Malta's Heritage in Stone: from Temple Builders to Eurocodes 6/8.

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ABSTRACT

The Maltese archipelago has been inhabited since 3000BC and the evidence of occupation is preserved within the fabric of the cultural heritage. It is not clear whether it was the central Mediterranean location of the limestone resource which attracted the Temple Builders around 3000BC and resulted in the high concentration of Neolithic temples. Malta's stable semi-arid Mediterranean climate resulted in durability for its compact limestone resource the use of which followed the tradition of excavated burial chambers and the many centuries of use of caves by the Maltese as residences. A French study defines a compact stone having a crushing strength lying between 10N/mm^2 & 40N/mm^2, a soft stone <10N/mm^2, and a hard stone > 40N/mm^2 [1]. There is little preservation of structures from the Arab occupation from 870 up to 1090. However the construction methods in vernacular construction used in Malta from this point to the mid-20th Century derive from the methods first introduced at this time. Some of this early work which included weak rubble construction was destroyed in the earthquake of 1693. The expertise of the military engineers of the Knights of St. John who began to build Valletta in 1570 was shared with Maltese masons and led to significant structural improvements. The British period 1813 – 1964 brought along the Corp of Royal Engineers and introduced the neo-classical/gothic into masonry constructions. Steel joists were introduced and widely utilised in this period, embedded in masonry floor slabs. Building regulations were also introduced which had an effect on floor plans, with the traditional central courtyard layout overtaken by construction with a backyard. The British masonry codes of practice resulted in the construction of up to 8-storey cellular residential constructions rather than the previous maximum of 5 storeys. The aesthetics together with the sound reverberation proportions of masonry spaces is introduced. The role of the structural engineer in designing a building is to establish their numerical competence with respect to both the aesthetic proportions and the impact which these have on the "reverberation" characteristics. A comparison is then drawn between the BS & EC masonry codes with the characteristic strengths for the Maltese masonry building block outlined in the respective codes. The seismic rigidity of the Maltese masonry constructions is then outlined according to EC8. The effect of blast loadings is then also considered. It is found that a only a small number of buildings in structural compact masonry 8 stories high, with ages just exceeding 100 years conform with the characteristic strengths in the EN masonry codes. The rigidity of these regular planned masonry constructions is subjected to low seismic risk is confirmed as adequate, however this is not so as when subjected to blast loadings. An appendix is provided which introduces a calculation for the verification of thin masonry slabs, which was an important Maltese building element up to the mid-1960s. The importance of this structural check becomes necessary, when the building use is to be changed resulting in additional loading.

KEYWORDS: globigerina Franka limestone, vernacular construction, historic development.

NOTATIONS

BM -	Bending moment
K -	Dimensioned natural stone coefficient taken at 0.45, in general purpose mortar
MDR -	Mean Damage Ratio
MM -	Modified Mercalli
N_{ad} -	Maximum design arch thrust per unit length of wall.
N_{Ed} -	Design value of vertical load
PGA -	Peak ground acceleration
d_a -	Deflection of an arch under the design lateral load
dpc -	Damp proof course
f_b -	Normalised mean compressive strength of a masonry unit
f_d -	Design compressive strength of masonry in the direction being considered
f_k -	Characteristic compressive strength of masonry
f_m -	Compressive strength of masonry mortar
h_{tot} -	Total height of a structure, from the top of the foundation, or a wall, or a core
l_a -	The length or the height of the wall between supports capable of resisting an arch thrust
r -	Arch rise
t -	Thickness of a wall
γ_m -	Partial factor for a material property, also accounting for model uncertainties and dimensional variations.
λ -	Shape factor, a coefficient dependant on the height and thickness of the masonry unit.
v -	Angle of inclination to the vertical of a structure in radians
δ -	Deflection

1. INTRODUCTION

The Maltese Archipelago is a small island state of 316km^2 situated in the centre of the Mediterranean. The main islands are Malta, Gozo and Comino, and the smaller Fifla and St Paul's Islands. With a population of 434,403 in 2015 growing annually by 0.7%, it is the most densely populated country in the EU at 1,375 persons/km^2 [2].The climate of Malta is a stable semi-arid Mediterranean marine environment with a normal annual rainfall between 400 and 700mm where annual global rainfall is approximately 1,000mm per annum. Wind direction is North Westerly for approximately 40% of the time at speeds between 0.5 and 11 m/s (1 & 21 knots) [3].

The Maltese Islands lie in the Sicily Channel on a relatively stable plateau of the African foreland, the Pelagian Platform.

Seismic events are rare although have been noted in the historical record of recorded earthquakes dating since 1530 [4]. Although damage to buildings has been serious on the rare occasion where earthquakes have occurred, no deaths from seismic action are recorded.

A simplified version of the Maltese geological layers can be represented of a 4-layer sedimentary sequence of the Oligocene-Miocene Age. This sequence is highly disturbed by vertical faults which control the process of weathering and erosion and includes for 4 formations of limestone sedimentary deposits as shown in Figure 1 subsequently listed from the youngest to the oldest [5].

1/- The Upper Coralline Limestone (UCL) locally known as *Tal-Qawwi*, with a maximum recorded height of 162m, but it may be greater beneath Comino, where 80m outcrops occur at the surface. It is used both as an aggregate and for the production of lime. Its dry crushing strength lies in the range of 8.8N/mm^2 – 67.2N/mm^2.

2/- A marly clay formation, known as Blue Clay (BC), important for the perched water aquifers. It attains a height of 70m in Gozo.

3/- A Globigerina Limestone formation (GLS) of 250m maximum thickness, which is divided into three distinct geological zones designated as the Upper, Middle and Lower Globigerina Limestones. It is from the lowermost strata that compact softstone, locally referred to as known as *Franka* (freestone) is extracted. This main building stone has a dry crushing strength in the range of 9.0N/mm^2 – 22.0N/mm^2 and a total porosity which may be as high as 40%.

4/- A Lower Coralline formation known as *Taz-Zonqor* (hardstone), with the exposed formation reaching a thickness of up to 120m. Its dry crushing strength is in the range of 7.0N/mm^2 – 105.0N/mm^2 and average porosity value around 16/% [7]

Tal-Qawwi and the *iz-Zonqor* formations are the main local sources for crushed concrete aggregates and also used as aggregate in local concrete and bituminous macadam production road construction, although often criticized as being too dusty, due to crushing. Prior to the advent of damp proof courses, these “hardstone” variants were also used placed in the lower courses of a building to minimize the effect of rising damp. It is also noted that prominent buildings constructed facing a shoreline, had their facades built in this stone type as it visibly exhibits a better durability to salt-load damage when compared to the Lower Globigerina freestone.

The majority of Malta’s traditional buildings were built of the *Franka* building block, laid on a bedding mortar of between 2.0N/mm^2 strength, but not exceeding 5.0N/mm^2.
This combination of the masonry unit and the bedding mortar has given excellent service in use, as evidenced by major buildings/churches constructed around 400 years or more ago. With correct detailing deterioration over the ages has been limited. It is only when backfill and/or moisture penetration is presented, that severe honeycombing occurs to the *Franka* limestone.

The best masonry building units, are located in the *Lower Globigerina* building stone which has been recorded to have compressive dry strength as high 30.0N/mm^2, however the ‘normal’ quality *Franka* extracted from this formation has been observed to exhibit lower dry compressive strengths generally within the range of 17.0N/mm^2 – 21.0N/mm^2 . It has also been observed that whereas the compressive strength and apparent density of the Lower Globigerina increases gradually with depth of extraction, its weathering characteristics rapidly deteriorate. Indeed, layers or bands of ‘bad’ quality stone (locally referred to as *Soll*) are encountered in otherwise good quality stone quarries. The *Soll* stone type is characterized by compressive stresses approaching to 30.0N/mm^2, and with a relatively low total porosity of 27.5%. Recent research on LGL has established a correlation between durability problems, and the higher concentrations of quartz and phyllosilicates mineral fractions. *Soll* & *Franka* are colloquial Maltese terms which translate to ‘‘stones of inferior or good quality respectively’’[8]

Selective extraction and careful choice of masonry has aided the durability from the renaissance period to early colonial buildings from the Valletta Basin area [9].

The durability of masonry is frequently gauged with respect to its resistance to salt-crystallization damage. It was assumed generally that the more porous masonry is more prone it is to ingress and movement of water and hence to salts in solution within it. However, it is now also universally acknowledged that it is not the total porosity which really determines the durability characteristics of any stone type but the interconnectivity, size and size distribution of the pores.

The variably humid and salt-laden Mediterranean climate should therefore be a challenging environment for highly porous calcarenite building stone like *Franka.* However, the apparently good weathering characteristics of *Franka* must also be understood within the context of a temperate Maltese climate which rarely if ever witnesses frost/thaw cycle conditions [3].

Figure 1: The only location in Malta along Dingli Cliffs where all the geological formations are in view. Note the limited depth of the GLS formation, which in other locations can tend towards 100m in depth. [6]

Figure 2: The excavated Mnajdra Neolithic Temple. Note outstands of the masonry blocks in the adjacent fields. [12]

The further advantage in adopting this compact globegerina limestone masonry block is that this masonry block can be carved with ease to produce elaborate mouldings. On exposure to the air, the stone slowly forms a hard crust so that any carving has to be carried out soon after the masonry has been placed. If the carving is not untaken within 4 years, the hard surface may break and crack, as the masonry becomes friable and powdery. If this occurs, the damage will spread rapidly to the adjoining stones. Masonry capitals can sometimes be seen in Malta left as mere masonry uncarved blocks.

Limestone is further known to possess a very low coefficient of expansion, and this characteristic combined with the low mortar strength mostly utilized has aided in limiting crack patterns in wall panels.

Although masonry is a brittle material, due to robust geometrical forms adopted, crack patterns that can develop often do not result in a structural failure, as sharing of the "overstressed" portions can be undertaken via arching effects in the wall panels.

The measurement of crack widths gives an indication of damage sustained. The Building Research Establishment BRE publication [10] classifies damage into six categories: 0–5 according to the existing crack width. Categories 4 and 5, which indicate structural damage, note crack widths as varying from 15mm to over 25mm. Category 3 includes cracks that require some opening up and can be patched by a mason. Doors and windows may stick. Service pipes may fracture. Weather-tightness often impaired. Typical crack widths are 5 to 15 mm, or several of, say, 3 mm. Category 2 damage, occurs with crack widths up to 5mm which may be easily filled. This may lead to sticking of doors or windows which requires easing and adjusting, together with lack of weather tightness. Category 1 includes fine cracks that can be treated easily using normal decoration, with typical crack widths up to 1 mm. Category 0 refers to hairline cracking, where the width is less than 0.1mm, requiring no action.

Crack width may not be the defining factor, although this depends on the length, shape and density of cracks. Cracks may have a negative aesthetic impact or they may need to be filled to reduce penetration of sound and odours or the passage of fire. Finally, the age of the building also comes into the equation. The older the building the less sensitive is its user to its existing cracks, deflections and vibration effects.

2. TEMPLE BUILDERS

Around 3600BC, before the Egyptians experimented with their stepped pyramids, a group of Stone Age hunters & gatherers on the Maltese archipelago shifted huge stone blocks (megaliths) to build their temples. These megaliths could reach a height of 5.5m and weigh up to 50 tons.

Some 36 of these sites are known, though less than a dozen possesses substantial remains. It is thought village rivalry that compelled these farmers to conceive such remarkable monuments comparable to the same rivalry in more recent times to construct monumental churches spread over all the villages of the Maltese Islands. These temple builders, amongst a population probably not exceeding 5000 persons disappeared towards the end of the Copper Age.

If the construction of these megaliths is impressive, the plan layout consisting of a series of parallel semi-circular apses, connected with a central passageway is intriguing. In elevation the façade curves not only inwards in the horizontal plane but as it rises, the notched ends also curve outwards in the vertical plane. The impression of comfortable stability is thus combined with a pleasant sensation of gentle motion [11].

Figure 2 shows such a construction. The Photograph shows the plan, and the section together with 3 layers of massive lintels, conforms with the writings in a technical paper [13]], which concluded that Stonehenge was roofed over, although in timber. Timber is not easily available in Malta and was probably even more limited during the Stone Age period, and these massive masonry lintels could indicate that these temples were roofed over in thick masonry slabs. This shows the temple builders' knowledge of building principles and techniques. Despite the arch system not being fully developed, their corbelling system led them to utilize high tensile ring forces developing in the encircling massive masonry lintel blocks. This knowledge had not even been known to the Egyptians and the Greeks.

Their knowledge was not limited to building principles but also included for the judicious use of building materials. In the more refined temples of the Maltese Archipelago, the softer globigerina limestone was adopted for the interior chambers, as well as the façade. The intention behind this softer but less durable limestone was providing for a smoother and more expert finish. In older temples the rough more durable masonry was plastered over [11]. The soft limestone was sometimes carved as in the highly decorative temple of

Tarxien, as located over Malta's Grand Harbour heights. This is provided with handsome relief carvings of spirals as well as friezes with rows of animals.

The temples in Malta show evidence of a clear progression in temple building from small to larger rough boulders interspersed with multiple massive masonry lintels [9], and finally including dressed stones which produced more refined temples. Corbelling of the walls was used as the temples became larger, and while it is not known whether this was taken up completely to close the roof, this would be possible by the use of flat masonry slabs. Alternatively structures such as the Tarxien temple could have been have been roofed over in timber joists [14].

The excellent preservation of the temples does suggest that these temples were roofed over whilst in use. The soft globigerina limestone adopted in their construction shows little deterioration to the internal surface finishes over the years. Subsequent burial below the earth's surface has prevented further deterioration. The presence of roofed over Stone-Age monuments defy the interpretation that their sole purpose was for astronomical purposes, and indicates instead their use as a gathering space for a large number of people, with Temple use widespread during for this period [13].

3. FROM THE TEMPLE BUIDLERS UP TO 1530

From the Temple Builders onwards little is known of the subsequent dwellings. This suggests later dwellings were constructed in materials that were subjected to deterioration that could not survive the passage of time. Further, up until recently a substantial number of Maltese were cave dwellers, except for the wealthy that resided in the central Mdina or coastal Birgu.

However, since the Bronze Age following the Temple Builders, the largest civil engineering project over the Maltese Islands was undertaken. This consisted of the construction of the terraces for agriculture in places where no cultivation had previously been possible, due to the gradient and its consequent denudation of soil by wind and rain. The main purpose of the terrace-building was to produce more food crops – wheat, rye, barley, beans and fodder to sustain goats, sheep and cattle. Attempts would have been made to grow olives, carobs and vines [15].

This massive project changed the life style of the Maltese from hunters & gatherers to that of farmers, which then enabled the increase in the population. This involved the construction of dry stone walling to terrace and separate the fields. From the earliest of times the following method of construction had been adopted.

1/- Larger sized stones were placed at the bottom, except for the keystones, which bonds both leaves. If a rock face existed the lowest course was placed directly on these, whilst if clay was in existence, this was excavated to a depth of 1m and the wall commenced at this depth, to give the stability required.

2/-.the space between the outer masonry skins was infilled by the careful placement of a hard-core which consisted of small sized rounded stones with no soil. This provided a drainage layer through and at the base of the wall and also prevented the outer wall skins from collapsing inwards.

3/- the wall was constructed such that it inclined from bottom to top. This inclination could measure 15cm on both sides of the wall over a 3m height [16].

4/- the top of the walling was often finished off in a clay puddle coping. Shedding of the water and the provision of a French drain at the base was considered a very important element of construction, which retained their stability by reducing water pressures behind the wall.

This form of dry stone walling construction has lingered on for many centuries. First it was adopted in the double-walled corbelled stone-hut shaped like a truncated cone, termed a *girna* (Figure 3) [17]. Late into the 14^{th} century many residences continued to be constructed in dry stone walling, except for the stiffened corners, which were constructed in fair faced masonry.

Tombs & burial chambers hewn into rock are found practically all over the Island dating from the early classical period around the Punic 800 B.C. These take the form of a shaft sunk down into the rock meeting the burial chamber, originally round in shape, later developing into a rectangle (2.15m X 1.5m). Catacombs, a system of underground cemeteries were then developed during the Roman period, following Roman laws, which were strongly averse to burials within the city walls. It is unfortunate that the Maltese Islands, so prosperous during the Roman Period, yielded relatively so little of architectural value. Following the Roman Period up to the 15^{th} century, the inhabitants had little money to invest in building and with the departure of the Arabs in 1090 the Maltese continued to worship in catacombs and caves, suggesting that few possessed the skill to construct free-standing places of worship. It is interesting to note that naturally occurring caverns within the limestone adapted as places of residence for many Maltese inhabitants, who appear to have felt more than comfortable in these spaces. The skills of the Maltese mason began here with an understanding of the characteristics of the limestone. Basic subdivisions using masonry were created in these cave abodes, enabling understanding of the principles of rough arch constructions. The practice of whole communities living in these cave like shelters has ceased, however it did linger in isolated pockets as late as up to the end of the 20th Century.

There is then a drought of information over a long period following the Romans, with the first surviving basic structures dating from the 13^{th} & 14^{th} Centuries. These are as a result of village master masons, not of trained architect-engineer, and consisted of a small rectangular space. Roofing consisted of a series of arched ribs at 1.8m centres spanned by flats slabs of dressed stone, 55mm thick. In later years the slabs were placed direct on the ribs from the springing upwards, thus achieving a vaulted effect [11].

Alongside the cave dwellings there existed primitive residences in the central capital of Mdina inhabited by the wealthy, whilst the less wealthy lived in the central outlying villages away from the coast, due to the pilfering that occurred from the Corsairs raiding the Islands. Prior to 1530, there is evidence of houses with roofs that were thatched or made of reeds, similar to African huts. It is not known whether the early houses of Mdina were in ashlar constructions, or a combination of ashlar and rubble. Using this form of construction, the Catalan inspired elongated windows with round-headed double lights separated by a slim colonette, could have also been included to the houses of the wealthy. Late medieval buildings reserved ashlar for walls that were visible from the street and for the arches that supported the ceiling slabs. On the other hand, documentary evidence for

Figure 3: A corbelled hut (girna), constructed in rubble masonry of locally sourced UCL, being maintained by hunters. The same construction is utilised as in the dry stone walling, as separating the fields [18]

ashlar-built country houses is extremely scarce before the year 1545 [19].

This roofing technique employed by Maltese builders in the late middle Ages consisted of a masonry slab of 115mm thickness that spans 2.25m without cracking on a bearing of about 7cm. For rooms with a width of 2.75m the span was achieved by sloping the walls slightly inwards and then decreasing the span further by adding masonry corbels, just below these masonry slabs. For rooms wider than 2.75m, arches were constructed across the room at about 1.2m centres, with thinner masonry slabs of 45mm thickness spanning onto these arches, on a bearing of 2cm – 3cm. The Maltese mason regained his skills from the Sicilian craftsmen, with the floor spanning system either copied from surviving Arab structures or adapted locally [11].

This system of roofing in masonry slabs is first observed in the 4th – 7th century Christian churches of the Hauran district of Syria. During that period two influences mingled to form the Byzantine Christian type basilicas, the Hellenistic and the Syrian. There like in Malta, a scarcity of timber and a plentiful supply of good building stone prevailed. Unfortunately the distinctive Byzantine church which consisted of a dome covering a square space below, culminating in the construction of Hagia Sophia in Constantinople did not reach Malta, arriving as far as Ravenna in central Italy facing the Adriatic sea. The Syrian roofing system was not unknown to the Arab conquerors in 870 from Tunisia. It is presumed that this system of construction was introduced locally by the Arabs and which, like their language, was preserved. Further whilst houses in Sicily generally had sloping roofs, those in Malta have always been flat like those in North Africa [11].

The Tunisian connection can also be reaffirmed by the Tunisian *ghorfa*, which finds its place in Maltese vocabulary. The Tunisian *ghorfa* served neither as the farmer's country residence nor as his animal pen, first and foremost it was a multi-level grain store. It employed a random mixture of cut stone and rubble and a barrel-vaulted roof requiring no timber. The overall effect is not dissimilar to the Maltese *razzett* compound, which represents the vernacular architecture of the time of the outlying hamlets [14]. On the other hand the Malta *ghorfa* was the residential component of the *razzett* or common farmhouse. This occupied the 1st floor and was therefore set apart from the stables, animal rooms and storage generally located at ground level. Connection was via rudimentary steps external bonded into the thickness

Figure 4: Construction in Gozo, note rubble infill walling with ashlar at the corners, together with the top string ashlar course. (SOURCE: Author)

Figure 5: this basement construction in Rabat probably pre-dates the overlying 16th century palatial construction. Rubble infill masonry abuts onto the street walling, whilst the supporting masonry arch quoins are formed in ashlar masonry. 1m masonry slabs span onto the arches, whilst flooring is in *tal-qawwi flagstones.* (SOURCE: Author)

of an external wall. Its box-like, flat roof structures are scattered here and there over the countryside of Malta and Gozo among patch-work of fields enclosed within dry stone rubble walling [19].

In comparison the small round *Girna*, fabricated in dry-stone walling form a double-walled corbelled stone-hut shaped like a truncated cone. These are less commonly square or rectangular and were used as a farmer's storehouse for crops, tools or as a welcome temporary shelter from the heat and rain. Some of the larger *giren* may have represented a rudimentary type of farmhouse used both for animal rearing and for human habitation. Building techniques also included for corbelling, infilled double walls, the large corner walls and the relieving apertures over lintels, together with the masonry slabs roofing system [17]. Quarrying of stone and its transport to the building site is referred to in 1495, together with the laying of foundations after excavating the earth to bare solid rock. Ashlar blocks were reserved for corners of rooms, double walls were infilled with rubble stones, whilst lime was utilised as mortar and for whitewashing [19].

The Arab building connection 870 - 1090 had one failing. Malta's climate is characterised by a small diurnal temperature range, unlike in North Africa or the Middle East, where it is much higher. Thus the building fabric of thick walls and small openings is not ideal from a climatic point of view. An improved construction would take advantage of sea breezes, encouraging internal air movement and taking advantage of natural ventilation by locating buildings in the directions of the main winds blowing over this windy archipelago [20]. Even though the building construction of the time evolved from the Arabic form of construction almost nothing is known about building during this period, with the earliest information available as referring to ecclesiastical and secular buildings constructed during the 100 years +, prior to the arrival of the Knights of St John [11].

Although not many churches from the 13th Century are recorded, Duzzina the Apostolic Delegate in 1575 reported 430 churches on the Island. Of these, most were in a bad state of repair, 49 were in ruins, 146 had floors of beaten earth. The earlier churches had been planned as single-cell rectangular buildings, with the troglodytic element still evident. That these churches had the base dug in rock was due to the fact that the load path for the horizontal thrust created by the barrel vaulted roofs to the founding level had not as yet been successfully resolved.

An exception to the above is the Mdina Cathedral constructed under the time of the Normans and which collapsed in the earthquake of 1693. It is probable that this 13th century construction was of the Palermitan (Palermo) type in the Arab with pointed arches and Byzantine tastes, on a basilican plan with a low timber ceiling. This consisted of a nave and side aisles, separated from the main aisle by four Corinthian columns on either side [11].
The masonry course height for these early churches had already measured 26.5cm, which is the height still in use in Malta to this day [11].This course height relates to the old cane (2.1m - *qasba*) measures, with a *xiber* k/a the Maltese foot, equivalent to 1/8th of a *qasba* measuring 26.25cm. The *qasba* measure is still in use today. This uniformity in the course height has acted as unifying aesthetic proportions across the centuries.

4. THE KNIGHTS' LEGACY 1530 - 1798

To fully appreciate the precious legacy of Malta's built environment, the arrival of the Knights of St John in 1530 is significant. Some basic demographic data will aid in understanding the form of construction as undertaken from that period onwards. With the coming of the Knights of St John, the population stood at 10,000, increasing to 100,000 on their departure in 1798. During the British period, as at 1900, the population stood at 200,000 increasing to 434,000 nowadays, as noted in Introduction. [21].

The prosperous years enjoyed during the Roman Period had waned following the Arab occupation of 870. Malta was then dragged into poverty following the departure of the Arabs, partly due to the exposure of the Islands to frequent raids. Initially only the central part of the Islands was guarded. Mdina in the centre of Malta is said to date back to the time of the Phoenicians as far back as 700BC. The Gran Castello or the Citadella in the centre of Gozo, on the other hand dates back to the 13th Century. The arrival of the Knights saw the building of long lines of defence and an intricate system of fortification. Look-out towers gave warning, forts guarded the bays & creeks, castles gave some measure of protection to the wealthy who dwelt in the countryside and miles of outworks, bastions, cavaliers and curtain walls, all constructed in this yellow bleached sharp edged globigerina limestone, added security and prosperity to the native population. The Maltese fortifications illustrate a part of the story of the great struggle between the Islamic and Christian worlds with this clash of ideologies, unfortunately still present today [22].

The coastal look-out towers varied in size. The small ones consisted of a small room on each of the two floors reached by a ladder. The base of the building was constructed of thick stone walls in ashlar masonry built sloping inwards and the roof usually had crenulations to indicate that the tower was built to withstand a battle. These towers were constructed mainly round the coastline and could signal to each other in the event of danger from marauders. Bonfires were lit on their flat roofs, as a warning of an invasion a signalling system was devised from ship to shore also. The importance of these massive masonry fortifications only comes to mind, when it is realised that the garrisons of this archipelago only totalled 8,000 infantry at the time. Due to the masonry fortifications in place this limited resource managed however to avert the Turkish force over a 200-year period that could muster a compliment of 30,000 persons [22].

Following the fortification of the Islands, in 1566 the youngest capital city of Europe Valletta, was built on a globigerina limestone peninsular promontory. The added prosperity and security spread out into the villages where Baroque parish churches were constructed, heightened by their setting among small plain tight-packed houses crowded in narrow winding streets, their orientation dating back to the Arabic period. The masonry domes and towers of the parish churches stand out above the lower groups of flat-roofed houses. The Knights of St John adopted the flat roofs that they found on the Island with the exception of just two buildings constructed in pitched roofs; the Infirmary and the Grand Master's Palace. During this period timber joists were imported and these replaced the arched masonry ribs on the upper floors of dwellings [11].

It is to be noted that whilst the earlier churches had been planned as single-cell rectangular buildings, at the end of the 16th Century the new parish churches were large and all built in the form of a Latin cross. In their constructions the masons followed the methods to which they were accustomed, combining semi-circular ribbed barrel vaults, from which a masonry dome spanned [11].

The Knights of St John brought over to Malta the most famous military engineers and town planners in Europe at the time to fortify Malta and plan a fortified Valletta, which after much debate was built to Laparelli's grid-iron pattern and subjected to the Laparelli Codex, which refers to town planning on climatic parameters, together with building construction details, such as the rusticated corners to facades [23].

When it came to the building of civil buildings however, this was overtaken by the Maltese master builders who had trained under these engineers/planners and even furthered their building knowledge by forays overseas to study building monuments in Naples and Rome. The influence of the kingdom of the Two Sicily's was very much alive, also drawing on its Spanish influence. Thus was born the Maltese architect-engineer from the master mason [11].

The building of Valletta is noted as having been undertaken in a very sustainable way. The masonry blocks which served for constructing walling to the upper floors were retrieved by excavation of the basements and of wells for the harvesting of rainwater. Minimal material was thrown to waste, meaning a significant reduction in the need to transport material, whilst also reducing dust in the environment [23].

Initially main buildings were undertaken in the simple mannerist style in humble *melitan fat mouldings* (Malta's first typical primitive domestic architecture, seemingly with no Italian influence) decorating the windows, with the wall panels growing in importance, whilst rusticated corners decorated the facade. The main rooms were on the first floor, the *piano nobile* (the main floor of a large house, above the ground floor), which had a 5m high storey height to compensate for the summer heat build-up. Between the ground floor and the first floor there was usually a low *mezzanine* floor which in elevation was grouped with the ground floor, so that the façade could be read as two floors of equal height. Having noted these Maltese Architect/engineers being apprenticed to military engineers, it is not surprising that a military style of architecture was adopted where the Tuscan order ousts the more decorative Corinthian forms used more in an unfortified context [11].

This was then overtaken in the late 17th century by the baroque style where the decorations become more decorative and flowing. It is however remarkable that this Maltese archipelago in constant contact with its European neighbours has managed via its local Architects-engineers to have produced a building style that is essentially Maltese, somewhat disciplined and affording relief after the extravagances of Sicily and Southern Italy [20].

5. THE BRITISH PERIOD 1800 – 1964.

With the Knights removed by Napoleon in 1897, the French were themselves expelled, as a results of their pilfering of the churches, with the aid of the British in 1800. The British initially thought that theirs was a brief sojourn in Malta; however it then extended up to 1964. It had finally been recognised by the other European powers in the Treaty of Paris signed in 1814 [21].

As administrative buildings dating from the 17th Century, were well established in Malta, in contrast to Singapore, no Westminster type administrative district was constructed in Valletta. In time some neo-classic monuments were undertaken. Public buildings were constructed in the outlying areas, which included a prison, a mental asylum, an old people's home and others including elementary schools in every town and village. The horizontal banding of the village elementary schools was again undertaken in masonry construction, competed with the verticality of the religious edifices. In Valletta a closed food market was installed in cast-iron pillars with glazing incorporated in the roof steel trussed system together with a Royal Opera house in a neo-baroque style. Both buildings had wall panels in load bearing structural masonry [11].

During the mid -19th century, the Victorian period the salubrious effect of the sea-side was established. So besides the works in the outlying areas, the towns of Sliema and St Julian's came to be, initially as summer houses for the residents of Valletta, a pattern following Bournemouth and Tynemouth in the UK. Then late 19th Century various barracks for the soldiers' resident in Malta were undertaken, generally external portions were undertaken in rough-hewn masonry a way to represent solidity. The British construction took heed of the climate with open arcades undertaken to protect the buildings from the heat build-up. On these islands swept with the sea breeze, natural ventilation was considered to be beneficial to the internal temperature control of buildings [20].

The Barrack's design was according to a Galton/Sutherland 1863 report which found most of the barracks then in use to be badly ventilated, overcrowded, damp badly lit and lacking sanitary installations. This report also called for recreation facilities, to include for ball courts, skittle grounds, gymnasia & reading rooms.

The British towards the mid-19th Century introduced steel joists which were used in parallel with timber joists. The steel joists were normally embedded into the masonry slabs producing a flat soffit, however left exposed on the underside of the roof flat slabs as otherwise the resulting rainwater moisture penetrations would have caused severe rusting to these steel joists. This would in turn crack the masonry slabs and require complete replacement of the roof slab. The works as undertaken by the British were completed by the Corp of Royal Engineers who was responsible for the building of fortifications throughout the British Empire, having been recognised by the British Army since 1683. These also adapted to the Maltese's form of masonry construction in the major forts being undertaken, now being adapted to differing forms of warfare, than those as undertaken previously during the times of the knights. Maltese masonry is undertaken in wide mortar joints approximating to 10m and although the Royal Engineers had twice tried to adopt thin joint mortar (much to the bemusement of the Maltese mason) the thin joint mortar created severe cracking to the masonry blocks on both occasions and ruled against its use. The reason could be that as Malta's building block is not a strong but noted as a compact unit, the thin mortar layer did not distribute the imposed loads as well as general purpose mortar with a 10mm thickness did, as adopted through the ages.

Maltese floor construction in masonry slabs progressed during the British period notwithstanding the importation of steel joists. It was only in the 1930's that reinforced concrete was introduced in Malta, however this form of masonry slabs continued right into the early 1960's.

The Code of Police Laws Chapter 10 relating to the sanitary conditions of buildings was introduced in 1854. This included for the laying of a damp proof layer at the base of masonry walling, thus improving the durability of the constructed masonry and dictated thicknesses of party walls & façade walls at 2' 6" (76cm) thickness. This wall thickness was achieved by a cavity wall with 2 skins of masonry 23cm thick, only fair faced on the external face. Over time, on health and safety grounds to reduce the handling weights of these masonry units, wall thicknesses reduced as per a legal Notice in 1976 stipulating the thickness of this double wall at 38cm, by constructing a double wall in 2 skins of masonry 15cm or 18cm thick with both faces fair faced. Improved insulated constructions could now dictate thinner walls. This then dictated the creation of backyards, together with internal yards, which resulted in the demise of the central courtyard type of house. The terraced house was also introduced which, with the proper orientation, provided good cross ventilation properties, as noted earlier and being important for the prevailing type of climate [11].

Further to building construction details in 1837, His Majesty's Commissioners of Enquiry recommended the establishment of a Chair of Civil Architecture and Land Surveying at the University of Malta, The first complete course for architects and land surveyors covering studies of algebra, geometry, trigonometry, land surveying, planimetry, stereotomy, valuation, and livellation. By 1863, the courses had a three-year duration. In the 1920 Ordnance, the *perit* now became known as Architect & Civil Engineer linking this with a professional warrant [24].

6. FROM VERNACULAR TO CLASSICAL BUILDINGS

The above outline of Malta's masonry construction methods adopted over the millennia notes how the complex erection procedures developed by the Temple Builders had over the centuries descended to the pits of cave dwellers. On the departure of the Arabs, in the 11th century, Sicilian masons had to teach building skills to the Maltese. The Maltese mason had at a point in time prior to the arrival of the Knights of Malta been master builders, able to construct single-cell troglodytic rectangular churches. These modest churches figures 6 & 7, had measurements averaging out at 7.5m long by 4.5m wide by 3.6m high (figure No. 6). These dimensions within a short span of time increased to14.5m by 9.1m by 6.7m, with the masonry slabs spanning 2.15m instead of the previous 1.525m (figure No. 7) [11].

From the mid-16th century onwards with the apprenticeships of the Maltese mason with Europe's main military engineers and planners, they developed into master masons. They were then in a position to undertake Latin cross basilica type parish churches in the villages. These were based loosely on the plans of Michelangelo in the Medici Chapel and the proposed façade of San Lorenzo in Florence, now meant that the vernacular required the application of the classical proportions that was underway in Europe. The plan of these churches now consisted of a wide nave with a choir at the far end and a series of chapels with saucer type domes on either side of the nave. The span of the wide nave had now increased to 15.5m. The overall width of the building 36m and its length, 57.5m, whilst the overall height was was 19.5m [20].

The tightly guarded principles which guided these master builders to create these large spaces was achieved via the long journey of apprenticeship to the career grade of master mason, and were mostly dependant on proportions, whilst adhering to low masonry stresses, with stocky piers ruling out instability problems due to buckling. The masons knowledge on load paths had improved, as by now they had resolved the problem of the horizontal thrust induced by the barrel vaults via sloping buttresses contained within the thick walls of the side chapels, now included in the plan layout [25].

An indirect parameter was used to express the strength of the stone chosen for the design of great masonry arches – based on the height to which, theoretically, a column of the stone might be built before crushing at its base due to its own weight. For medium sandstone and limestone, the height is 2km; for granite, 10 km. in the churches the piers carry more than their own weight, and must support the vault, the timber roof, and wind forces – nevertheless, stresses are very low. The crossing piers carrying a lantern in a basilica type will be working at an average stress of less than one tenth of the crushing strength of the stone; other main structural elements – flying buttresses, webs of masonry vaults – at one hundredth; and infill panels and the like at one thousandth of the potential of the material [25].

The Aesthetics of a structure is the outcome of the Social, Cultural, Geographical and Economic Contexts. From ancient times, two mathematical systems bring a sense of proportion to the world of design, namely the commensurable and incommensurable systems of proportion. Aesthetics refers to a commensurable system of proportions 1:2, 2:3 and 3:4 mostly related in the major scales of western music. When spaces or objects are organised and designed around these simple whole number ratios, they convey a sense of musical harmony. For example, the walls of cathedral naves are divided into three horizontal rows of arches called (from the bottom) the arcade, triforium and clerestory. The heights of these rows display whole number ratios such as 3:2:1,2:2:1 or 2:1:1 [26].

Another ancient system of proportions offered a different, perhaps even richer method of finding harmony between the parts and the whole. This is done not through whole number ratios that produce the harmonics in music, but through incommensurable ratios, like 1:√2, 1:√3, and 1:φ (or the golden ratio = 1:1.618).These are the very same numbers that appear in simple geometric shapes, such as the square and other equilateral polyhedral. The golden ratio appears frequently in nature too, most notably in the proportions of the human body. For example, the navel divides the human height into the golden proportion, and the line of eyebrows divides the human face in the same proportion [26].

Beauty being difficult to measure is not a luxury, but a human right. The concept of price, cost & value have different meanings. Low cost is not sustainable as it will not be here tomorrow. The beautiful & pleasant surroundings are what give added value. This appears modern rationale, but in truth refers to the Roman Vitruvian virtues or triads which dwell on practicality, durability & beauty

The Maltese master mason besides being well versed in the practice of stereotomy, defined as the art of cutting three-dimensional solids into particular shapes, was known to have a copy of Vignola's 5 orders on architecture (published in 1572). Vignola (Figure 8) had adopted most of the Roman architect, civil & military engineer Vitruvius's proportion principles in the multi publication De Architectura circa 50 BC. Vitruvius although producing an extensive 10 volume publication was less than an original thinker or creative intellect than a codifier of existing architectural practice, citing older works in his writings. This publication was lost and rediscovered in 1414 and then published by Alberti. However, the 5 Orders of Architecture by Vignola published in 1562, is considered one of the best architectural textbooks ever written. This despite having no text apart from the notes to the 32 annotated plates and the Introduction [27].

Figure 6: Chapel of Hal-Millieri in masonry construction Mqabba, consecrated 1480: 4.5m width, depth 7.5m on a 3.6m height – stone slabs spanning 1.525m onto masonry ashlar pointed arches, note rubble infill walling panels (SOURCE: Author).

Figure 7: Chapel of Bir Miftuh in masonry construction in Gudja, built circa 1430: 6.7m width, depth 14.5m on a 6.7m height – stone slabs spanning 2.15m onto masonry pointed arches (SOURCE: Author).

Laparelli in his earlier years had been the trusted assistant of Michelangelo on the building of St Peter's in Rome, hence the knowledge of the proportions of Michelangelo's buildings. On Laparelli's departure from Malta in 1569 his apprentice Maltese Gerolamo Cassar took over the planning of the major buildings in Valletta. Gerolamo Cassar became the Order's resident engineer and on his death in 1592, his son Vittorio Cassar succeeded him as the resident engineer in 1600. This confirms that these late medieval architect/engineers guarded tightly their well-known building principles. It is a well-known medieval practice that craftsmen kept the secrets of their trade within their own family [25]. This master mason during the time of the Knights of Saint John could have been elevated to a *perit (*the Italian word *perito* refers to an expert*)*. A *numerus clausus* was imposed at the time, with the number limited to 12, as prescribed by existing statutes like the Vilhena Code of 1724. A master mason could only be elevated to a *perit* on the death of an acting *perit*. There was some theoretical instruction, normally in Mathematics and Surveying [12]. The De Rohan Code of 1782 then references '*Periti Agrimensori*' and '*Periti Calcolatori*'. The primary role for *periti* was to measure and to establish the value of rural or urban properties, or other damages and interests in buildings [24].

The change from the vernacular to the classical constructions endowed various skills to the master builder, now also qualified as Architect/engineer. The engineering skills were related to providing robust buildings constructed to low stress levels, with however a high degree of proportionality principles in place. Prior to the use of bending theory, proportions were utilised for the sizing of timber joists, for example, dividing the span in feet by 2 and then add 2"to this answer to give the joists depth in inches. At that point in time load paths were being established, in the 16th Century Leonardo was aware of the cantilever action of a beam, whilst an arch was noted as an inverted catenary. It was the Industrial Revolution that witnessed constructions undertaken to structural engineering principles that we are aware of today. The 19th Century engineers imparted aesthetics in the design of the masonry bridges carrying the railway, whilst aesthetics impacted on the impressive 3-pinned steel structures, utilised for the opening up of the train stations in the centre of the cities. The masonry harbour works undertaken both in their layout & section wall profiles, broke up the impacting shoreline waves. Malta's Grand Harbour 2-arm breakwater completed in 1909 was constructed from the hardest stone available, an upper coralline limestone *Tal-Qawwi*, quarried from Gozo and has extremely good long-term weathering and durability properties.

It seems that the notion that the local coralline limestone was more durable than concrete in a marine environment held sway up to the early 20th century [28].

Building with engineering led to acoustically pleasing spaces, even though reverberation theory was not available as yet, in the same way that structural engineering was still
at its infancy. Towards the end of the 19th century Sabine published reverberation theory, which is a property of how sound decays in a space, thus placing acoustics within an engineering field.

The above discussion of aesthetics, proportion and acoustics can also guide today's structural engineer, given his expertise in numeracy. As Pevsner quotes in his Introduction [29], *a bicycle shed is a building: nearly everything that encloses space on a scale sufficient for a human being to move in is a building.* Thus the maxim for structural engineers to design in elegance and economy, is relevant and certainly also in masonry.

If, for example, a structural engineer is commissioned to design an assembly hall of plan dimensions 6m X 10m. By applying the golden rule to the diagonal plan dimension (8m) an aesthetically proportioned building height is calculated to be at 5m. Having established the volumetric proportions of the designed space, the structural engineer can then, by undertaking simple reverberation checks, be in a position to advise his client on the sound suitability for the use of the space being designed for, whether a living room, warehouse, or assembly hall. A short reverberation time in the region of 0.5sec - 1sec is more conducive to speech intelligibility, whilst a long reverberation time in the 2 sec region increasing to even 9 sec in Gothic Cathedrals improves on the quality of the music. If the reverberation time in a lecture hall is higher than 1sec, the listener will have to contend with multiple words at a time. The simple equation established by Sabine in the early 20th century notes the reverberation time as being directly proportional to the space enclosed and inversely proportional to the absorptive characteristics of the enclosed surfaces multiplied by a factor of 0.161. The more absorptive the materials used on surfaces together with the presence of an audience, the quieter the space becomes. Thus the above proposed assembly hall with an enclosed volume of 300m^3 and enclosed surface area of 280 m^2, with an assumed average absorption coefficient for surfaces at 0.3 taken as at 500Hz, gives a reverberation time of:

$0.161 \times 300/(280 \times 0.3) = 0.575$sec.

Today various calculators are available online, whereby the reverberation time is calculated, with the various absorptive coefficients for the various wall or ceiling surfaces given, thus reducing the design time involved.

In the case of party walls WHO/Europe's (30) guidelines for night noise, published in 2009, note annual average night exposure should not exceed 40 decibels (dB), corresponding to the sound from a quiet street in a residential area. Persons exposed to higher levels over the year can suffer mild health effects, such as sleep disturbance and insomnia. Long-term average exposure to levels above 55 dB, similar to the noise from a busy street, can trigger elevated blood pressure and heart attacks.

For airborne sound insulation assessments tests, involve measuring the noise level created by a loud sound source in one room and comparing it with the resulting noise level in the adjacent receiver room. The 'sound reduction index' (in dB) *of* a sample is a measure of the ratio of the sound energy incident on the sample to that transmitted through it.

Figure 8: Statue of Jacopo Barozzi (known as Vignola) with the 5 Orders annotated plates in La Rocca (Castle) Vignola Italy. (SOURCE: Author)

Figure 9: An 8-storey high apartment block constructed, in 1908 using compact globigerina limestone, Valletta. (SOURCE: Author)

A wall separating sole occupancy units, or between a sole occupancy unit and a public corridor, plant room, lift shaft, stairway, hallway, should have a Weighted Sound Reduction Index (R_w) not less than 45. R_w ratings are determined measurements conducted in one-third octave bands over all frequencies between 100 Hz and 4000 Hz inclusive (31).

Where a habitable room such as a living room, dining room, family room, bedroom, study and the like, but not including the kitchen, in one sole occupancy unit is situated next to a bathroom, sanitary compartment, kitchen or laundry in an adjoining unit, the wall separating the units must have an R_w not less than 50. In addition, the dividing wall construction must provide a "satisfactory" level of impact sound isolation. With the typical background levels in most suburban areas, an R_w 45 wall construction, would usually ensure television, telephone ringing and conversation will sound "muffled", but still audible. Unless the background sound level within the receiving room is very low, the transmitted sound should from these sources not be intrusive.

The difference in noise level between source and receiving rooms is not just a function of the 'apparent sound reduction index' of the separating structure. If the receiving room contains a high level of sound absorptive material (eg carpets and a sound absorptive ceiling) then the difference in noise level between the two rooms will be greater than if the receiving room contained hard surfaces. The size of the connecting structure also has an effect. The larger the area of common structure, the greater the sound energy transmitted.

Therefore, with identical wall constructions, room finishes and room sizes, the difference in noise level between two rooms will be less if they adjoin by their long walls, rather than by their short walls (32).

For a wall to reach its optimum acoustic performance, the construction must be solid without gaps through which air, and therefore sound, cannot pass. Rendering one side, of a wall increases the R_w rating primarily because the render seals the fine pores in the brickwork and also eliminates partially filled and unfilled mortar joints.

In addition, a layer of 13 mm render increases the mass of the wall and there will also be an increase in the acoustic performance. Once one side of a wall has been rendered, little acoustic benefit will be gained by rendering the other side (31).

A CSIRO technical study (31) notes that 215 kg/m^2 is the minimum mass per unit area required by an unrendered wall to ensure that an R_w of not less than 45 will be achieved when a layer of 13 mm render is applied to one side.
A simple rule of thumb that can be applied to materials to calculate their approximate transmission loss is the 'mass law' equation (33):

$$TL = 20 \log_{10} (mf) - B$$

Where: TL = transmission loss (dB)
m = surface mass (kg/m^2)
f = frequency (Hz) within a range of 100 -4000.
B = 48 dB (on average but can range from 45-53).

7. FROM LOW TO HIGHLY STRESSED MASONRY BUILDINGS

The present discussion has dwelt on the construction of basilica type churches and 3/5-storeyed high well-proportioned palaces/auberges noting the masonry in place to be stressed well below its allowable level.

From the 20th Century a number of buildings within Valletta replicate the happenings in the historic centres of European cities. Within Valletta's fortified city congestion led to residence buildings reaching heights of 8 floors or more (fig 9), inclusive of additional basement floors. Until the present, Europe has not embraced the multi-storey constructions as undertaken in America and Asia. In Malta the structural engineering principles which guided these architects/engineers on the overall height of these residences is outlined below. While aesthetics and proportion were guiding principles, the concept of adhering to low stresses was no longer applied. The soft globigerina limestone which could be so easily worked in producing mouldings was being stressed to its limit.

There is currently no simple way of assessing the basic compressive strength of masonry in-situ. Eurocode 6 [30] like all similar codes is aimed at the design of new structures to be constructed with modern materials. However, if the compressive strengths of the masonry units and mortar are known, then the characteristic strength of the existing masonry panel may be determined [34].

Globigerina masonry units at a dry density of 17.5kN/m^3, come in thicknesses of 230mm, and due to the material's acoustic property as gauged from equation i, is normally utilised as party walls in dwellings, whilst the 180mm thickness is utilised for internal partitions, or else as double walling when used on the façade, with a bond stone tying the two leaves together.

Table 1 and 2 outline the characteristic compressive strengths of the masonry panel constructed in a general purpose mortar M2 & M4, to the crushing strength of the unit noted. Compact globigerina together with the hardstone coralline are both illustrated in these tables. These values have been calculated as per equation 3.4 in EN 6.1.1, with K for dimensioned natural stone in general purpose mortar taken at 0.45. λ is noted as the shape factor, a coefficient dependant on the height and thickness of the masonry unit.

French studies (which to date results have not been confirmed) carried out to examine compact masonry in general purpose mortar [1] indicate an updated formula for the characteristic compressive stress f_k

$f_k = 0.4 f_b^{0.85} f_m^{0.15}$ ii - as opposed to:

$f_k = 0.45 f_b^{0.7} f_m^{0.3}$ iii - as quoted in EN 6.1.1.

Table 3 summarises calculation made by author for the characteristic loading capacity of the wall thickness per metre length. The factory of safety γ_m as per EC6.1.1 Cl 2.4.3 for this type of construction is taken at 2.2. This is arrived at by classifying Maltese masonry units as Category II, with any type of mortar being adopted, whilst workmanship is outlined under Class 2. The respective γ_m for BS 5628 was taken at 3.1.

Adopting the French studies [1], the proposed equation ii, outlines a 30% increase to the axial loads to table 3 for M2 mortar, whilst achieving a reduced 17% increase for the compact masonry units in M4 mortar. In truth this signifies a K factor (table 3.3 of EC6.1.1) for equation ii, as varying between 0.58 & 0.5 for the various compressive stresses of

Table 1 - Characteristic compressive stress f_k of 230mm thick masonry N/mm² for specified crushing strength - as per EC6-1-1

fk=k*(fb^0.7)*(fm^0.3)			fb= compressive strength*λ		
Mortar Designation	Globigerina				Coralline
	Compressive strenght of unit (N/mm²)				
	15	17.5	20	35	75
M4	5.16	5.75	6.31	9.33	15.91
M2	4.19	4.67	5.12	7.58	12.93

Table 2 - Characteristic compressive stress f_k of 180mm thick masonry N/mm² for specified crushing strength - as per EC6-1-1

fk=k*(fb^0.7)*(fm^0.3)			fb= compressive strength*λ		
Mortar Designation	Globigerina				Coralline
	Compressive strenght of unit (N/mm²)				
	15	17.5	20	35	75
M4	5.37	5.98	6.56	9.71	16.56
M2	4.36	4.86	5.33	7.89	13.45

Table 3 - Design axial loads for various wall types $N_{ed}=f_k*1000*t/\gamma_m$:as per EC6-1-1 and BS 5628

Material	Crushing strenght N/mm²	M2 -EC6 KN/m	M2 -EC6 KN/m accidental /seismic	Mortar type IV - BS 5628 KN/m	M4 - EC6 KN/m	M4 -EC6 KN/m accidental/ seismic	Mortar type III - BS5628 KN/m
225 franka	20	536	786	537	660	967	602
180 franka	20	436	640	493	537	788	551

masonry & mortar. The lower K values were also noted to relate to the higher M4 mortar grade.

It thus appears that Malta's compact masonry block should probably be better classified as being more akin to manufactured stone with a K value of 0.55 than dimensioned natural stone with a K value of 0.45, as outlined in table 3.3 of EC6.1.1. These are both defined as Group 1 masonry units, as per table 3.1 of EC6.1.1.
Table 3 also caters for the accidental/seismic condition. For this scenario the factor of safety γ_m as per EC8.1.3 Cl 9.6(3) for this type of construction is taken at 1.5 instead of the above 2.2. Cl 9.6 (3) notes recommended value for γm is 2/3 of the value specified, but not less than 1.5.

The above crushing strengths are based on dry masonry, loaded normal to the stratification. When loaded in the other direction an 8% loss in strength occurs. In a fully saturated state, the loss in compressive stress is on average 39% [36]. This loss in strength should be catered for in foundation works, where masonry is found in humid conditions or where the exposed façade is continuously wetted. The fire resistance for both types of thicknesses are in the 1½ hr range, as noted from table N.B. 5.2 in part 2 of Eurocode 6 [30].

Under the action of fire, limestone undergoes the following transformations. For temperatures up to 400°C pink or reddish brown coloration occurs for *franka* containing Fe_2O_3. Free of Fe_2O_3, a greyish colour develops, with the depth of coloration rarely exceeding 20mm. Around 600°C, colour disappears & calcinations occur with depth rarely exceeding 1cm. Calcinated limestone has a dull earthly appearance. No significant reduction in crushing strength occurs up to 400/450°C. At 600°C the masonry retains 60% of original strength thus it can be expected, based on analysis, that it is safe to re-build on existing walls except those stressed in tension.

This applies for elements stressed in compression. For masonry thin simply supported floor slabs which utilise the tensile strength of masonry, have been noted to be one of the first structural elements to collapse in a fire. The same may be said of masonry stair threads with only one end chased into a masonry load bearing wall.

Table No.3 also refers to the design strength of natural stone masonry. EC6 [30] does not refer to random rubble masonry, but BS5628 [37] notes that the characteristic strength of random rubble masonry may be taken at 75% of the corresponding strength of natural stone masonry built with similar materials.
In the UK prior to EC6 [30], the limit state masonry code BS 5628 [37] was introduced in 1978. This superseded the elastic state code CP111 [38] introduced in 1948. Prior to 1948, thicknesses of load bearing walls were listed in the London Building laws. These had been in existence since 1774. The laws of 1887 listed masonry buildings as high as 100' (30.5m), (8 stories high – this coincides with the European standards quoted earlier) – and required wall thicknesses at the base of 26" (66cm) decreasing to 9" (23cm) thickness at the top [44]. It is now interesting to note the extensive building regulations existing in the US, spanning between 1840 and 1920. Here data is given for load bearing masonry buildings 15 – 17 stories in height on an overall height of 275 '(83.75m). Here the thickness of the masonry wall at the base of the building is quoted at 7' (2.15m) thick. This is then to be compared to the 12" (30cm) and 16" (40cm) thickness quoted for masonry curtain walls. The promotion of high rise construction is indicated in these early US regulations [35].

Figure 10: streetscape in San Sebastian, Spain facing the river not exceeding 8 floors (SOURCE: Author).

As noted above in 1837 the first course had been undertaken for architects and land surveyors in Malta. These Periti of the time had contact with the Royal Engineers in Malta. These would have introduced the local *perit* to the requirement for the thickness of load bearing walls as outlined in the London Building laws. A document [40] issued in 1840 notes in its schedule C, wall thickness for residential and warehousing buildings. The greatest height quoted at 85' 0" (26.9m) (representing a building exceeding 7floors) has a wall thickness at 21 ½" (55cm) decreasing to 13"(33cm). The question now arises as to whether these recommendations for the thickness of these load bearing walls was based on structural calculations or whether reference was made to the theory of the column height prior to its crushing at the base due to its own weight.

In the early 20th century a total of 2 load bearing masonry apartment blocks had been constructed in Valletta each 8 stories in height, where the previous maximum was 5 storeys. They consisted of corridor type apartments serving rooms of approximate measurements 4.5m X 5.5m. The front corner room is an impressive 6m X 6m slabbed over in embedded steel joists (vibrations however noted disturbing to the user), supporting thin masonry slabs at 1m centres. The masonry wall thickness applied at the time related to 76cm for external walls, with internal load bearing partitions being 23cm thick. In certain strategic locations such as the stairwell, the thickness of the internal wall increased to 30cm. The loading on these encircling walls 23cm thick is calculated at 536kN/m. This load per metre corresponds with the load capacity of a 23cm thick wall as noted in table 3, which for M2 type mortar is quoted at 536kN/m. It is however to be noted that the load/m as calculated refers to a typical room dimension. The following describes how, the early 20th century Maltese engineers arrived at this building height limitation, as limited by the strength capacity of the globigerina building block.

In an 8-storey building, redistribution of loads will occur to the less loaded areas fronting corridors, bathrooms & box rooms. Towards the base of the building the total loading from the cumulative apartment floor area should be distributed on the load bearing walls included below this apartment floor. The above calculation then provides for some factor of safety in reserve for when possible structural alterations during the lifetime of the building create openings. Further weakening may occur to the building, for example, during refurbishment works which could involve intensive chasing requirements that go beyond the spirit of Tables 6.1 & 6.2 in EC6 [30].

Although CP111 [38] had first appeared in 1948, it was probably not availed of in Malta prior to 1970. This coincides with the introduction of the B.Sc.(Civil Eng) course introduced at the Malta Polytechnic in the mid-sixties. Prior to the adoption of CP111 in Malta, the masonry wall strength had been based on longstanding empirical practice within the profession at an elastic strength of 10.5ton/ft^2. This is equivalent to the ultimate strength of 3.5N/mm^2, which is below the ultimate stresses quoted above in tables 2 & 3 averaging out at 5.25N/mm^2 (16ton/ft^2).

The masonry structural Eurocode, EN6 [30] appears to refer to a maximum building height of 25m (8 stories) together with a maximum storey height of 4m. This can be inferred by referring in combination to Cl 5.3 (2) in EC6-1 together with Figure 3.1 in EC6-2. The workmanship Cl 9.1 which then refers to EC6-2 is also of relevance. These requirements have now been tabulated in Table 4, leading to a question. Have the medium rise buildings of around 8 storeys height located in the various European cities Figure 10, guided the above EC6 limitations?

Referring to Figure 3.1 EN 6.2 [30], the out of plumb of a vertical building should not be > 50mm. Table 4 notes the 50mm vertical alignment as obtained on a building height of 25m. This is noted to fall short of the height to deflection ratio of 300 (Table 4), now being a more severe span to deflection ratio of 500.

Figure 3.1 EN 6.2 [30], then also notes that for a storey height out of plumb to vertical alignment is not to be > 20mm. Table 4 notes the 20mm vertical alignment as obtained on a storey height of 4m. This does not follow the height to deflection ratio of 300, representing a less severe span to deflection ratio of 200.

8. STRUCTURAL DESIGN FOR MASONRY THIN FLAT SLABS.

This roofing technique was employed by Maltese builders in the late middle Ages and consisted of a thin masonry slab has been discussed in Section 3. The form of construction with timber or steel joists instead of masonry arches, continued in the Maltese Islands well into the early nineteen sixties, when reinforced concrete slabs took over completely. The design of these traditional masonry slabs as outlined is only presently required when old constructions are being refurbished and/or when a change of use is being contemplated. This may involve, for example conversion of an original residence to office or retail use.

The masonry codes as listed above only refer to the construction of modern buildings. However reference [39], states *that if the engineer is satisfied that the structure has already been subjected to a high proportion of its design load without physical distress, then the structure should be assumed to be serviceable, even if it does not comply with the code requirements. The guiding principle should be: "if it works leave it alone".* If a change of use is contemplated for this structure adequate calculation checks will have to be undertaken or if not possible load testing may have a role in demonstrating that the structure will be adequate to carry the loadings arising from the intended future use. This document further notes that *BS5628, like all similar codes, is aimed at the design of new structures to be constructed with modern materials. It does however contain information which, if suitably interpreted, can provide the basis for appraisal, once the strength of the unit together with the mortar is known.*

In Appendix A, a design method adopted from EC6 [30] Cl 6.3.2 dealing with walls arching between supports, to check the adequacy of stone slabs for their intended change of use is included. This is considered to be less time consuming and expensive than the alternative of carrying out a load test. Note however that Cl 6.3.2 (4) deals exclusively with the arch thrust developed solely from the applied lateral load, thus excluding vertical loading. This is to be expected as this code deals only in modern forms of construction, stone slabs not falling within this definition. On the other hand there is no reason not to apply its rationale for use in the case of refurbishment jobs for old premises necessitating a change of use, which requires a higher live loading, than previously subjected to.

The following calculations undertaken as per equation Nos. 6.18 – 6.20 in EC6 [30] outline this method as undertaken for vertical loading. This is undertaken for an overall floor thickness of 26.5cm, whilst the stone slab thickness is given at 4.5cm. For the roof, the environment is considered as humid, hence the compressive crushing stress of masonry is taken at 17N/mm^2, whilst for internal slabs, the dry condition is used giving a strength of 20N/mm^2.

The calculations as included for in Appendix A, note that for roof loading the spacing of these stone slabs between arch ribs or steel/timber joists is to be centred at 0.9m, whilst for office loading this is reduced to 0.81m. On the other hand for stone slabs 11.5cm thick, the maximum room span works out at 2.575m.

It is to be noted that during a fire, due to their limited tensile strength capabilities, these are one of the very first structural elements to fail.

9. SEISMIC VULNERABILITY OF MASONRY CONSTRUCTIONS IN MALTA.

A historical catalogue of "felt" earthquakes in the Maltese Islands has been compiled dating back to 1530. Although no fatalities were officially recorded during this time as a direct

Table 4 - Imperfections - out of plumb requirements to EN 6 .1.1: Cl 5.3.2

Height - m	δ=Ht/300	$v=1/100\sqrt{h_{tot}}$	δ
m	mm	rad	mm
4	13.33	0.005	20
9	30	0.0033	30
16	53	0.0025	40
25	83	0.0020	50
36	120	0.0017	60
49	163	0.0014	70

consequence of earthquake effects, damage to buildings occurred several times. In the catalogue time period, the Islands experienced EMS-98 intensity VII-VIII once

then notes the reduced MDR's between type C & B buildings for the various earthquake intensity.

Table 5 - Classification of Building: According to Anticipated Earthquake Intensity Damage [42]

Type	Description	Base shear design % of gravity
A	Building of fieldstones, rubble masonry, adobe and clay. Buildings with vulnerable walls because of decay, bad mortar, bad state of repair, thin cavity brick walls, etc.,	0.5%
B	Ordinary unreinforced brick buildings, buildings of concrete blocks, simple stone masonry and such buildings incorporating structural members of wood;	0.7%
C	Buildings with structural members of low-quality concrete and simple reinforcements with no allowance for earthquake forces, and wooden buildings, the strength of which has been noticeable affected by deterioration;	0.9%

Table 6 – Mean Damage Ratio (MDR) & Death Rates for building types B & C [42]

Building Type	B		C	
Earthquake Intensity MM	MDR	Death Rate	MDR	Death Rate
5	2%	-	-	-
6	4%	-	1%	-
7	20%	0.03%	10%	-
8	45%	1%	25%	0.4%

(11 January 1693) and intensity VII, or VI-VII five times [4]. The ESC-SESAME Unified Hazard Model for the European Mediterranean Region [41] classifies Malta in the top end of the 'Low Hazard's region', with a 475-year return period corresponding to PGA values of 0.04-0.08 g.

The worst recorded damage was during the 1693 event, which caused 60,000 deaths in Sicily. In Valletta it is reported that there was not one house that did not need some repair. The facades of some major buildings were detached from the main structure, and needed immediate repair. Some churches suffered major damage to their domes and severe cracks in walls. Serious damage was done to the old mediaeval city of Mdina. Here the Cathedral suffered partial collapse and many other buildings suffered serious damage. It should be noted that there are several remarks in the reports that show that many of the buildings in the city were very old and had been neglected for many years. In particular, the 13th century cathedral was already showing serious signs of disrepair before the earthquake, and plans had in fact already been drafted for its rebuilding. In Gozo, it was noted that the damage to the fortified Cittadella, was most probably due to long years of neglect, as was the damage to coastal towers.

Table 5 notes that the partially collapsed buildings in the1693 event were classified as old and neglected, falling under Type A (5% PGA), on the other hand the buildings in Valletta suffering damage are classified as type B (7% PGA). At 6% PGA seismic activity the MM for this event falls between VI & VII.

Table 6 gives a further indication that this event was below MMVII, due to no casualties being reported. Table 6 also indicates that an improvement could have been undertaken to these masonry buildings, this being if tying had been undertaken at the corners between the wall and the floor slab. Had this been undertaken, then these buildings would have been classified as type C buildings as per Table 5. Table 6

The MDR's referred to in table 6 refer to symmetrical buildings. For higher irregularity & asymmetry buildings these MDR's are 5 times or even higher. Nowadays the creation of soft storeys at street level, by opening up the floor plans for commercial use has increased the risk for seismic damage in the event of an earthquake.

EC8 [43] provides for the following detailing rules for masonry buildings in low seismic areas.

1/- Shear walls in unreinforced manufactured stones units are to have a thickness not:
< 175mm & $h_{ef}/t = 15$.
The masonry block thickness in use for a single leaf wall between party walls presently stands at 230mm, this also provides for good noise reduction characteristics between neighbours. Since 1976 internal partition walls have adopted a 180mm thickness. So rigidity in shear walls is provided for.

2/- For unreinforced masonry buildings, walls in one direction should be connected with walls in the orthogonal direction at a maximum spacing of 7 m.

3/- the number of storeys above ground for low seismic areas as noted in table 9.3 EC8 [43] should not be more than 4 floors, constructed to a mortar strength of M5. As noted above, masonry buildings constructed over 100 years ago are 8 stories in height and built in M2 mortar.

The following 2 equations from EC8 [43], note the importance of the q factor on the calculation of the seismic horizontal force. Eq 3.14, then notes that the higher the material value of q, the lower will be the seismic horizontal force.

$$F = S_d(T_1)\cdot m\cdot\lambda \qquad \text{(iv)}$$

Where $S_d(T) = a_g \cdot S \cdot 2{,}5/q \qquad T_b < T < T_c \qquad \text{(v)}.$

PGA a_g, determined for a mean return period with a value recommended in EC8 of 475 years. It is further to be noted that this PGA is to be determined for rock or other rock-like

formation, **including mostly 5 m weaker material at the surface.**
F is the horizontal seismic force acting on the structure, m is the seismic mass of the building & a correction factor λ = 0.85 is applied if the building has more than 2 storeys, otherwise λ = 1. The seismic mass which as quoted in [44] approximates to ball park figures of 1.2ton/m^2 for concrete buildings & at 0.6ton/m^2 for steel buildings.
The behaviour q factor is a structure-dependent parameter used to reduce seismic design forces below those corresponding to elastic response. This masonry seismic force reduction factor or behaviour factor, known as the q-factor, accounts in an approximate way, for inelastic response at ultimate.
Masonry buildings normally have long party walls, which for low seismicity can normally take the induced seismic jolt. In the transverse direction limited masonry stair/lift cores together with limited additional lengths of masonry walling may provide limited rigidity for the applied seismic jolt. In this instance couple action kicks in on the separate party walls & the existing vertical loading may be sufficient to counteract the induced uplift forces during a seismic jolt. The induced vertical loading is not to exceed the accidental/seismic load capacity of the masonry unit as noted in table No. 3.

There is presently discussion in the European seismic literature with respect to above masonry limitations in seismic regions.
As per [45] it is noted that *recent earthquakes as the 2012 Emilia earthquake sequence showed that recently built unreinforced masonry (URM) buildings behaved much better than expected and sustained, despite the maximum PGA values ranged between* ***0.20 - 0.30g,*** *either minor damage or structural damage that is deemed repairable. Especially low-rise residential and commercial masonry buildings with a code-conforming seismic design and detailing behaved in general very well without substantial damages.*
However, the results of the safety checks adopting linear methods of analysis applied to common real structural configurations of masonry buildings using a q-factor equal to 1.5-2.0, as suggested by some seismic codes like the current version of EC8, were found to be overly conservative and in contradiction with the experimental and post-seismic evidence. It was evident that using a q-factor equal to 1.5-2.0 as suggested by some seismic codes (e.g. the current version of EC8, CEN 2005a), it was practically impossible to satisfy strength safety checks for any configuration of two- or three storey URM buildings for PGA greater than 0.10g. In many cases, the strength safety checks would not be satisfied even for a_gS *greater than 0.05g.*

As a result of the investigations, rationally based values of the behaviour factor q to be used in linear analyses in the range of 2.0 to 3.0 are proposed for well-constructed box behaviour URM buildings. A strong irregularity can produce a decrease of the behaviour factor of about 30%.

Earlier work undertaken in Slovenia [46], noted the results of models of masonry buildings tested on the shaking-table noted values of ***q = 2.84,*** *2.69 and 3.74 had been obtained for the cases of* ***unreinforced****, confined and reinforced masonry buildings, respectively.*

Following the above discussion, table 9.3 in EC8 [43], is presently being replaced by table 14.3. This latter table notes that unreinforced masonry buildings (URM) in the 0.36g range are now stable up to 4floors & in the 0.48g range up to 3 floors, when in the previous table 9.3 no URM building was acceptable from 0.2g upwards.

What however appears strange between tables 9.3 & 14.3 in [47] is that whilst the minimum area of shear walls as at updated table 14.3 for 0.36g stands at 6.5%, this reduces solely to 4.65% at 0.07g. This to be compared to previous table 9.3, which had provided for 0% at 0.36g & 5% for 0.07g for all masonry constructions as founded on rock.

Calculations as undertaken by the lateral force method of analysis gives an indication of the percentage of walling as required to vary from 6.5% for 0.36g, down to 1.875% at 0.07g. These calculations are based for URM buildings founded on rock & at a q value of 2.5 not 1.5.

To go for lean structural seismic design, the above notes that the lateral seismic force induced depends largely proportionally on the peak ground acceleration for the region under consideration together with the q-factor in an inversely proportional manner. Should not a distinction be undertaken in deciding on the upper range of the q-factor, whether masonry is in ashlar or deteriorated infilled masonry constructions?
Hence the importance of not overdesigning for the peak ground acceleration & the q-factors to be adopted, as this otherwise creates repercussions to our Climate Emergency strategy.

Further discussion on Malta's construction vis-a-vis EC8, whilst also comparing seismic as against wind forces may be gauged from [48]. The following section discusses low seismic areas in combination with robustness requirements.

10. STRUCTURAL ROBUSTNESS TO BLAST DAMAGE

On 12 September 1634, a Hospitalier gunpowder factory in Valletta constructed around the late 16th or early 17th century accidentally blew up, killing 22 people and causing severe damage to a number of buildings. The gunpowder factory was not rebuilt and around 1667, a new factory was constructed in Floriana, far away from any residential areas. This practice is still adhered to today, with gunpowder factories constructed only outside villages. When a gunpowder factory blows up,

Figure 11: The devastation that resulted following the arson "chemical" explosion that went wrong, and which brought down a block of apartments and shops (Paola 1992) [49].

the blast occurring is too great, with the stiff geometric properties of these small compact rooms not sufficient to counteract the blast effect, resulting in many casualties. Fig.11 notes an arson event in a residential area, with the existing masonry construction reduced to a pile of rubble. Unfortunately 2 casualties occurred in this event.

On the other hand bottled gas explosions cause limited damage, with normally the catenary action of the masonry building coming into play to prevent fatal casualties. To limit progressive collapse, observance of the stability clauses for accidental damage as quoted in EN 1991-1-7 [50] should be undertaken. Tying of the walls with the floors as noted previously to limit seismic damage, should also be undertaken to limit blast damage. Sources [48] & [51] introduce the catenary/arching major effect that occurs in a corridored apartment layout plan.

It is also to be noted that anisotropic behaviour is well documented with Maltese masonry. This is a property where materials have varying strengths in different directions. Annex E in EC 6 [30] provides coefficients for 2 way spanning masonry adapting a method that has been applied successfully for water and soil retaining structures; however it unfortunately does not predict sufficient rigidity when applied to the damaging blast forces discussed here.

EN 1991-1-7 [50] further notes that for identified vertical ties, the minimum thickness of a solid wall is to be 150mm, with the 180mm thickness noted as being superior. Mortar is defined at M5, whilst the M2 adopted locally is noted as being inferior. Initially an M5 mortar should be adopted in the construction of firework factories.

The specific requirements as addressed in [44] are noted to be very similar to the masonry requirements for low seismic areas outlined in section 9 [43]. It is thus noted that the requirements for Consequence Class 2A buildings provides sufficient guidance for the detailing of masonry buildings in low seismic areas. For Class 2A buildings, horizontal tying should be provided, with vertical tying not addressed. Structural robustness requirements for Class 2A buildings [48] note that in masonry, it is usual to require the external walls and piers to be adequately connected to the floor construction to prevent their premature failure under outward pressure. This can be achieved by relying upon the shear strength of the connection, based on the type of masonry unit, mortar strength class and design vertical loading or on its frictional resistance based on design vertical loading and appropriate coefficient of friction if the wall is loadbearing. This anchorage obtained in practice, works abrogates the need for the horizontal ties as stipulated in [52].

Further, "key" elements are a structural component designed to withstand an accidental design load of 34kN/m2 without collapse. In the case of load-bearing masonry construction a more practical option could be to include for the notional removal of a section of a wall at a time.

Referring to reference [53], this document states *that load bearing masonry often presents a considerable surface area to a blast wave. Since loadbearing masonry is often associated with other elements of flooring or roofing which largely rely on gravity for interconnection, the destructive effects of a blast on masonry buildings is often extensive. Load bearing masonry is usually considerably redundant and distributing stresses through areas which, under other circumstances, could be omitted entirely from the structure. There is little logic in replacing a substantial section of a wall which may have been slightly displaced by the effects of an explosion if it is still capable of preforming its prime function in the new location.*

These comments however do not apply to the ultimate force of explosion as had occurred in Figure 11, but will apply to accidental gas explosions, which due to the mass of the masonry, may not affect a building' s overall stability.

In general blast standards prohibit the use of unreinforced masonry in the construction of new buildings to withstand significant blast effects. Research is ongoing on the use of a variety of materials such as fibre composite laminates, geotextiles, with wire meshing and spray-on polymers for retrofitting existing unreinforced masonry for blast protection [54].

In contrast, because of the ductility provided by the reinforcement and the mass provided by the grout, even minimally reinforced fully grouted masonry provides a high level of blast resistance. The distinction between unreinforced masonry and reinforced masonry is very important because properly designed and detailed reinforced masonry can provide a high level of protection at relatively low cost.

11. CONCLUSIONS

The Neolithic Temple Builders understood simple statics for the lifting of the megaliths in place, with their stability enhanced from their trilithons layout, leaning inwards in elevation. The doorways were then capped in a triple corbelled arching system in plan, which may have included a horizontal tying action induced by the thick masonry roofing slabs. From these elaborate massive masonry constructions, the Maltese Islands developed basic underground residences, evolving out of hewn out burial places.

The Arabs developed a basic roofing system that was based totally on masonry construction due to timber not being available. This roofing method was used in basic residences and modest churches. A single rectangular “ecclesiastical” space was not possible due to the thrust from the roof. To obtain stability the floor level was embedded in the ground, with the upper courses of the wall section above ground level.

The high period in building construction occurred with the coming of the Knights of St John to Malta in the mid-16th century. The Maltese mason mingled with the European military engineers, and in time the Maltese mason graduated from master mason onto *perit*. The buildings constructed at this time were of a modest classical design, and depended on their stability due to the low compressive stresses generated in masonry. This was evident in the basilica type of church construction adopted, with the roof thrust and load paths to the side, now fully understood. Nevertheless even in the palaces and residences undertaken, none exceeded 5 stories in height, although the compressive stresses developed were higher than in church construction, the compressive stresses developed were still significantly below the ultimate strength that could be developed by these wall panels.

Timber joists became readily available during the time of the Knights, whilst steel joists became available during the period of the British, early 19th century. During the latter period, mingling of the Maltese *perit* occurred with the Royal Engineers who were aware of the London Bylaws which dictated the thickness of walls to be adopted in medium rise buildings. In the early 20th century the first 8-storey buildings were constructed in Valletta. Here the masonry walling is noted to be stressed close to the ultimate strength of the Maltese masonry wall panels, on internal wall thicknesses at 0.23cm & 0.3m.

The seismic vulnerability of masonry buildings in Malta over the years is noted to have given good service in use, with no casualties having been reported. Buildings are noted as being quite robust in plan, whilst the good bonding practices of the masonry units, does not warrant the use of confined masonry construction, as adopted in countries with weaker masonry work practices. Current practice is to introduce soft storeys at ground level, and it is yet to be confirmed how these modern masonry buildings will perform when subjected to a substantial seismic event. This suggests, that whilst the Maltese Islands are noted as a low seismic risk, the seismic vulnerability of buildings over the past 35 years in the medium rise masonry category of 5 to 8 floors heights together with additional basement floors has been increasing.

Tying at the corners of the vertical walling with the floor slab will help in reducing the mean damage ratios MDR's, both for seismic and blast damage. In the event of a large scale incident such as an explosion of a works factory the masonry is likely to be severely affected.

Further, with modern constructions in masonry, the opening up of the ground floor has been referred to. This has created structures, whereby the overlying rigid masonry structure could be supported on a transfer slab at an upper level. If brittle partitions are adopted, then to limit the extent of stepped cracking to develop in these partitions, deflection limits of this transfer slab are to be increased from the span to deflection ratios of 1:250 normally adopted. Publication [55] notes span to deflection ratios in the range of 1:500 – 1:1,000, although even higher ratios are quoted. As noted in the Introduction, unlike the owners of older constructions who may be tolerant of cracking, nowadays the owners of newer constructions have a lower tolerance level to the development of cracks, even hairline cracks, classified as category 0 in [10], are unacceptable often resulting in litigation.

This work has traced the use of the *franka* globigerina limestone formation as quarried over the Maltese Islands for a period extending to over 6000years. The initial major works were in Neolithic Temples, which then scaled down to more modest domestic constructions. The roofing and floor slabs also incorporated thin *franka* slabs, initially supported on masonry arches, then timber joists and more recently onto steel joists, with this flooring construction surviving into the 1950's. The climax on the use of the *franka* material is noted during the Knights of St John Baroque period with the elaborate mouldings executed, utilising the property of its soft carving to a maximum. Besides in these palazzos its artistic merits were further taken advantage of in the funerary artistically carved globigerina limestone headstones as undertaken during the British period, adorning the cemeteries spread within and outside the Valletta masonry fortifications. This extended history is significant proof of the adaptability and ongoing viability of this particular Maltese building stone.

The ongoing courses in Dry Stone Wall Restoration (20hrs) or the more elaborate Stone Mason's course (120hrs) together with conservation courses on existing masonry facades help towards keeping alive this ongoing masonry heritage. It may however be frustrating to note the declining numbers in the number of annual applicants for the mason's course.

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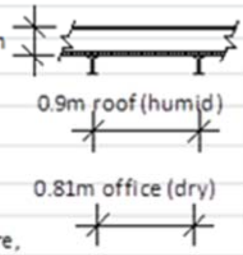
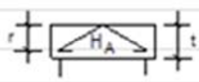
dhi PERITI STRUCTURAL CONSULTANTS		job No:	APPENDIX A	sheet No:	F01
		member / location.:	ROOF & INTERMEDIATE FLOORING		
		drg ref.:	to EN 1996-1-1 [15]		
job title:	MASONRY SLABS	made by:	DHC	date:	07/03/2017

Ref.	Calculations					Outputs
	Masonry slab 45mm thick and 230 mm wide					
	Shape factor λ=0.65					
	As no mortar involved use thin bed masonry equ					0.25m 
	f_k=0.75 $f_b^{0.85}$	(equ 3.3)				
						0.9m roof (humid)
	0.75x $17^{0.85}$	=	8.34	N/mm^2 (humid)		
	0.75x $20^{0.85}$	=	9.57	N/mm^2 (dry)		0.81m office (dry)
EN 6-(Cl. 2.4.3)	f_d= $f_k\lambda/\gamma_m$			where γ_m=2.2		where,
						f_b(humid)=17N/mm^2
	8.33x0.65/γ_m	=	2.46	N/mm^2 (humid)		f_b(dry)=20N/mm^2
	9.57x0.65/γ_m	=	2.83	N/mm^2 (dry)		
Roof Loading						
EN 6-(equ 6.19)	$q=f_d(t/l_a)^2$					
	$q=2460(0.045/0.9)^2$	=	6.15	kN/m^2		
ENO [29]						Roof
equ 6.10	0.25x 18x1.35+0.75x1.5	=	7.20	kN/m^2		L.L. 0.75kN/m^2
equ 6.10a	0.25x 18x1.35+0.7x0.75x1.5	=	6.86	kN/m^2		for maintanence access only!
equ 6.10b	0.85x0.25x18x1.35+0.75x1.5	=	6.29	kN/m^2	≠6.15kN/m^2	
Office Loading						
EN 6-(equ 6.19)	$q=f_d(t/l_a)^2$					
	$2830(0.045/0.81)^2$	=	8.73	kN/m^2		Office
						L.L. 2.5kN/m^2
ENO [30]						
equ 6.10	0.25x 18x1.35+2.5x1.5	=	9.83	kN/m^2		
equ 6.10a	0.25x 18x1.35+0.7x2.5x1.5	=	8.70	kN/m^2	< 8.73kN/m^2	
equ 6.10b	0.85x0.25x18x1.35+2.5x1.5	=	8.91	kN/m^2	< 9.54kN/m^2	
	Masonry Slab 115mm thick and 230mm wide					
	Where shape factor δ=0.84					
	f_d=8.33x0.84/2.2	=	3.18	N/mm^2		adequate for roof loading!
	$q=3180(0.115/2.575)^2$	=	6.34	kN/m^2	< 6.26kN/m^2	
	Strut and Tie Analysis for roof slab 45mm thick - 0.9m span					
	N_{ad}=BM/r					
EN 6-(equ 6.17)	r=0.9t-d_a			(d_a=0 as 900/45=20 < 25)		
	$N_{ad}=(6.15x0.9^2/8)/(0.9x0.045)$	=	15.375	kN/m		Roof loading condition
EN.6 equ 6.19	$N_{ad}=1.5f_d(t/10)$					
	1.5x2460x0.045/10	=	16.61	kN/m		
		≈	15.5	kN/m		
	Tensile strenght of masonry block 3.5 N/mm^2, with γ_m= 2.2					
	x = (16.61x2.2)/3.5	=	10.4	mm		