Malta’s Heritage in Stone : From Temple Builders to Eurocodes 6 & 8.

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USES OF THE VARIOUS ROCK FORMATION LAYERS

The Majority of Malta's traditional buildings were built of the Franka building block, laid on a bedding mortar. The combination of masonry with the bedding mortar has given excellent service in use, as evidenced by major buildings/churches constructed around 400 years ago or more.

The best masonry building unit is located in the Lower Globigerina layer.

A typical Maltese Quarry

TEMPLE BUILDERS – 3600 B.C.

A millennia prior to the Egyptian 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. It probably was village rivalry that compelled these farmers to conceive such remarkable monuments.

These temple builders, amongst a population not exceeding 5000 persons by much, just disappeared towards the end of the copper age.

TEMPLE BUILDERS - 2

Note Large slabs – Example taken from Hagar Qim Temples

STRUCTURAL ENGINEERING OF TEMPLES

If the construction of these megaliths is impressive, the plan layout consisting of a series of parallel semi-circular apses connected with a central passage way 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.

STRUCTURAL ENGINEERING OF TEMPLES - 2

The Excavated Mnajdra Neolithic Temple. Note Outstands of the masonry blocks in the adjacent fields

STRUCTURAL ENGINEERING OF TEMPLES - 3

The details as described in plan and section together with the 3 layers of massive lintels in place conforms with the writings in a technical paper which concludes 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 units in place could indicate that these temples were roofed over by thick masonry slabs.

STRUCTURAL ENGINEERING OF TEMPLES - 4

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 that of providing for a smoother and more expert finish. In older temples the rough more durable masonry was plastered over.

STRUCTURAL DECORATIVE ENGINEERING OF TEMPLES

The soft limestone was then availed of to carve the highly decorative temple of Tarxien, as located over Malta's Grand Harbour heights. This was provided with handsome relief carvings of spirals as well as friezes with rows of animals.

Tarxien Temples with carvings

FROM TEMPLE BUILDERS TO ARABS
870 – 11th CENTURY

A corbelled hit (girna), constructed in rubble masonry of locally sources UCL

FROM TEMPLE BUILDERS TO THE ARAB PERIOD – BYZANTINE SYRIAN 6th CENTURY CONSTRUCTION.

Our roofing technique consisted of masonry slabs of 45mm thickness spanning 1.2m onto masonry arches, on a bearing of 2cm – 3cm.

Masonry slabs of 115mm thickness span 2.25m without cracking on a bearing of about 7cm.

For rooms with a width of 2.75m this was facilitated by sloping the walls slightly inwards and then decreasing the span further by adding masonry corbels, just below these masonry slabs.

AESTETHICS OF EARLY MALTESE MASONRY BUILDINGS

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.

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.

NORMAN PERIOD UP TO THE KNIGHTS

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

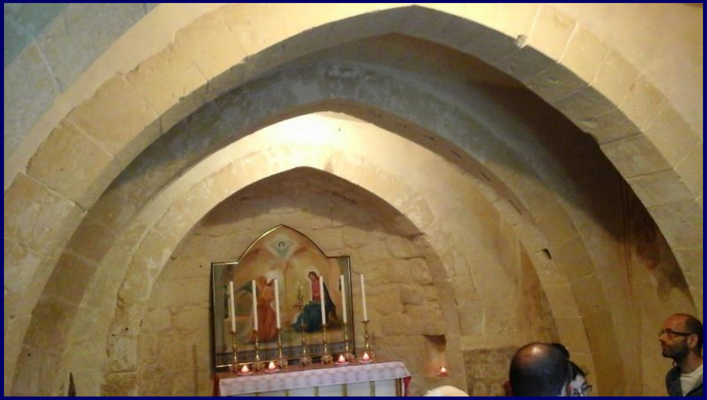
Construction in Gozo, Note rubble infill walling with ashlar at the corners, together with the top string of ashlar course

VERNACULAR 1300's TO CLASSIC PLACES OF WORSHIP -1

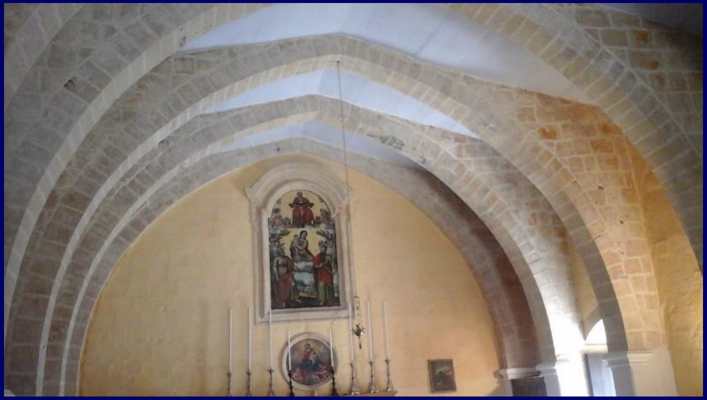
The Maltese mason & the single-cell troglodytic rectangular churches.

These modest churches had measurements at 7.5m long X 4.5m wide X 3.6m high. Within a short span of time these increased to 14.5m X 9.1m X 6.7m. Now masonry slabs now spanned 2.15m instead of the previous 1.525m.

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 had not as yet been successfully resolved in its descent to founding level.



Hal Millieri Church



Bir Miftuh Church

VERNACULAR TO CLASSIC 1500's PLACES OF WORSHIP -2

Mid-16th century onwards the apprenticeships of the Maltese mason with Europe's military engineers and planners, developed into master masons.

Churches now consisted of a wide nave with a choir at the rear & a series of chapels with saucer type domes on either side of the nave. The span of the wide nave now increased to 15.5m on an overall width of 36m X 57.5m depth X 19.5m height.

Sloping buttresses contained within the thick walls of the side chapels, had sorted the side thrust problem.

THE KNIGHT'S LEGACY 1530-1798

During this period timber joists were imported and these replaced the arched masonry ribs in the upper floors.

A typical timber joist ceiling

THE BRITISH PERIOD 1800-1964

The British towards the mid-19th Century introduced steel joists which were then used in parallel with timber joists. The steel joists were normally embedded into the masonry slabs producing a flat soffit.

A typical townhouse soffit from the British Period

The Code of Police Laws 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.

AESTHETICS, PROPORTION AND ACOUSTICS -1
As relating to Structural Engineers' numeracy.

As Pevsner quotes in his Introduction , *"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"*

To design an assembly hall of plan dimensions 6m X 10m, by applying incommensurable ratios, like 1:√2, 1:√3, and 1:ϕ (or the golden ratio = 1:1.618).to the diagonal plan dimension (8m) an aesthetically proportioned building height is calculated at 5m.

AESTHETICS, PROPORTION AND ACOUSTICS -2

A short reverberation time in the region of 0.5sec - 1sec is more conducive to speech intelligibility, whilst a long reverberation time 2-9 sec region in Gothic Cathedrals improves on the quality of the music. In a lecture hall, if time is higher than 1sec, the listener will have to contend with multiple words at a time.

Sabine's simple equation, early 20th century notes reverberation time as being directly proportional to the volume enclosed, inversely proportional to the absorptive characteristics of the enclosed surfaces multiplied by a factor of 0.161.

FROM LOW TO HIGLY STRESSED MASONRY BUILDING - 1

In the UK prior to EC6, the limit state masonry code BS 5628 was introduced in 1984. This superseded the elastic state code CP111 introduced in 1948. Prior the London by-laws had been in existence since 1774, listing bldgs 8 stories high. In the US regulations 1840 – listed bldgs. 17stories high.

Prior to the adoption of CP111 in Malta, around the 1970's, the masonry wall strength had been based on longstanding empirical practice at an elastic strength of 10.5ton/ft^2. This is equivalent to the ultimate strength of 3.5N/mm^2, below the ultimate stresses quoted later in table 1 at 5.25N/mm^2 (16ton/ft^2).

FROM LOW TO HIGLY STRESSED MASONRY BUILDING - 2

Dating 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 residences to building heights of 8 floors or more, inclusive of additional basement floors.

San Sebastian Spain 8-storey facade buildings

FROM LOW TO HIGLY STRESSED MASONRY BUILDING - 3

EN6 appears to refer to a maximum of 8 floors on 25m (50mm) height for a max storey height of 4m (20mm).

This may be inferred by linking Cl 5.3 (2) in EC6-1 with fig 3.1 in EC6-2. Workmanship Cl 9.1 is also related. These requirements have now been tabulated in table 4.

Have the medium rise buildings of around 8 storeys height located in the various European cities figure 10, guided the above EC6 limitations?

Table 1 – 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

An 8 storey high apartment block constructed, as 1908 in compact globigerina limestone, Valletta

Table 2 - Characteristic compressive stress f_k of 230mm thick masonry N/mm² for specified crushing strength - as per EC6-1-1

$f_k=k*(f_b\hat{}0.7)*(f_m\hat{}0.3)$			f_b= compressive strength*λ		
Mortar Designation	Globigerina				Coralline
	Compressive strength of unit (N/mm²)				
	15	17.5	20	35	75
M4 - 230	5.16	5.75	6.31	9.33	15.91
M2 - 230	4.19	4.67	5.12	7.58	12.93
M4 - 180	5.37	5.98	6.56	9.71	16.56
M2 - 180	4.36	4.86	5.33	7.89	13.45

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

Material	Crushing strength N/mm²	M2 -EC6 kN/m	Mortar type IV - BS 5628 kN/m	M4 - EC6 kN/m	Mortar type III - BS5628 kN/m
225 franka	20	536	537	660	602
180 franka	20	436	493	537	551

SEISMIC VULNERABILITY OF MASONRY CONSTRUCTION IN MALTA – 1.

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 due to earthquakes, damage to buildings occurred several times.

The worst recorded damage was during the 1693 event, causing 60,000 deaths in Sicily. Serious damage was done to the old mediaeval city of Mdina, with the Cathedral suffering partial collapse. Reported that many of the city buildings were very old and neglected for many years.

SEISMIC VULNERABILITY OF MASONRY CONSTRUCTION IN MALTA – 2.

Noting the damage sustained over this 475-year period, together with no casualties occurring, Malta is being defined of low risk seismicity.

The detailing as outlined in EC8 refers to a Minimum masonry thickness of 175mm in Grade 5 mortar.

Construction has to be cellular with maximum Spacing on orthogonal wall at 7m centres.

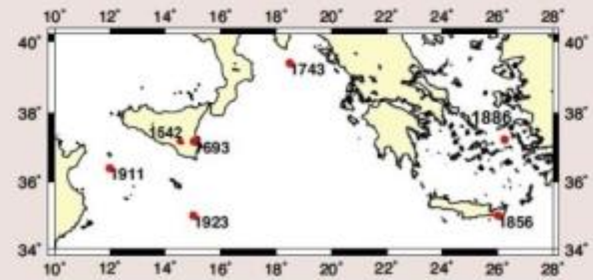
Maximum storey heights taken at 4 to 5.

To gain a robust construction best that tying Requirements as outlined in EN1-7 Appendix A Are abided by.

This includes for internal,
Peripheral & vertical tying requirements.

When Malta shook

The seven tremors that caused damage in Malta & Gozo



Date	Epicentre	Magnitude	Damage caused
10 Dec 1542	Eastern Sicily	7.0	Felt very strongly in Malta and a few one-floor dwellings (casupole) collapsed.
11 Jan 1693	Eastern Sicily	7.4	Most houses in Valletta damaged, some seriously;collapse of several church domes in Malta and Gozo; serious damage to Mdina, partial collapse of cathedral
20 Feb 1743	Ionian Sea	6.9	Damage to Mdina cathedral and numerous other churches
12 Oct 1856	Crete	7.7	Many houses in Malta and Gozo seriously cracked; several church domes and walls damaged
27 Aug 1886	Aegean Sea	5.5	In Valletta the Court of Justice, some churches and many houses suffered damage, as well as some buildings and the Cathedral in Mdina
30 Sep 1911	West of Gozo	7.3	Mostly felt in Gozo, where it produced significant damage to domes and houses; damage to Fort chambray; much less felt in Malta
18 Sep 1923	East of Malta	6.4	Mostly felt around harbour area, Malta; non-structural damage to churches and cracks in walls.

STRUCTURAL ROBUSTNESS TO BLAST DAMAGE -1

On 12 September 1634, a Hospitalier gunpowder factory accidentally blew up, killing 22 people and causing severe damage to a number of buildings. Around 1667, a new factory was constructed in Floriana, far away from any residential areas.

When a gunpowder factory blows up, the blast occurring is too great, with the stiff geometric properties of these small compact rooms not sufficient to counteract the blast effect, with many casualties occurring.

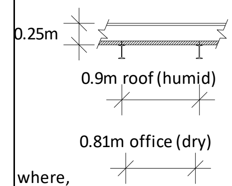
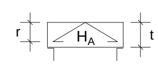
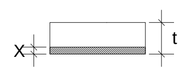
STRUCTURAL ROBUSTNESS TO SEISMIC & BLAST DAMAGE - 2

When a gunpowder factory blows up, the blast occurring is significant, with the stiff geometric properties of the small compact rooms not being sufficient to counteract the blast effect, resulting in many casualties.

This photo notes the devastation that resulted following the arson chemical explosion that went wrong, which brought down a block of apartments and shops. Unfortunately 2 casualties occurred in this event. (Paola 1992)

Much thicker walls than the 180mm thick specified for seismic design are necessary to counteract blast effects.

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
	<u>Masonry slab 45mm thick and 230 mm wide</u>					
	Shape factor λ=0.65					
	As no mortar involved use thin bed masonry equ					
	f_k=0.75 $f_b^{0.85}$				(equ 3.3)	
	$0.75x17^{0.85}$	=	8.34	N/mm^2(humid)		
	$0.75x20^{0.85}$	=	9.57	N/mm^2(dry)		
EN 6-(Cl. 2.4.3)	f_d= $f_k\lambda/y_m$				where y_m=2.2	where,
						f_b(humid)=17N/mm^2
	8.33x0.65/y_m	=	2.46	N/mm^2(humid)		f_b(dry)=20N/mm^2
	9.57x0.65/y_m	=	2.83	N/mm^2(dry)		
<u>Roof Loading</u>						
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	0.25x18x1.35+0.75x1.5	=	7.20	kN/m^2		L.L. 0.75kN/m^2
equ 6.10a	0.25x18x1.35+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	$\neq$6.15kN/m^2	
<u>Office Loading</u>						
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	0.25x18x1.35+2.5x1.5	=	9.83	kN/m^2		
equ 6.10a	0.25x18x1.35+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	
	<u>Masonry Slab 115mm thick and 230 mm wide</u>					
	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	
	<u>Strut and Tie Analysis for roof slab 45mm thick - 0.9m span</u>					
	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 y_m = 2.2					
	x = (16.61x2.2)/3.5	=	10.4	mm		

THANK YOU

FOR YOUR ATTENTION

Reference;
Camilleri D. H., “Malta’s Heritage in Stone: from Temple Builders to Eurocodes 6/8.’’ *Journal of the International Masonry Society Masonry International, Vol. 31, No. 2, 2019*