, a similar investigation of buttresses in Lombard churches seems to indicate a height-width ratio of approximately 2 is widespread. Medieval campaniles at Roman churches appear to show a height-width ratio of 6, and other investigations of a similar nature are expected to reveal further similarities.
Bibliography

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Wikimedia Commons:

Wikimedia Commons:


Wikimedia Commons:
https://commons.wikimedia.org/wiki/File:Santa_Sabina_inside.JPG


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The Edwin Mellen Press.

# Appendix A

## Buildings in study list

<table>
<thead>
<tr>
<th>Church Name</th>
<th>Type</th>
<th>Date</th>
<th>Col. diameter (m)</th>
<th>Pier spacing (m)</th>
<th>Intercolumniation Ratio</th>
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<td>-------------------</td>
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**RELIEVING ARCHES**

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**PORTICOES**

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**Key**

- **Civil Roman basilica**
- **Early Christian church**
- **Early Medieval church**
Appendix B

List of excluded Churches

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<th>Name</th>
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<td>SS Alessio e Bonifacio</td>
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<tr>
<td>S. Andrea in Catabarbara</td>
<td>Single nave</td>
</tr>
<tr>
<td>S. Angelo in Pescheria</td>
<td>Currently only façade remains. No available measurements</td>
</tr>
<tr>
<td>S. Apollinare</td>
<td>No clear drawings, some assumed reconstruction</td>
</tr>
<tr>
<td>SS. Apostoli</td>
<td>No drawings</td>
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<tr>
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<tr>
<td>S. Crisogono</td>
<td>Single nave</td>
</tr>
<tr>
<td>S. Croce in Gerusaleme</td>
<td>Single nave with walls across nave</td>
</tr>
<tr>
<td>S. Ermete</td>
<td>Single nave. Catacomb</td>
</tr>
<tr>
<td>S. Eusebio</td>
<td>Ruins, some columns stand. No measurements available</td>
</tr>
<tr>
<td>S. Giovanni in Laterano</td>
<td>Heavily modified</td>
</tr>
<tr>
<td>S. Gregorio Magno</td>
<td>No available measurements from early Christian Church</td>
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<tr>
<td>SS. Quirico e Giulitta</td>
<td>Single nave</td>
</tr>
<tr>
<td>S. Sebastiano</td>
<td>Arcade on masonry piers</td>
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<td>S. Silvestro in Capite</td>
<td>Simple nave with chapels currently, no original measurements</td>
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<td>S. Sisto Vecchio</td>
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<td>S. Stefano Degli Abessini</td>
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Appendix C

Glossary

Ambulatory: prolongation of the aisled spaces on either side of the nave, around the apse or the chancel, to form a continuous processional way.

Apse: part of a Christian church opposite to the entrance, in where the person celebrating the Christian ritual stands.

Atrium: is a Latin term, a central court or entrance hall of an ancient Roman building, generally open-roofed.

Breaking load: the limit load which causes fracture.

Chancel: east end of the church where the main altar stands.

Clerestory: upper wall of the nave containing windows.

Colonnade: a row of continuous columns.

Consignatorium: Italian term referring to the room where the sacrament of Confirmation takes place.

Domus ecclesiae: term applied to earliest Christian places of worship.

Gallery: raised area of a church, above the aisle, with view to the nave.

Hinge: point of the structure where there is no bending moment.

Insulae: a Latin term meaning islands, was denominated to apartment buildings in Rome.

Keystone: the stone piece at the apex of a masonry arch.

Limit state: condition of a structure, in which it no longer complies the original design criteria.

Mass: rite of worship in the Christian religion.

Martyr: person killed as a result of their religious beliefs.

Mausoleum: Latin term referring to a building containing a tomb.
Mithraeum: from the Latin Mitraea, is a classical large temple for worship of Mithras.

Navicella: Italian term meaning little ship.

Pavonazzetto: a marble material consisting of dark red veins with blue and yellow tints.

Presbyter: Christian religion minister that celebrates the Liturgy.

Spolia: the reuse of architectural elements in another building and location.

Thrust: outward force exerted by an arch.

Titulus or titular church: Roman residence given over to worship by titled property holder.

Trabeation: beam or lintel above columns used as a structural system.

Triumphal arch: a large arch that spans across the nave in churches.

Transept: part of a church perpendicular to the nave, forming a cross shape.

Vestibulum: a Latin term meaning entrance hall.

Voussoir: piece of shaped stone conforming an arch.
Appendix D

Statistic tests

ANOVA: Arcades-Architraves-Relieving Arches

The pooled standard deviation is used to calculate the intervals.
One-way ANOVA: Arcades, Architraves, Relieving Arches

Method

Null hypothesis  All means are equal
Alternative hypothesis  At least one mean is different
Significance level  $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor  Levels  Values
Arcades  3  Arcades, Architraves, Relieving Arches

Analysis of Variance

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Model Summary

\[ S \quad R-sq \quad R-sq(adj) \quad R-sq(pred) \]
\[ 1.27340 \quad 11.86\% \quad 5.56\% \quad 0.00\% \]

Means

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Pooled StDev = 1.27340
T-test: Arcades-Architraves

### Boxplot of Arcades, Architraves

#### Two-Sample T-Test and CI: Arcades, Architraves

Two-sample T for Arcades vs Architraves

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Difference = \( \mu \) (Arcades) - \( \mu \) (Architraves)

Estimate for difference: 0.893

95% CI for difference: (-0.576, 2.361)

T-Test of difference = 0 (vs ≠): T-Value = 1.38  P-Value = 0.202  DF = 9

T-test: Arcades-Architraves excluding Santa Francesca Romana
Two-Sample T-Test and CI: Arcades, Architraves

Two-sample T for Arcades vs Architraves

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Difference = μ (Arcades) - μ (Architraves)
Estimate for difference: 1.440
95% CI for difference: (0.652, 2.228)
T-Test of difference = 0 (vs ≠): T-Value = 3.86  P-Value = 0.001  DF = 17
Appendix E

Stress calculations

Santa Francesca Romana-Stress calculation

Wall weight:

Thickness = 0.90 m area= 21.78 m$^2$

Volume = 19.60 m$^3$

$19.60 \text{ m}^3 \times 2400 \frac{\text{kg}}{\text{m}^3} = 470448 \text{ kg}$

\[
s = \frac{-P_a}{z} = \frac{23522 \times 0.41}{0.0234} = 412144.6154 \frac{kg}{m^2} = 4.04 MPa
\]

\[
z = \frac{l}{y} = \frac{a^3}{6} = \frac{0.52^3}{6} = 0.234 m^3
\]

$s = \text{stress}$

$z = \text{elastic section modulus}$

$l = \text{moment of inertia}$
## Appendix F

### Direct Measurements of visited Churches

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Source: Direct Measurements
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Source: Direct Measurements