PRESTRESSED KETTON STONE PERIMETER FRAME : THE QUEENS BUILDING, EMMANUEL COLLEGE, CAMBRIDGE

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ABSTRACT

The Queen's Building at Emmanuel College, Cambridge, was completed in April 1995. It provides the College with a 170 seat auditorium, reading rooms and music practice rooms. The building features a structural stone perimeter frame constructed from Ketton Stone, an Oolitic Limestone from Ketton in Lincolnshire. The frame comprises 28 prestressed Ketton Stone columns, and rings of Ketton Stone flat-arches at first floor, second floor and eaves level. In addition to providing support for the heavy acoustic roof and upper floors, and contributing to overall stability of the building, the frame forms part of the weatherproofing envelope and contributes to the thermal and acoustic performance of the envelope.

A testing and development programme was undertaken to determine the relevant properties of Ketton Stone including compressive strength, elastic modulus, creep, durability and its resistance to rain penetration. From the results of this programme the design of the frame was completed and a series of procedures were established for the manufacture and construction of the frame.

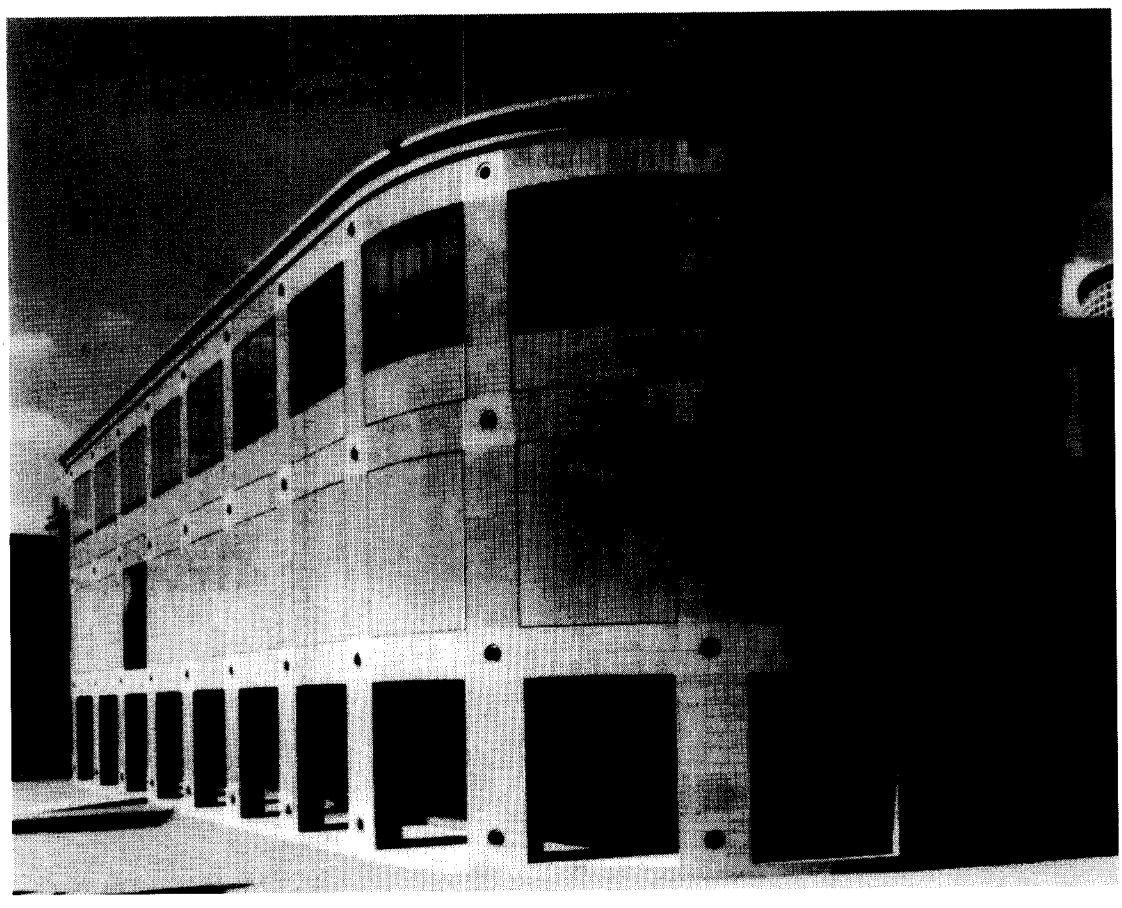

Figure 1: The Queens Building: Emmanuel College, Cambridge

INTRODUCTION

In July 1992 Emmanuel College, Cambridge invited several Architects to submit scheme designs for a new auditorium building to be built adjacent to the College's 17th century Christopher Wren Chapel. As a result of this competition Michael Hopkins and Partners were appointed as Architects for the new building, and Buro Happold were appointed as Structural Engineers and Building Services Engineers.

The building is 3 storeys high and 31 metres long by 12 metres wide, with each end curved to a radius of 6 metres. The ground-floor includes music practice rooms and reading rooms. Much of the first and second floors are occupied by the 170 seat auditorium, with the remainder being occupied by a common room, foyer and reception room.

It was decided at an early stage that the perimeter of the building would be of Ketton Stone to be in keeping with the adjacent Wren Chapel, and that it would be in a form of a load bearing frame featuring solid stone columns and flat arches.

DESCRIPTION OF KETTON STONE PERIMETER FRAME

The perimeter frame comprises Ketton Stone columns, 3 storeys high, with Ketton Stone flat arches spanning between columns around the perimeter of the building at first-floor, second floor and eaves level. The columns provide support for the building's heavy acoustic roof, the upper floors and a cantilever gallery around the auditorium. It also contributes to overall stability of the building. To accommodate the resulting flexural stresses each column is prestressed by means of a 32 mm diameter stainless steel post-tensioning rod. Non-structural infill panels above first and second floor are formed by triple-glazed windows and Ketton Stone cavity-walls. There are no infill panels at ground floor level, thus creating a colonnade around the perimeter of the building.

Figure 2 shows a part elevation on the stone frame

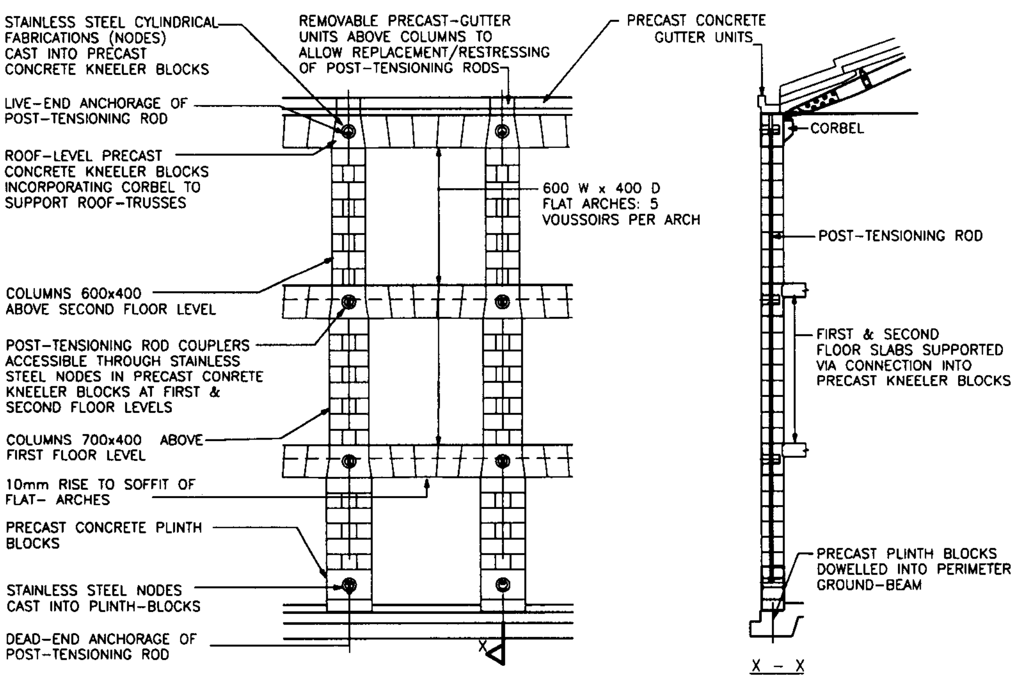

FIGURE 2 : PART ELEVATION ON STONE FRAME

The columns are 800mm wide by 400mm thick at ground floor level, reducing to 700mm wide at first floor level, and 600mm wide at second floor level. They are built off precast concrete plinth blocks at ground floor level and incorporate precast concrete kneeler blocks at first floor, second floor, and eaves level. The plinth blocks and kneeler blocks are cast with white cement and selected aggregates, to achieve a colour resembling that of Ketton Stone. The kneeler blocks taper in width, thus providing the transition in column width at each floor level and providing springing points for the flat aches. They also transfer the floor loads into the columns. The roof level kneeler blocks also incorporate corbels to support the roof trusses.

The dead-end anchorage of the post-tensioning rod is achieved by a large nut bearing against a stainless steel plate within a cylindrical fabrication (known as a node) cast into the plinth block. A similar arrangement within the roof level kneeler block provides the live-end anchorage. Each rod is installed in 3 lengths connected by couplers which are accessible through nodes cast into the first and second floor kneeler blocks; this allows inspection and replacement of the post tensioning system and expresses it architecturally.

The frame is constructed to very fine tolerances; individual masonry units are manufactured to within ± 1mm and the thicknesses of mortar joints varies between only 2 mm and 4 mm.

DESK STUDY

An initial desk study was carried out to investigate relevant aspects of Ketton Stone including availability, methods of extraction, geology, physical properties, weatherproofing, durability and the ability to cut and work the stone economically.

The quarry, in the village of Ketton in Lincolnshire, is owned by the Castle Cement Company. The quarry-face is 2 miles across and 25 metres high. The quarry mostly comprises limestones and mudstones used in the cement making process. 3 metres from the top of the quarry face is a band of Oolitic Limestone; it is this stone which is known as Ketton Stone, and which has been extracted since Roman times.

The quality of freestone varies considerably throughout the quarry. This has resulted in previous projects suffering delays due to the supply of Ketton Stone disappearing part way through the project. Ketton Stone also has a greater degree of flaws within it than other Oolitic Limestones; this results in high wastage factors and requires considerable skill to obtain finished masonry units of reasonable sizes. The limited amount of strength data available suggested strengths of the order of $15N/mm^2$ to $30N/mm^2$, although it was not clear whether these were average or characteristic strengths, or whether they related to stone specimens or completed masonry. Nevertheless, this limited information was sufficient to conclude that the concept of the building could be pursued.

Discussions with stone masons experienced with Ketton Stone, indicated that to produce the 200 tonnes of finished masonry required for the building, approximately 900 tonnes of useable freestone would be needed. To obtain this some 4000 tonnes of stone would have to be extracted from the freestone bed (the remainder being blocks too small to use).

The desk study concluded that Ketton Stone would be suitable for the stone frame, subject to a strength testing programme being carried out to verify its properties and subject to rain penetration tests being carried out to verify the suitability of solid Ketton Stone in the weatherproofing envelope. It also concluded that negotiations with the Castle Cement Company, and investigations into procurement routes should start immediately, to ensure that the stone could be obtained in time.

STRENGTH TESTING

General

The original strategy for strength testing and construction technique development was to :

- Carry out small scale tests on specimens of stone to determine the range of compressive strengths and other relevant properties.
- Interpret the test results to predict the characteristic compressive strength of completed masonry.
- Test a storey height column, built using the mason's proposed technique, to verify whether this would result in a strength consistent with the prediction.

In the event, after the large scale column test, a further programme of construction technique development was undertaken and a series of scaled down columns tested, after which a further large scale column was tested. This programme of development and testing was carried out jointly between the authors and Ketton Architectural Stone, (the masons appointed for the construction of the stone frame). The majority of the testing was carried out at the University of Cambridge Structural Engineering Laboratories.

Small Scale Testing

The small scale testing included compressive strength tests, elastic modulus tests, creep tests, point load tests and flexural strength tests. The tests were carried out on both dry and saturated specimens. The majority of the testing comprised compressive strength tests carried out perpendicular to the bedding, though some was carried out parallel to the bedding, in order to assess the effect of individual masonry units being orientated incorrectly. The results of the compressive strength tests are summarised below :

- Dry, perpendicular to bedding : Average = 30 N/mm^2 [Char. = 20N/mm^2]
- Wet, perpendicular to bedding: Average = 24 N/mm^2 [Char. = 15N/mm^2]
- Dry, parallel to bedding : Average = 21 N/mm^2
- Wet, parallel to bedding : Average = 17 N/mm^2

The creep test results confirmed that creep effects level out quickly. The results were plotted as strain against log time and the curve extrapolated to predict the specific creep strain at 100 years; this allowed long term prestress losses to be estimated.

Prediction of f_k From Small Scale Testing Results

The characteristic compressive strength of Ketton Stone masonry was estimated by analysing the small scale testing results, and considering the effects of :

- The reduced extent of external restraint against lateral tensile splitting of stone within a column compared to that of specimens in a testing rig.
- The presence of mortar joints between individual courses.

This resulted in a predicted Characteristic Compressive Strength of 12.5N/mm^2.

Construction Technique Development

In determining the construction technique to be adopted, consideration needed to be given to achieving a number of objectives including structural performances, durability, weatherproofing, appearance and buildability.

The originally proposed construction technique was investigated by means of a single large scale column test. Although the ultimate strength of the test column represented a significant factor of safety over the calculated maximum service stress in the columns, the strength was less than the predicted characteristic compressive strength. A detailed post-mortem of the test column was carried out which concluded that the lower than anticipated strength was due to a combination of :

- Occasional unevenness within the mortar beds (resulting in high local stresses)
- Cramps, used as fixing aids, acting as stress raisers.
- The possibility of a few masonry units having been installed such that they were loaded parallel to the bedding.

The manufacturing and construction process were reviewed in the light of the post mortem. The use of cramps was deleted, and further safeguards introduced against accidental incorrect orientation of individual units. A series of column trial builds showed that the unevenness in the mortar beds was due to the stone sucking moisture from the mortar as soon as they made contact, with the result that any minor adjustment during laying broke the bond and caused unevenness in the mortar bed. Modifications were made to the water content and mix proportions of the mortar to improve its water retention properties. This, combined with priming the mating surfaces with a slurry coat prior to laying dramatically improved the quality of the mortar beds. Trial builds proved that with these modifications, uniform mortar beds across 95-100% of the bed joint were consistently achieved.

Scaled Down Column Tests

To verify that the revised technique would result in a strength consistent with the predicted strength, 10 scaled down columns were built and tested. The columns were 300mm by 200mm by 800mm high.They were tested at ages ranging from 4 days to 7 days. The average of the test strengths for the 10 columns was 16.5N/mm^2, with a Characteristic Strength of 12.5N/mm^2.

Second Large Scale Column Test

Prior to construction proceeding on site, a further large scale test was carried out on a storey height column.The 500 tonne capacity of the test rig (representing an applied stress of 20N/mm^2) was reached prior to failure of the column. This proved that column strengths in excess of the predicted Characteristic Strength could be achieved in practice.

RAIN PENETRATION TESTING

The rain penetration study was carried out and co-ordinated by Michael Hopkins and Partners as follows:

- Desk Study
- Preliminary tests to compare the behaviour of Ketton Stone Masonry and concrete blockwork masonry
- Quantitative tests on panels of Ketton Stone masonry

The desk study identified that the area of the building most vulnerable to rain penetration would be on the north and east elevations, immediately beneath the parapet gutter, and that the worst spell in a 10 year period would result in 17 litres of wind driven rain per square metre per spell.

Empirical data suggested that a 400 mm thickness of dense blockwork masonry would be more than adequate to resist such exposure. A simple comparative test was carried out to compare the behaviour of Ketton Stone masonry and blockwork masonry. Panels of each were constructed in Ketton Architectural Stone's yard and sprayed with water. The tests showed that Ketton Stone Masonry offered greater resistance to rain penetration than blockwork masonry.

In order to confirm the suitability of 400 mm thick Ketton Stone masonry a 1.8m x 1.8m x 400 mm thick test panel was built at Ceram Building Technology's laboratory at Stoke-on-Trent, and subjected to water spray. It was considered that the worst 1 in 10 year spell could be simulated by applying spray in 8 periods, each of 5.7 minutes at 1.2 litres per minute. In fact, a total of 10 spray periods were applied, over a 2 day period.

At no stage did any water penetrate any mortar joints. Local penetration of the masonry units was observed only on the 9th and 10th period i.e. after the simulated 10 year spell. It was also acknowledged that in fact the penetration resistance of the actual frame would be greater than that measured, due to the fact that Oolitic Limestones are known to form a protecting skin on surfaces exposed to weather, due to the progressive crystallisation of "quarry sap" on the surface.

MANUFACTURE AND CONSTRUCTION

Prior to manufacture and construction commencing, critical aspects of the process were identified, and procedures defined, either by adapting traditional techniques, or by reference to the findings of the research, testing and development programme.

The procedures included:

- A marking system to trace stone from quarry face, through the mason's yard, into the frame. This, combined with procedures for operating the saws ensured that each unit should be installed correctly orientated.
- Strict inspection procedures to ensure that all units were of the required quality.
- Continuing to monitor the strength of the stone by carrying out tests on specimens cut from finished units selected at random.
- Rigorously applying the construction technique established from the testing and development programme.

The procedures were strictly adhered to by Ketton Architectural Stone, with independent monitoring and supervision being carried out by the authors and Sir Robert McAlpine Management Contractors. The construction of the floors and roof were carefully integrated with that of the stone frame to ensure that the loads acting on the frame were controlled at all stages. Construction of the frame was completed in July 1994. The building was opened by Her Majesty Queen Elizabeth II in April 1995.

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