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Repair and Conservation of the Four Courts Dome, Dublin.

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ABSTRACT: The Four Courts was built between 1786 and 1802. Fire events, the 1922 civil war, pollution and exposure have damaged the building's fabric. A conservation project by the Office of Public Works focussed on the dome, an outstanding structure built with limestone, fire-clay brick and granite. This paper presents the results of the material's investigation prior to the restoration.

There were concerns that the new concrete dome, placed after the civil war, had altered the loading path of the original timber structure and was now transferring the weight of the roof onto the Portland stone and brick parapet. The similar compressive strengths of the original Portland stone in the dome (50 MPa) and the quarry stone (41-54MPa) suggest that there is little or no strength loss due to permanent loading in time therefore, the stone is probably not carrying any loads. The strength of the granite is lower than expected. This was mainly attributed to the use of granite boulders and the different shapes of the specimens (cubes vs cylinders). Except for 2 granite specimens which showed significant bucking before failure, all Portland stone and granite specimens failed in axial splitting and shear fracture indicating a brittle behaviour. The bricks display common features of the historic Dublin range suggesting that they were made locally. Despite the presence of pebbles, lime inclusions and black core, the strength of the bricks is outstanding, similar (often superior) to contemporary machine-pressed brick ware. Their failure evidenced significant plastic behaviour. Fracturing due to expansion of iron fixings embedded in the Portland stone was identified. Several Portland soffit stones were face bedded resulting in the opening of cracks along the bedding. Petrography evidenced repairs made with crushed Portland stone and white Portland cement largely in good condition however, the introduction of some polymer-based composites resulted in advanced deterioration.

KEY WORDS: CERI 2018; Full paper; Sample file.

1 INTRODUCTION

The Four Courts was designed by James Gandon and built between 1786 and 1802. There are 24 Portland limestone columns surrounding the dome, each with a carved capital. The fabric also includes Leinster granite and fired-clay brick. The building was almost completely destroyed by fire in the Civil War of 1921-22 when the original timber dome collapsed [1,2].

After the Civil War, T.J. Byrne, principal architect at the Office of Public Works, run a restoration project where the dome was rebuilt with concrete, in a single pour operation involving twenty men working for thirty hours. The capitals were rotated so that the damaged side was facing inward. Some were restored and two of them had to be entirely replaced with casts in artificial stone [3].

In 2011, a fragment of one of the capitals fell on to a roof below. This was attributed to the oxidation and subsequent expansion of a steel ring encircling the concrete dome [4].

In 2016, J. Cahill, principal architect at the Office of Public Works, run a conservation project and put together a team to deal with structural issues and the restoration of the capitals. There were concerns that the concrete dome had altered the loading path in the original timber structure (where the load of the roof was transferred down through the granite drum walls) and the load was now was transferring the weight of the roof onto the stone and brick parapet. There were also concerns that some of the material repairs introduced in the past were damaging the original fabric.

Weathering of historic materials is often related to the use of mortars, resins and metal fixings that are incompatible with the substrate. The need for physico- chemical compatibility between historic materials and their repairs has been investigated for decades and it is widely accepted [5, 6, 7, 8, 9].

Masonry was removed and the wall opened to determine the depth and condition of the existing stonework. The parapet brickwork, Portland stone and granite cores extracted during the opening works are studied in this paper. A condition assessment of the Portland stone capitals was carried out and former repairs removed and analysed to inform the project. This paper is part of a wider research program aimed at designing and testing compatible repair mortars for the dome.

2 MATERIALS AND METHODS

The strength of the brick, Portland stone and granite cores extracted during the opening works was measured according to EN 1926:2006 [10]. The strength was measured on 10 specimens of Portland stone (c.44 mm diameter and 109-114 mm height except for one -95 mm); 5 of Leinster granite (c.44

diameter / height 113-115mm) and 11 bricks. The bricks were cut to avoid peak points on the loading face and the compressive strength normalised to take into account the shape factor. Figure 1 displays the location of these materials in the dome. The condition assessment of the Portland stone capitals was mapped on images assembled by the Dept. of Surveying of the DIT. The composition, microstructure and current condition of the old repairs was studied with a petrographic microscope. Samples were removed, cut and polished to the standard thickness of approximately 20 microns and examined with a petrographic microscope. The petrographic examination was carried out by using transmitted both natural and polarised light at x2, x10, x20 and x40 magnifications.

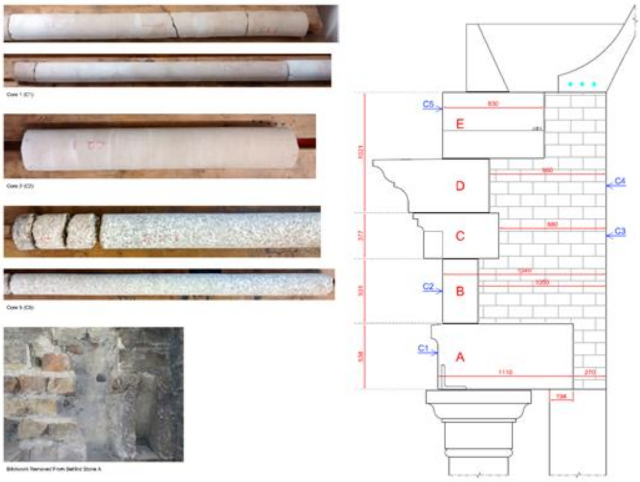

Figure 1. Location of the materials studied in the dome. Cores 1 and 2 (C1-C2) Portland stone; C5 Leinster granite; C3-C4 bricks. Figure by McFarland and Associates Ltd. 2016.

Portland stone, a Jurassic limestone quarried in the Isle of Portland, UK, has been used for building since the Roman times. In Dublin, most of the civic and administrative buildings which survive from the 18th c. are of Portland stone including City Hall, the Houses of Parliament, Custom House, the General Post Office, the National Gallery, the National Library and most historic buildings in Trinity College. Portland stone was used in London (the British Museum, Somerset House, the General Post Office, the Bank of England, Mansion House, the National Gallery, St Paul's Cathedral, Buckingham Palace, Westminster Palace and the Tower of London); Manchester, Liverpool, Cardiff, Plymouth, Bristol and Oxford. It is still used today, examples are the extension to the National Gallery, the United Nations headquarters in New York City, Casino Kursaal in Belgium and the BBC Broadcasting House in London.

Leinster granite is one of the main historic building materials in the Dublin area. Most of the granite used in Dublin was drawn from nearby quarries in Counties Dublin and Wicklow and used in most of the buildings constructed between the 17th and the 19th centuries often combined with Portland limestone. It is generally a medium to coarse rock with essential quartz (30%), feldspar (35%), plagioclase (25%), muscovite (7%) and biotite (3%) and minor sericite, kaolinite, chlorite, opaques, zooisite, tourmaline, rulite and sphene. It is typically strong and durable however, it can be affected by micro-fracturing, mineral alteration, staining, salts and general damage resulting from acid and alkaline cleaning and blasting [11,12].

The fired-clay bricks are solid, pressed bricks displaying some common features of historic Dublin range. The varying colour as well as the presence of pebbles, sand matrix, black core and reduction areas suggest that they were probably made using a local raw material.

3 RESULTS

3.1 Compressive strength

The failure modes observed in the Portland stone under uniaxial compression were predominantly axial splitting and shearing along single planes- figure 2. The results were various types of brittle fracture. Longitudinal splitting by the uniaxial load was apparent in most specimens often in combination with conic fractures probably induced by boundary effects. Figure 2 illustrates some the most representative failure modes.

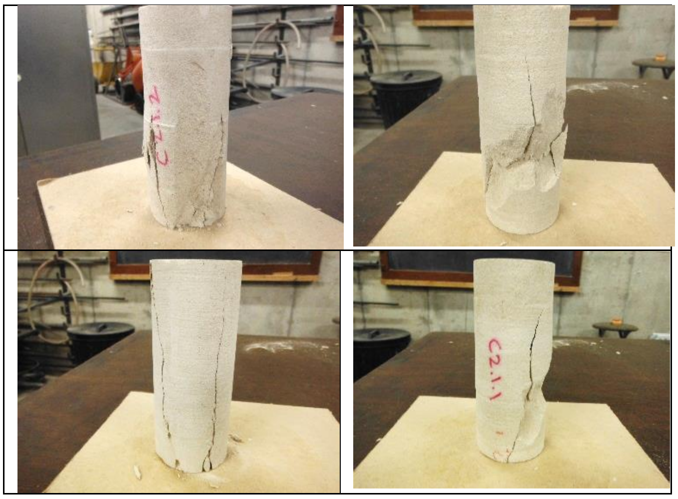

Figure 2. Brittle failure modes in Portland stone with predominant longitudinal splitting.

Table 1. Compressive strength and density of the Portland limestone from the dome. COV – coefficient of variation.

Portland stone specimen	Compressive Strength (MPa)	Density (Mg/m3)
C1.1	57.2	2.50
C1.2	47.4	1.85
C1.3	51.5	2.14
C1.4	42.6	2.15
C1.5	50.7	2.14
C1.6	55.2	2.15
C1.7	59.7	2.14
C1.8	42.3	2.14
C2.1	62.3	2.11
C2.2	30.3	2.14
AM	50 *COV 19%*	2.14 *COV 7%*

The compressive strength of the Portland limestone from the Four Courts dome, loaded perpendicular to the bedding is 50 MPa (arithmetic mean of 10 tests- table 1). The compressive strength of the un-weathered quarry stone ranges from 54.23 (arithmetic mean of 6 tests) to 41 MPa (reported by the supplier)- table 2. Therefore, the strengths of the dome and quarry stone are very similar. However, when the load is applied parallel to the bedding (face bedding) the strength drops to c. 39 MPa [14].

Table 2. Mechanical and hygric properties of the un-weathered Portland Stone from the quarry. COV (%).

Property	By supplier	Pavía and Aly [13]
Compressive strength(MPa)	41.15	54.23 *(1.76)*
Flexural s. (MPa)	6.85	6.23 *(1.12)*
Porosity (%)	18.81	15.40 *(0.6)*
Water absorption (%)	8.86	7.19 *(0.79)*
Capillary suction ($gm/m^2.sec^{0.5}$)	-	82.16 *(2.54)*
Vapour Permeability (kg/m·s·Pa)	-	$2.75x10^{-11}$ *(7.83)*
Bulk density (Kg/m^3)	-	2159.15 *(0.60)*

The arithmetic mean of the compressive strength of the 5 boreholes of granite tested is 35.8 MPa- table 3. This is lower than expected when compared with fresh Leinster granite (102.00 -139.00 MPa [15]) however, still a high strength when compared to the average strength of masonry building units. Figure 3 illustrates the characteristic failure modes of the granite. Only specimen one (right) and 5 (left) showed significant bucking before failure. All other specimens failed in shear fracture indicating a brittle behaviour.

Table 3. Mechanical and hygric properties of the Leinster granite in the dome. COV(%).

Granite Specimen	Compressive Strength (MPa)	Density (Mg/m^3)
C5.3.1	38.7	2.49
C5.3.2	37.8	2.50
C5.3.3	29.8	2.51
C5.3.4	35.6	2.52
C5.3.5	37.1	2.52
AM	35.8 *COV 9.8*	2.50 *COV 0.4*

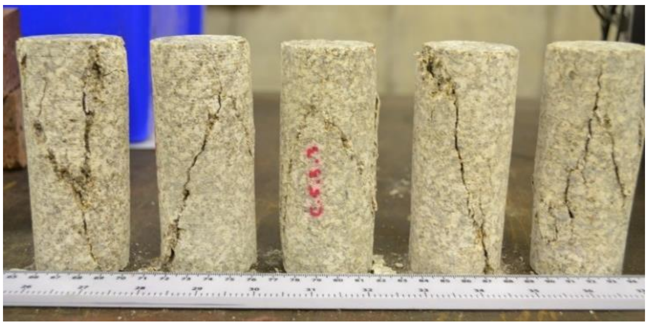

Figure 3. Failure modes of Leinster granite cores.

As expected for historic solid, pressed bricks the strength varies. The strength of brick number 8 is not representative as its features suggest that it was underfired. The arithmetic mean of the brick strength is 31.55 MPa (excluding brick 8), superior to common values for historic solid ware (13-22 MPa [15]) and comparable or superior to contemporary machine-pressed, single frogged ware (>20MPa, EN 771-1[16]). Figure 4 illustrates the characteristic failure modes of the bricks showing crushing, split tensile failure and pore collapse. Their ultimate stress and failure were characterised by a progressive collapse rather than a sudden shattering evidencing a plastic behaviour. An initial collapse of the specimens occurred by shear and cracking but the final collapse was only reached at a later stage by increasing the applied load.

Table 4. Compressive strength of bricks.*excluding brick 8.

Brick No.	Density Mg/m^3	Comp. Strength MPa	Shape Factor (d)	Corrected strength MPa
1.a.	1.81	38.1	0.843	32.1
1.b.	1.76	34.7	0.837	29.0
2	1.85	23.1	0.890	20.6
3	1.64	19.8	0.818	16.2
4	1.76	43.0	0.873	37.5
5	1.64	37.2	0.836	31.1
6	1.74	41.0	0.872	35.7
7	1.75	36.9	0.864	31.8
8	1.57	15.2	0.829	12.6
9	1.74	41.1	0.833	34.2
10	1.72	54.1	0.875	47.3
AM	1.72 *COV 4.6*	29.82 *COV 33;* 31.55* *COV 27*		

Figure 4. Failure modes of the bricks in the dome.

3.2 *Condition assessment*

Fracturing induced by expansion of iron fixings embedded in the fabric was identified together with several generations of mortar repairs and resins. Several Portland soffit stones were face bedded which has resulted in the opening of cracks along the bedding. Varying weathering forms and intensity were evidenced in the material including: spalling, soiling, surface loss and cracks. Black crusts were found especially in sheltered areas. The results of the condition assessment were mapped, a representative example is included in figure 5.

Most repairs are cement or polymer-based composites which are currently failing. Polyester or epoxy resins with aggregate of crushed Portland Stone and/or siliceous sand were noted. These are generally incompatible with stone substrates as they exhibit different behaviour in ambient conditions. Some have resulted in advanced deterioration. Most of the Portland cement repairs consist of crushed Portland stone and a PC binder (figure 6). In contrast with the polymers, some of these are in good condition and do not evidence salts or strong damage however, they are progressively detaching from the Portland stone probably due to differential thermal and hygric expansion at the interface.

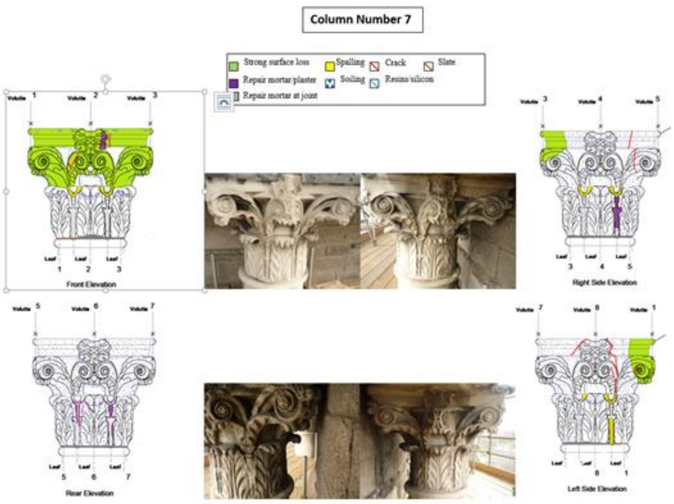

Figure 5. A representative example of the mapped condition assessment- column capital No 7- on drawings assembled by the Dept. of Surveying of the DIT.

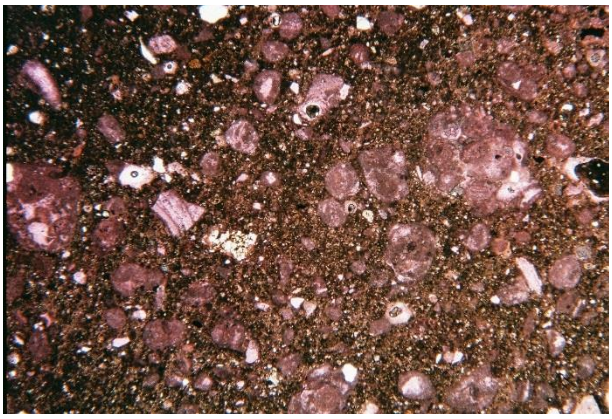

Figure 6. Petrographic photograph of a cement repair made with crushed Portland stone and a PC binder in good condition. 2X natural light. Field of view c. 7 mm.

4 DISCUSSION AND CONCLUSION

The original loading path of the dome's copper roof went downwards through the granite wall in the drum (behind the columns) so that the Portland stone capitals and columns had an aesthetic rather than a structural role. There were concerns that the new concrete dome, placed after the civil war when the Four Courts was rebuilt, had altered the original loading path of the timber structure and was now transferring the weight of the roof onto the Portland stone and brick parapet. There were also concerns that the Portland stone (see soffit stone A in Figure 1) was acting as a cantilever, as it projects 150 mm over the 450 mm wide granite wall below (B McFarland, P. Harrison pers. com. 2016).

Strength loss may be related to permanent loading in time. Creep strains can lead to strength loss and cracking resulting from constant compressive loads. When subjected to sustained stresses, masonry can fail due to the coalescence and unstable growth of microcracks induced by creep strains which has been the reason for the collapse of some medieval towers [17].

The compressive strength of the original Portland stone (placed in the building before 1802) is 50 MPa comparing well to the quarry stone (41-54MPa). Given the variability of natural rock this difference is not significant which suggests that the rock may not be carrying any loads at the dome.

On the contrary, the strength of the granite is much lower than expected (102.00-139.00 *vs* 35.8 MPa - quarry and building respectively). This could be partly attributed to strength loss due to permanent loading however, the granite core tested came from the top of the parapet (figure 1) which is probably outside the load path and does not seem to carry or have carried any significant loads.

The granite's low strength may be due to a combination of factors including use of granite boulders and the different shapes of the specimens tested (the quarry values come from cubes while the Four Courts granite was tested as cylinders). Cubes are stronger than cylinders as the ratio of length to height determines how strains build up in the specimen and is one of the main parameters that affect the strength measured (a factor of 1.2 is used to convert cylinder to cube strength for normal-strength concrete) [18]. Despite applying the concrete factor to the Four Courts granite the strength remains low.

The bricks display some common features of historic fired-clay brick including rock fragments (limestone, flint and others), cinders and occasional black core. These features suggest, that they were made locally. Despite the presence of pebbles, lime inclusions and black core, the strength of the bricks is outstanding as it is similar (often superior) to contemporary machine-pressed brick ware.

The weathering is typical of Portland stone in urban atmospheres. The PC repairs are generally failing but haven't been significantly detrimental to the Portland stone however the introduction of some polymer-based composites resulted in advanced deterioration.

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