RICHARD IRELAND • PLASTER & PAINT

CONSULTANCY & CONSERVATION OF HISTORIC BUILDINGS

FIBROUS PLASTER CEILING INVESTIGATION

THE APOLLO THEATRE

SHAFTESBURY AVENUE

LONDON

AUDITORIUM CEILING

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1.0 CEILING INVESTIGATION

1.1 Introduction

The Apollo Theatre is situated in Shaftesbury Avenue London. On the night of 19th December 2013 a partial collapse of the auditorium ceiling occurred during the course of a show falling on to the public below.

Richard Ireland has been asked by Westminster City Council (WCC) to provide a detailed investigation into the causes of the fibrous plaster ceiling collapse and to advise on repair, preservation and subsequent means of inspection as outlined in detail below.

The structural engineers Alan Baxter & Associates (ABA) have been asked by WCC to report principally on the structural issues of the likely causes of the collapse, the form and condition of the remaining ceiling construction and to recommend a strategy for the repair of the ceiling.[1]

The focus of the investigation by Richard Ireland is on the materials and methods of the fibrous plasterwork and the mechanisms of failure of the plaster. This is being undertaken in parallel and in collaboration with Alan Baxter & Associates who are focussing on the structure that supports the ceiling.

1.2 Report Structure

Section 1 provides a brief background and identifies the main sources referenced to inform the report together with a summary of aims and objectives. Section 2 details historic construction materials and methods used at the time of the Apollo ceiling fabrication together with present research of fibre properties. A description of the Apollo ceiling follows in Section 3 detailing observed fabrication method, description and subsequent condition following its partial collapse. Section 4 examines the Apollo ceiling failure mechanisms. [redacted] The 2013 Ceiling Standards are discussed in Section 7. The Duty Holder and compliance with the Health and Safety at Work etc. Act 1974 (HSWA) is covered in Section 8. [redacted] fibrous plaster repair methods detailed in Section 10. Future approaches to ceiling inspections are briefly looked at in Section 11. Sections 12 and 13 provide conclusions and recommendations respectively. The subsequent appendices A to I reference the English Heritage listing, plaster development, textile performance, [redacted], HSWA extracts, and illustrations of fibrous plaster development [redacted]

1.3 Sources

Historical construction context is provided by the first dedicated pre-eminent plastering manual written by William Millar and published in 1897 detailing typical contemporary historical fabrication and construction methods used for the 1898 ceiling construction of the

[1] Alan Baxter & Associates , Final Report, (December 2014) *Apollo Theatre, Shaftesbury Avenue Structural engineering notes on ceiling collapse.*

Apollo Theatre.[2] Historic plastering development is outlined.[3] Modern suspended fibrous plaster ceiling fabrication methods are detailed for current context.[4]

Materials research of some of the key construction materials informing physical characteristics and decay mechanisms is provided by earlier twentieth century texts and modern research.[5]

[redacted] Inspection criteria that has to be met for the licensing of places of entertainment is referenced from Part D and Part M of the Technical Standards for Places of Entertainment.[7] [redacted]

Inspection regimes followed by architects and surveyors on ecclesiastical buildings provides further context regarding what can and should be expected from building inspections.[9]

Other references and contextual information has resulted from seminars and working groups initiated in the wake of the Apollo ceiling failure incident and attended by other construction and relevant professionals who have debated a number of pertinent issues and have involved a wide range of professionals and theatre owners including structural engineers, surveyors, architects, national heritage bodies, fibrous plaster manufacturers, research scientists and health and safety specialists.

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2 See Millar, W., (1897) *Plastering Plain and Decorative. A Practical Treatise On The Art & Craft Of Plastering And Modelling. Including Full Descriptions Of The Various Tools, Materials, Processes, And Appliances Employed; Also Of Moulded Or "Fine" Concrete As Used For Fireproof Stairs And Floors, Paving, Architectural Dressings &c. &c. Together With An Account Of Historical Plastering In England, Scotland, And Ireland, Accompanied By Numerous Examples*, 1st Ed. B.T. Batsford, London, (Reprinted Donhead 1998) which provides a detailed manual of accepted fibrous plaster practice of the period leading up to the building of The Apollo Theatre which first opened in 1901.

3 Appendix B: Plaster Historical Development is the ongoing result of the authors archaeological and archival research gathered over the past twenty years working on the conservation of plaster.

4 These standard texts are widely used in the teaching of all aspects of plastering to NVQ and SVQ students: Pegg, B., Stagg, W., (2007) *Plastering An Encyclopaedia*, 4th Ed. Blackwell Publishing, Oxford and Taylor, J. B., (1987) *Plastering* 4th Ed. Longman Scientific & Technical (Reprinted 1989. First published by George Godwin Ltd 1970)

5 These papers range from American geological and research texts of the 1900s together with British papers of the 1930s and 1950s. Research relating to relevant fibre textile decay has been the result of a literature review of more than 1,500 papers by Dr Anita Quye previously Principal Conservation Scientist in the Department of Conservation and Analytical Science at the National Museums Scotland, and presently Lecturer in Conservation Science, The Centre for Textile Conservation and Technical Art History, University of Glasgow who has summarised the 3 relevant papers found. The summary is reproduced in Appendix C.

6 [redacted]

7 The Technical Standards are compiled by and in association with The Association of British Theatre Technicians, The Chartered Institute of Environmental Health, The District Surveyors Association and the Institute of Licensing. The 2013 publication is being updated and is referenced together with previous editions of, and amendments of 2005, 2008 and 2009 versions.

8 [redacted]

9 See Appendix F for reproduction of a Quinquennial Inspection report of a church undertaken in 2013.

1.4 Aims & Objectives

This Fibrous Plaster Ceiling Investigation report should be read in conjunction with the 'Apollo Theatre, Shaftesbury Avenue, Structural engineering notes on ceiling collapse' report written by Alan Baxter & Associates.

The principal aims and objectives of this report are to establish the primary physical causes and role of contributory factors that led to the collapse of a section of the ceiling at the Apollo Theatre on the night of 19th December 2013. The full scope is detailed below in section 1.5. To provide as complete a picture as possible, original historic construction will be outlined, recent past maintenance regimes and treatment are examined and the role of the duty holder and ceiling inspection personnel and methods scrutinised as to their role [redacted] The report outlines key recommendations in the light of the findings to extend the safety and preservation of such fibrous plaster ceilings.

1.5 Scope

For professional advice in regard of relevant aspects relating to determination of the ceiling incident and subsequent investigation as detailed in the outline request written and signed Steve Harrison, Operational Director, Premises Management Delivery Unit, WCC provided on 31st January reproduced below:

- To determine why the theatre suspended ceiling collapsed and what led to it
- To assess the integrity of the remaining parts of the ceiling and its supporting structure and if any remedial actions are necessary to make it safe.
- [redacted]
- To advise what, if any, additional steps by way of inspection or testing need to be taken to ensure the adequacy of the ceiling inspection certificate in relation to this theatre.
- [redacted]
- To define the competency necessary for the inspection and testing of suspended ceilings and ornamental plasterwork.
- To define the steps that should be taken to enable a competent person to certify that such an installation is safe and the frequency of further inspection.
- To advise upon any significant issues that are relevant to this investigation subject to those additional issues being agreed with the City Council prior to them forming part of this brief.

1.6 Inspection

A site visit and inspection was undertaken at The Apollo Theatre on 31st December 2013 enabling examination of the fallen debris on the auditorium floor, observation of the ceiling loss from the upper gallery, inspection of parts of the ceiling void accessed from flooring lifted in the attic above and inspection of the roof.

Further inspections were undertaken on the 4th February 2014 following completion of a safe work platform and crash deck and again on the 28th February 2014.

2.0 DEVELOPMENT AND DETERIORATION OF FIBROUS PLASTER

2.1 Fibrous Plaster Development Since The Nineteenth Century

To understand the issues relating to the partial collapse of the auditorium ceiling at the Apollo Theatre, it is necessary to first consider the fabrication and construction methods and materials originally employed. The following brief development history will be referenced throughout the body of the report on the ceiling investigation. The report makes extensive use of the contemporary account by William Millar (see Plate1) and should be read in conjunction with the accompanying photographs and illustrations in Appendix B: Plaster Historical Development.

Materials and methods, whether applied externally or internally, remained largely unchanged over several centuries in Europe until the older methods were gradually ousted during the nineteenth century by faster setting alternatives that included gypsum (plaster of Paris) and artificial cements.[10] In particular, the introduction of fibrous plasterwork transformed the construction and fabrication of ornamental plasterwork and especially ceilings and led to its widespread use by the end of the nineteenth century – a means of fabrication which has changed little to the present day.

Fibrous plaster is a form of lightweight construction using cast gypsum plaster generally found incorporating timber laths and hessian scrim for reinforcement. It was introduced into Britain from France in the mid-nineteenth century by Leonard Alexander Desachy. Millar describes that Desachy's patent of 1856 was for "producing architectural mouldings, ornaments, and other works of art formed with surfaces of plaster." Millar writes that 'the materials named are plaster, glue, oil, wood, wire and canvas, or other woven fabric' and quotes 'that a part of the specification reads: "To facilitate the fixing of such moulded surfaces to other surfaces, wires are, when required, laid into and between the two or more layers of canvas. Flat surfaces are strengthened with canvas, wires, hooks, or pieces of wood may be inserted whilst the plaster is in a fluid state." The specification also includes the formation of solid slabs of plaster strengthened with two layers of canvas in the centre.'[11]

Desachy introduced the manufacture of fibrous plaster decorations into London employing a large number of workers. When he retired, the business was taken on by two of his employees, McDonald and Hanwell, though the business was eventually taken over by

[10] See Appendix B: Plaster Historical Development for a more wider and extensive explanation of materials and methods and typical construction from the 1550s to the present.

[11] Millar, W., (1897) *Plastering Plain and Decorative. A Practical Treatise On The Art & Craft Of Plastering And Modelling.* 1st Ed. B.T. Batsford, London, (Reprinted Donhead 1998), Chapter XII, p.343.

G Jackson & Sons who acquired the then existing patents. Millar notes that [Jacksons] 'have introduced many improvements, and brought it to a high degree of perfection.'[12]

Millar writing in 1897 notes that 'Fibrous plaster during the last two decades has been worked by other firms, and it is now open to all plasterers.'[13] Large firms manufacturing fibrous plaster flourished across the country (see Plate 2) through the latter part of the nineteenth century. Fibrous plaster has been used for the Walter Crane panels in the Saloon at Combe Bank, Sevenoaks, Kent (1880). (See Plates 22 & 23)

Millar goes on to note 'Nearly the whole of the numerous theatres and music-halls which have been built in London and the provinces during the last generation have been decorated with fibrous plaster'.[14] (See Plate 25)

2.2 Historic Materials & Methods

Millar notes that the canvas used for fibrous plaster is also known by the name of "scrim".[15] Supplied in various mesh sizes, it was 'principally made in Dundee, from specially prepared yarns, to resist the process of decay. The nature of the fibre from which the yarns are made necessitates careful treatment in the preparation previous to spinning. It is chiefly supplied by A.F. Latto & Co., London.'[16] (See Plates 3 & 4)

Casts could be large or small, plain faced or decorative. Fibrous plaster was used extensively in the Paris Exhibitions of 1878 and 1900 for the construction of ceilings and walls of the principal edifices with the larger panels quoted as nearly 40 ft. square ($3.7m^2$).[17]

Techniques followed similar basic processes for the manufacture of both plain faced plaster sheets as well as for decorative sheets incorporating decorative enrichment. A thin initial pouring of plaster ('firsts') would be allowed to firm up to ensure a consistent even face of the cast, before the addition of loose woven hessian scrim (jute) to provide tensile reinforcement of the cast. Typically, narrow timber laths were also added at this stage of the process before further plaster of Paris ('seconds') was poured or brushed into the mould incorporating and sandwiching the added reinforcement till the desired thickness of the cast was achieved. (See Plates 5 to 9)

Skilled and experienced plaster manufacturers achieve a thickness of cast sheet between ¼ and $^3/_8$ inch (6.3-9.5mm). Thicker elements are made as required to suit the structural integrity of that element and enable required spans to be achieved without distortion. Reinforcement was added at fabrication to keep the panels and units as light and rigid as practical. (See Plates 10 to 13)

Additional reinforcement might also be added to the rear of a cast if required at installation. The completed and installed cast piece may be made up of several smaller items and especially where a large degree of undercut for the completed enrichment was required.

[12] Ibid. p.343.
[13] Ibid. p.343.
[14] Ibid. p.345
[15] Ibid.p.347.
[16] Ibid.p.347.
[17] Millar, W., Bankhart, G. P., (1927) *Plastering Plain and Decorative*. 4th Ed. rev. G. Bankhart 1927, B.T. Batsford, London, (Reprinted Donhead, 2009) p.242.

The fourth 1927 edition of Millar notes 'The castings, when made, are fixed into position with brass screws or nails, or secured to metal work construction with "wads" or bandages of canvas steeped in liquid plaster, which are wrapped round the metal and held until set hard and firm.'[18] The text continues 'This method of fixing is rigid and secure, and has never been known to fail.'[19] (See Plates 14 & 24)

Modern plaster manuals recommend wadding to be used to wrap around a wire tie enclosing and consolidating the wire preventing corrosion and untwisting. (See Plates 15 & 16)

Accurate levelling between panels is achieved with toggles or cleats.[20] (See Plate 17)

Moulds today are generally formed from cold cure silicone rubber supplanting first gelatine, and then the mouldable thermoplastics in use post 1950 such as Vinamold. (See Plate 18)

The general construction technique of the nineteenth century is still followed today for production of cast plaster suspended ceilings. Fibrous plaster panels are made in the workshop and delivered to site ready to be installed, levelled, secured and made good. (See Plates 19 & 20)

2.3 Mechanical Behaviour Of Hessian Scrim Textile[21]

Hessian scrim forms an essential component of fibrous plasterwork and is incorporated with plaster of Paris in the fabrication of mouldings as already described.[22] Hessian scrim is a loose generic term encompassing a number of plant derived cellulosic fibres. The fibres are utilised across a wide range of applications which exploit them for use as a cheap fibre that be woven as a coarse textile. The cellulosic fibres used to reinforce plaster are bast fibres. They include sisal, hemp, jute and ramie. They all have 10% moisture content and different levels of lignin and cellulose and hemi-cellulose. The stiffness differences between fibres reflect their differences in crystallinity of the cellulose.

There has been very little scientific research undertaken on age related decay mechanisms in bast fibres, though moisture appears to be the most significant factor in the mechanical strength properties of bast fibres used for reinforcement. Some significant factors influencing performance are that the strength of the fibres increases with moisture content and decreases with temperature, and Young's modulus decreases with moisture.[23] Deformation affects the

[18] Ibid. p.242.

[19] Ibid. p.242.

[20] A toggle or cleat is a short flat batten secured with a length of thin tie wire. Placed across matching panel faces spanning the gap between two adjoining panels, the toggle tie wire is looped over the supporting structure behind and drawn tight bringing adjacent panels level. The cast panel can then be wadded from above (or below) with tie wire recessed beneath the plaster face and made good over.

[21] See Appendix C: Cellulosic Fibre Performance Properties for a summary of the research papers reviewed by Dr Anita Quye.

[22] Typically a loose woven plant derived textile, hessian is also referred to as scrim, hessian scrim, sacking and canvas amongst other terms in the fibrous plaster industry.

[23] Young's modulus provides a measurement of the stiffness of an elastic material and provides a calculation of stress/load against strain/elongation. A material whose Young's modulus is very high is rigid. Do not confuse: rigidity and strength - the strength of material is characterised by its yield strength and / or its tensile strength; rigidity and stiffness: the beam stiffness (for example) depends on its Young's modulus but also on the ratio of its section to its length. The rigidity characterises the materials, the stiffness regards products and constructions: a massive mechanical plastic part can be much stiffer than a steel spring; rigidity and hardness: the hardness of a material defines its relative resistance that its surface opposes to the penetration of a harder body.

Young's modulus, and load release then repeated loading. There is some plastic deformation after the first release, i.e. the fibre relaxes without permanent deformation before re-elongation. The fibre becomes stiffer with repeated strain and load because of internal reorientation. Young's modulus decreases with fibre diameter – thicker fibres break more easily than finer ones.

There were no obvious publications on the effect of pH, either acidity or specifically alkalinity, of the plaster on bast fibres in reinforced plaster.

The research papers relevant to the use of bast fibres in plaster of Paris conclude that bast fibres can become stiffer and less elastic under a combination of load and moisture uptake cycles.

3.0 APOLLO AUDITORIUM CEILING

3.1 Background History Of Apollo

The Apollo Theatre is listed Grade II[24] and was constructed to designs by Lewen Sharp. It opened its doors in 1901. (See Figs 1 & 2)

3.2 Site Visits

A site inspection was undertaken at The Apollo Theatre on 31st December 2013 enabling examination of the auditorium floor, observation of the ceiling from the upper gallery, inspection of parts of the ceiling void from above and inspection of the roof.

Further inspections were undertaken on the 4th February 2014 following completion of a safe work platform and crash deck and again on the 28th February 2014 after interim protective support of the ceiling had been completed from the crash deck platform.

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[24] http://list.english-heritage.org.uk/resultsingle.aspx?uid=1236173 first listed 1972.

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4.0 FAILURE MECHANISMS OF AUDITORIUM CEILING PLASTER

4.1 Hessian Plaster Composite Wadding Ties

It is clear from the evidence of the inspections undertaken so far, that the principal cause of the failure of the ceiling is attributable to degradation and failure of the hessian and plaster composite wadding ties. Over an unknown period of time it would appear that the ties have lost sufficient structural integrity and tensile capability to maintain the load they have been subjected to leading to failure. This development appears to have been incremental and initially occurred sporadically across parts of the auditorium ceiling.

Plaster of Paris has relatively good strength in tension though a relatively low capability of transverse strength. That is, it can withstand much higher compressive and tensile loads than it can loads applied to the side, such as is necessary when spanning horizontal distances which plaster panels are generally required to do. It is however, a brittle material, and when it ruptures, the failure is sudden and complete with little warning.

Conversely, the cellulosic textiles made from jute, hemp and flax used in fibrous plasterwork effectively have no compressive strength and effectively no transverse strength. They are however, characterised by relatively great tensile strength. When new and fresh such materials are at their strongest. However, in common with other cellulosic plant derived textiles, temperature, humidity and light all have a significant effect on their load capabilities and performance. Repeated fluctuation of loading eventually leads to loss of strength as detailed in Section 4.1 'Mechanical Behaviour of Hessian Scrim Textile' above.

Used in combination with plaster, the open weave hessian scrim textile together with the rigidity of gypsum creates a composite that achieves properties greater than the sum of the two materials. The locking and enclosure of the rough textile weave by the plaster prevents the textile from moving. In tension this means the vertical hanging plaster wadding tie has greatly increased resistance to tension failure. At a micro scale, as a fracture develops, it is inhibited as it attempts to migrate through the chord of the wadding tie by the many vertical and horizontal textile fibres gripped within the plaster matrix.

The application of transverse forces similarly resists a bending moment due to the meshed fibre weave locked within which thereby resists being pulled out and away from the plaster matrix as transverse pressure is applied. In short, the roughness of the fibre texture and the grip of the plaster creates a robust and inherently resilient composite. It is this that allows such thin moulded plaster panels to be fabricated without risk of folding. When fracturing does occur from impact or application of another force, the spreading of load created by the nature of the composite of fibrous plaster enables it to perform and hold together under considerable deflection loads.

The net result means that the high performance capability of the fibrous plaster panels will mask failure in the overhead suspension system until transfer of loads by the final failures of wadding ties leads to a sudden and overwhelming overload that rapidly spreads out to adjacent areas – each overload of wadding tie and wire tie transferring ever increasing loads across the ceiling panels.

In the Apollo ceiling, it appears that the point of failure was associated with the cracking around the north west segment of the central pendant and spread rapidly outwards to the west side and north to the back, stopping at the perimeter rib. The comparatively straight line running north from the pendant suggests this formed a panel joint line.

The aggressive environmental conditions experienced diurnally in an active theatre exacerbate and accelerate textile deterioration driven by the rapidly and constantly changing environment as temperature and humidity fluctuate across a wide spectrum.

The absence of evidence of any obvious external water ingress to the auditorium ceiling plaster rules out leaks as a prime agent in the failure of the wadding ties observed within the remains of the fallen ceiling section as well as the still retained ceiling area.

Weakening and subsequent failure through age exacerbated by environment appears to be the most significant physical element leading to the eventual failure of the ceiling. The examined wadding ties accessible within the ceiling at the time of inspections do not contain wire. Once load capability is exceeded, the fibres will commence failing along the line of highest load and weakest strength. As a fracture develops in the plaster and textile wadding tie, the leading edge moves rapidly through the matrix in a succession of micro breaks. Textile fibres inhibit fracture migration till increasing tensile forces snap the weakened fibres and the fracture migrates to the next cluster of fibres. The cross-section of the tie and percentage of fibre incorporated in the matrix will have a direct influence on the strength of the tie. However, absence of relevant research precludes a definitive account of tensile strength and load capabilities.[27] When load exceeds tensile strength, fracture and failure of the wadding tie ensues.

[27] Presently, there is no known published research on the load capabilities of composite plaster and hessian wadding ties. Whilst industry standards provide for the quality of individual modern material components to be used for fibrous plastering in BS 5492 : 1990, the wide variations of the manner in which the products are used in combination is not provided for. Existing research on plaster of Paris alone, has found it particularly problematic to achieve consistency in the laboratory with mixed gypsum and water samples exhibiting variations exceeding 200% on same mix batch tests. The wide range of differing means of use typifying fabrication and site use introduces even greater variation. These include parameters such as: cross-section of wadding tie, addition of retarders, time to set, point in time of use following mixing of material, length of time mixing, freshness of plaster batch, effect of agitation in the container etc.

4.2 Panel Installation Wire Suspension Ties

The numerous wire ties used at the installation of the ceiling had to be capable of supporting the weight of the decorative panels as they were offered up and initially suspended for installation and levelled to each other. Only then were plaster soaked wadding ties used to fix and consolidate the panels to the structure above and to each other. The wire ties were intended as a temporary suspension device though capable of holding a high load.[28]

As wadding ties have intermittently failed through reducing load capability over an extended but unknown period – indicated by the dirtiness and aged appearance of some fracture gaps, so the ceiling load has been gradually transferred to the wire ties.

It is unknown how much of the surviving ceiling load was being provided by the wadding ties and how much had transferred to the wire ties prior to the subsequent recent propping off the crash deck structure.

4.3 Breaches of the Building Envelope & Water Ingress

Water ingress is a principal contributory cause to the weakening and subsequent failure of fibrous plaster ceiling structures. Water is also a principal cause of moulds and other fungal outbreaks typically associated with the decay and deterioration of structural timbers. The inspection surveys and site visits of 31/12/13, 04/02/14 and 28/02/14 found no evidence of any recent, recurring or current water ingress that could have contributed to the sudden weakening and failure that led to the partial collapse of a section of the main auditorium ceiling on the night of 19/12/13.

[redacted]

4.4 Other Environmental Factors & Events

Pressure changes and excitation of fabric has long been the subject of investigation and research in regard of the vibration impact of powerful acoustic systems installed in modern theatres. A recent presentation by an acoustician specifically addressing the subject of the effect of sound energy on suspended ceilings would appear to refute any suggestion of failure caused by such a manner on a sound ceiling.[29]

A thunderstorm occurred over the west end of London on the night of 19/12/13. Some initial and unsubstantiated comments, subsequently reported in the press, favoured attributing the violence of the storm as the cause of the auditorium ceiling collapse. A rapid fluctuation of

[28] A tensile test was informally undertaken by Mark Ormiston, Ormiston Wire Ltd on 09/01/2014 using their horizontal tensile, 20-tonne calibrated wire tensile strength testing equipment at their wire factory in Isleworth, Middlesex. A test to breaking point was carried out on a representative piece of wire from the Apollo ceiling. A data print out and graph recorded load at break of 58.571 kgf. Tensile strength was calculated and recorded as 491.52 N/mm^2. It should be noted that Ormiston Wire undertake rigorous in-house testing to industry standard, and though UKAS registered for Quality Management ISO 9001 : 2008 and Environmental Management ISO 14001 : 2004, the wire testing equipment used for this test is not UKAS certified.
[29] Paul Gillieron, Acoustician, Gillieron Scott Acoustic Design, talk at 'Inspection and Certification Seminar', The Theatres Trust, 22 Charing Cross Road, London, WC1V 0QR, Wednesday 5th March 2014.

changing air pressure is a typical occurrence in close proximity of lightning and its subsequent thunderclap.

A partially sealed plenum chamber formed in the ceiling void above the auditorium ceiling had been used to provide air changing for the main auditorium beneath. It is likely that some degree of pressure fluctuation might have been experienced within the chamber during the thunderstorm, though there is no reliable recorded means of knowing what air pressure fluctuation occurred at the time. However, whilst a high and sudden increase of air pressure may have had an effect, it is highly unlikely that this would have been anything other than contributory in nature. At the most, a sudden pressure increase could have provided the final tipping point of a structure already at breaking point. There were no other reports of buildings suffering from internal or external structural failure in the same vicinity as the Apollo on the night in question. Whilst the thunderstorm may have contributed, there is no material evidence to suggest it was the primary cause of the ceiling failure.

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7.0 PLASTER CEILING STANDARDS & CERTIFICATION TO 2013

7.1 Technical Standards For Places Of Entertainment

It is a statutory obligation that Theatres and other Places of Entertainment are appropriately licenced by the local authority in Westminster district. Guidelines and necessary inspection cycles are set out in the *Technical Standards For Places Of Entertainment* produced together by The Association of British Theatre Technicians, The Chartered Institute of Environmental Health, The District Surveyors Association and The Institute of Licensing. The current version at the time writing is dated June 2013. Earlier recent past editions are dated June 2008, amended November 2009 and January 2005. A new edition is presently being prepared which is expected to address some of the shortcomings and issues highlighted by the Apollo ceiling incident.

7.2 Part D & Part M Technical Standards

Part D addresses Stability: Commentary & Recommendations and in the 2013 edition refers in D1.05 to a 'suspended ceiling should be fixed and supported so as to prevent collapse.' And in D1.06 notes 'Provision should be made to enable the examination of any ceiling from above.' It goes on to state in D1.07 'A means of access should be provided for the examination of the ceiling and light fittings below a roof space or void exceeding 1m in height.'

Part M notes under Structural stability in M1.09 'Evidence of structural stability of satisfactory construction and installation of any fixture or fittings should be checked by a structural engineer every twelve months and the certification retained. More frequent inspections may be needed if there is any suggestion of failure.' And under the heading Ceiling and plasterwork, M1.10 states 'Any suspended ceilings and ornamental plasterwork should be regularly inspected both for water and also excessive noise and vibration damage.'

7.3 Plaster Ceiling Certification

A three yearly inspection and certification of plaster ceilings is required under the terms of the local licensing authority. Failure to provide a suitable certificate invalidates or leads to the withholding of a licence till compliant.

Specific wording across the three editions of the *Technical Standards For Places Of Entertainment*, noted above, has changed in the course of the editions examined. The 2008/09 edition notes under Part M Certification: Commentary 'Certificates should be reviewed before they expire. Any necessary replacements and/or repairs or maintenance should be undertaken and new tests and certificates provided. The competent person completing the certificate usually determines the frequency of testing; the frequency should be noted on the certificate' and specifies under Ceiling and plasterwork M1.15 'Any suspended ceilings and ornamental plasterwork.'

The guidance does not set out the manner and form of inspection in a sufficiently unequivocal manner. Instead, theatres and inspectors largely provide only what they deem necessary to satisfy their obligations and meet the non-specific 2013 M1.10 requirements regarding ceiling and plasterwork stating 'Any suspended ceilings and ornamental plasterwork should be regularly inspected both for water and also excessive noise and vibration damage.'

This necessarily leads to a wide variation in quality and value of information acquired from an inspection. Theatres with larger budgets and more engaged in the fabric of the building are often in a more advantageous financial position than the fringe theatres who are running on a relative shoestring by comparison.

8.0 THE DUTY HOLDER

8.1 Health And Safety At Work Etc. Act 1974 (HSWA)

Extracts from the HSWA include the following specific items quoted below:[70]

> SECTION 2
>
> General duties of employers to their employees.
>
> (1) It shall be the duty of every employer to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all his employees.
> (2) Without prejudice to the generality of an employer's duty under the preceding subsection, the matters to which that duty extends include in particular—
>
> > (a) the provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risks to health;
>
> SECTION 3
>
> General duties of employers and self-employed to persons other than their employees.
>
> (1) It shall be the duty of every employer to conduct his undertaking in such a way as to ensure, so far as is reasonably practicable, that persons not in his employment who may be affected thereby are not thereby exposed to risks to their health or safety.

8.2 Nimax Theatres

The Apollo Theatre is owned by Nimax Theatres who have a duty of care to employees and public who have use of the theatre.

8.3 [redacted]

[redacted]

[redacted]

[70] See Appendix G for a more extended reproduction of relevant parts of Section 2 and Section 3.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

8.4 [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

9.0 [redacted]

9.1 [redacted]

[redacted]

9.2 [redacted]

[redacted]

9.3 [redacted]

[redacted]

[redacted]

9.4 [redacted]

[redacted]

9.5 [redacted]

[redacted]

10.0 RECOMMENDED FIBROUS PLASTER REPAIR METHODS

10.1 Fibrous Plaster Longevity

The ageing process of the wadding ties will ultimately render them incapable of supporting the loads they have been carrying. In the absence of any published scientific research data, rather than prediction of the rate of decline before a representative wadding tie falls below an adequate safety margin, it is more appropriate to consider that, though the majority of the ceiling remains suspended, it will at some point be completely without adequate support.

10.2 [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

11.0 FUTURE CEILING INSPECTION CONSIDERATIONS

11.1 Plaster Inspections to 2013

At the time of the Apollo ceiling incident in December 2013, the leading plaster firms were providing relatively detailed reports, though set out to suit their own purposes and format.[redacted] Other less experienced firms were providing varying degrees of information ranging in quality and content from barely acceptable to completely without merit and value.

11.2 Quinquennial Inspection Format

The lack of a coherent approach and template to reporting is in contrast to the Quinquennial Inspection (QI), legally binding Measures of 1955 and 1991 for churches and cathedrals, that requires a five yearly inspection cycle of its buildings.[76] Each QI report must remain available at the specific site and is viewable by the architect or surveyor commissioned for the each report. Many churches are now on their 9th or 10th iteration of inspection with all preceding reports available to view.

QI reports are in three sections. Part A summarises the condition and lists works completed since the last report, outlines scope and limitations and recommendations for further (specialist) surveys. Part B describes condition of the fabric element by element.

[redacted]

[76] See Appendix F which reproduces a typical Quinquennial Inspection church report of 2013. The QI report content, layout and format has been defined by the Cathedrals Fabric Advisory Service, the Church Buildings Council and by the National Trust (quadrennial) system.

Recommendations are briefly described and tagged with a priority order from numbers I-V. These identify and cost items under five categories: I - For urgent attention; II - For attention within 18 months; III - For commencement within 5 years; IV - Long term repairs or desirable improvements; V - For maintenance or monitoring. Part C lists the work under each category of priority as a Summary of Recommendations.

It was notable that at the 'Inspection and Certification Seminar' set up to address some of the issues raised by the Apollo incident for professionals and theatre owners, that there was little awareness of such established QI survey practices and procedures and no evidence that any industry formalised survey procedure was in current common use.[77]

11.3 Inspection Requirements

Inspections must be fit for purpose. That purpose needs to meet the needs of Section 3 of the HWSA, quoted in 8.1 of this report (above).

[redacted]

The church Quinquennial Inspection reproduced in Appendix F demonstrates the format adopted for the inspection of churches and cathedrals since 1955. A similar format is used by the National Trust for its four yearly inspections and the same QI template approach has provided the template for other established buildings owners and inspectors – especially where historic fabric is concerned.

11.4 Master Structural Survey

Updating of the *Technical Standards For Places Of Entertainment* is expected to address and incorporate many issues which have been revealed by the Apollo Theatre incident. Chief among these must be the complete survey of the ceiling structures as outlined in Section 8 in the Alan Baxter and Associates Structural Engineers report.[78] In it, ABA emphasise the need for a complete and 'clear understanding and record (including sketches) of the construction of the ceiling and how it is supported off the main structure of the building.'[79]

Such a survey is necessarily comprehensive, though will only be required once in its fullest extent. Thereafter, additions and alterations can be marked up as amendments utilising the first plans.

11.5 Master Plaster Survey

A plaster expert is an essential element of the comprehensive survey report as a structural engineer does not usually attend to the fabricated fibrous plaster element that hangs from the

[77] 'Inspection and Certification Seminar', The Theatres Trust, 22 Charing Cross Road, London, WC1V 0QR, Wednesday 5th March 2014

[78] Howell, J., Alan Baxter & Associates, (December 2014) Final Report, *Apollo Theatre, Shaftesbury Avenue Structural engineering notes on ceiling collapse*

[79] Ibid. Section 8.6, p.6

structural supports. As with the master structural survey, so there needs to be a similarly comprehensive plaster survey detailing all known aspects of the plasterwork. Accurate distinctions should be made as to the nature of the materials surveyed – such as fibrous plaster, historic haired lime-based plaster, other specialist historic compounds and materials such as: composition, papier-mâché based panels as well as modern plasters and fabrication materials that may include Glass Reinforced Plaster, plasterboard and numerous compressed and cast tile compounds.

11.6 Plaster Inspector Competence

The plaster inspector needs to have a comprehensive understanding of a wide range of historic as well as modern methods and materials. The unbroken development and use of the finished fibrous plaster product for the fabrication of suspended ceilings has altered little since its introduction to Britain by Desachy in his 1856 patent. As a result, most of the techniques required for fibrous plaster fabrication and repair are learnt in the workshop. Trade craft fibrous plastering knowledge provides an insight unlikely to be shared by many structural engineers or general building surveyors. However modern trade craft alone is rarely sufficient to provide the breadth and depth of knowledge, insight and experience necessary to provide the level of understanding and detail for a comprehensive and useful plaster inspection survey. Declaration and awareness of the strengths and weaknesses of the suitability of an individual's inspection capabilities allows for more reliable collaboration and sharing of knowledge. In a competitive market place, this aspect can be especially difficult to establish and monitor, and more often, the thoroughness and appropriateness of an inspection is a reflection of the commitment care and conscience of the inspector who has carried out the work as well as a measure of the resources available to facilitate the work.

11.7 Ceiling Access

It is not possible to undertake a comprehensive inspection without accessing both ceiling face and ceiling back. This can be challenging in theatres and other large single volume spaces, such as halls and churches, where it may be necessary to go to considerable lengths and expense to obtain suitable access equipment for the task. Likewise, accessing the ceiling back and/or ceiling void above can be especially awkward. Rope access may be required in many instances to gain adequate access to a complex ceiling back and especially across fragile suspended ceiling backs. [redacted]

In some situations, access from the back of a ceiling is physically impractical and another means of entry must be formed. In such cases, it is imperative to ensure that any potential ceiling fabric intervention has been carefully considered for its purpose and to minimise impact. This is especially important for listed historic buildings and is discussed further in Section 11.8 (below).

11.8 Protection of Listed Buildings

Many historic theatres are listed by English Heritage and are subject to national & local conservation constraints, requirements and needs. Culturally significant fabric may be subject to severe limitations on the nature of the impact of any proposed intervention – especially where the forming of openings in a listed ceiling is concerned.

Buildings that are listed Grade I or II* where works are considered, need listed building consent or if demolition is proposed of a Grade II building. All applications for listed building consent are made to the relevant local planning authority. In London, local authorities are obliged to consult English Heritage on applications for all works requiring consent for theatres of all grades.

In the interests of safety as well as long term preservation, English Heritage is likely to be sympathetic to applications. Strict criteria govern consent, but in general, intervention needs to be as discreet as possible and consist of the minimum intervention practical to allow for the least invasive solution. This may not be the cheapest or the easiest to effect.

11.9 Survey Requirements

In addition to requirements noted in the preceding sections, other conditions should be met including: basic and continued housekeeping to provide and maintain clean ceiling conditions free of accumulated dirt so that ties and plaster surface can be properly examined and a ceiling back clear of debris, stores and rubbish.

Furthermore, continuity of survey information is essential to inform both owner and inspector alike. Establishment of a system such as that employed for QI's where information becomes permanently associated with the building, will assist in developing an increasingly useful picture of ongoing repair and maintenance with value increased at each inspection cycle.

11.10 Future Ceiling Surveys and Inspections

Surveys must incorporate recommendations and planned action as well as listing works carried out in the period since the previous inspection. By this means, a thorough understanding of the building, and especially critical elements like suspended ceilings, will be acquired for the benefit of budget management for targeting and repairs and alerting to developing issues.

Both a plaster specialist with appropriate expertise and a structural engineer should undertake inspections in combination and collaboration as in this investigation of the Apollo incident.

With full visual access obtained, it should be possible to issue ceiling certificates without caveats to provide useful assurance of structural integrity as well as a fuller understanding of condition.

12.0 CONCLUSIONS

The inspection of fibrous plaster ceilings varies widely. The best firms produce relatively detailed surveys. The surveys of the Apollo ceiling have been of the higher order across the industry. Significant caveats are commonplace to the recent reports on the Apollo.

[redacted]

Continuity of survey and maintenance is hampered by the absence of any imposed system. Owners have been free to establish their own systems. [redacted]

[redacted]

There is an absence of clear and unambiguous guidelines for ceiling inspections. Lack of standardised means of determining abilities of inspector leaves the onus on conscientious firms who undertake training of operatives.

Fibrous plaster wadding ties without incorporated wire are subject to deterioration by ageing in a weather tight environment. They have a finite life, as yet undetermined by research.

There is presently a lack of testing and research into long term ageing mechanisms of fibrous plaster decay beyond water damage.

13.0 RECOMMENDATIONS

Inspections and the guidelines outlining their requirements need to be significantly more robust and comprehensive. Visual inspections alone are not sufficient for the safe issue of a meaningful certificate in the case of fibrous plaster suspended ceilings.

Caveats should not be entertained for the issue of a ceiling certificate.

Appropriate ceiling face and back access is vital and must be made available by owners.

Surveys should be accompanied by a designated site staff member whose duty it is to have responsibility for maintenance and disseminating information to all interested parties.

Inspectors need to have more than trade craft awareness to undertake an appropriate inspection of a fibrous plaster suspended ceiling.

A means of ensuring adequately trained and experienced inspectors to undertake fibrous plaster ceiling inspections needs to be established.

Collaboration with a plaster specialist and a structural engineer is necessary to provide a comprehensive and meaningful report.

Richard Ireland

Richard Ireland FRSA
9th December 2014

GB VAT No 765 1959 89 IE VAT No 4342066B

14.0 REFERENCES & FURTHER READING

The Association of British Theatre Technicians, The Chartered Institute of Environmental Health, The District Surveyors Association, The Institute of Licensing, (Jun 2013) *Technical Standards For Places Of Entertainment 2013*.

The Association of British Theatre Technicians, The Chartered Institute of Environmental Health, The District Surveyors Association, The Institute of Licensing, (Jun 2008 & amend. Nov 2009) *Technical Standards For Places Of Entertainment 08/09*.

The Association of British Theatre Technicians, The Chartered Institute of Environmental Health, The District Surveyors Association, The Institute of Licensing, (Jan 2005) *Technical Standards For Places Of Entertainment 2005*.

Baley, C., (2002) 'Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase.' *Composites Part A: Applied Science and Manufacturing, Composites* 33:939-948

Bankart, G. P., (1908) *The art of the plasterer; an account of the development of the decorative development of the craft, chiefly in England from the XVIth to the XVIIIth century, with chapters on the stucco of the classic period and of the Italian renaissance, also on sgraffito, pargetting, Scottish and Irish and modern work,* Batsford, London, (Reprinted Donhead 2002)

Coburn, A., Dudley, E., Spence, R., (1989) *Gypsum Plaster. Its manufacture and use*, Intermediate Technology Publications.

Dalmay, Pierre, A. Smith, Chotard, T., Sahay-Turner, P., Gloaguen, V,. Krausz, P., (2009) 'Properties of cellulosic fibre reinforced plaster: influence of hemp or flax fibres on the properties of set gypsum', *Journal of Materials Science*, Vol.45, n3, pp.793-803, February 2010, Published online 12 November 2009 Springer Science+Business Media, LLC

Grimsley, G. P., (1904) *Michigan Geological Survey The Gypsum of Michigan and the Plaster Industry*, Vol.9, Part 2, Julius Bien, New York

Groves, A. W., (1958) *Gypsum and Anhydrite*; London: HMSO

Haddon, C. L., (1933) 'Gypsum Plasters'; in *Journal of the Society of Chemical Industry*; Vol.52, No.2, pp.24-27

Health and Safety at Work etc. Act 1974 accessible at http://www.legislation.gov.uk/

Howell, J., Alan Baxter & Associates, (December 2014) Final Report, *Apollo Theatre, Shaftesbury Avenue Structural engineering notes on ceiling collapse*.

Ireland, R, (August 2014) 'Decorative Lime Plaster Conservation and Repair', *The Journal of the Building Limes Forum*, Vol.21, 2014, Edinburgh, pp.24-39

Ireland, R., (2011) 'Methods And Materials' A new introduction to the facsimile edition of the 1975 original *Decorative Plasterwork In Great Britain* by Geoffrey Beard. Donhead Publishing, Dorset, (Reprinted 2011)

Ireland, R., (2009) *Conserving Decorative Plaster Part1* http://www.projectbook.co.uk/article_40.html

Ireland, R., (2009) *Conserving Decorative Plaster Part2* http://www.projectbook.co.uk/article_41.html

Karni, J., E'Yal K., (1995) 'Gypsum in construction: origin and properties.' *Materials and Structures* 28:92-100

Martin, W., Wood, C., (series eds) (2012), *English Heritage Practical Building Conservation Metals; Timber*. Ashgate Publishing & English Heritage, (2013) *Roofing*. Ashgate Publishing & English Heritage

Millar, W., (1897) *Plastering Plain and Decorative. A Practical Treatise On The Art & Craft Of Plastering And Modelling. Including Full Descriptions Of The Various Tools, Materials, Processes, And Appliances Employed; Also Of Moulded Or "Fine" Concrete As Used For Fireproof Stairs And Floors, Paving, Architectural Dressings &c. &c. Together With An Account Of Historical Plastering In England, Scotland, And Ireland, Accompanied By Numerous Examples,* 1st Ed. B.T. Batsford, London, (Reprinted 1998) London: Donhead

Millar, W., Bankart, G. P., (1927) *Plastering Plain and Decorative.* 4th Ed. rev. G. Bankhart, B.T. Batsford, London (Reprinted 2009) London: Donhead,

National Building Studies Bulletin No.6 Gypsum and Anhydrite Plasters, (1948), Properties of Set Material, Table 1. Effect of Water on the Transverse Strength of A plaster of Paris with 60 per cent by weight of mixing water, p.5

Pegg, B., Stagg, W., (2007) *Plastering An Encyclopaedia*, 4th Ed. Blackwell Publishing, Oxford

Rivers, S., Umney, N., (2005) *Conservation of Furniture* Butterworth Heinemann

Sawyer, J. T., (1951) *Plastering*, (Reprinted Donhead, 2007)

Stewart, J., Henry, A., (eds.), Ireland, R., - principal contributor, (2012) *Mortars, Renders & Plasters: Practical Building Conservation*, Ashgate Publishing & English Heritage

Summerscales, J., Nilmini P.J., Dissanayake, Amandeep, Virk, S., Hall, W., (2010) 'A review of bast fibres and their composites. Part 1 - Fibres as reinforcements.' *Composites Part A: Applied Science and Manufacturing* 41 (10):1329-1335

Taylor, J. B., (1987) *Plastering* 4th Ed. Longman Scientific & Technical (Reprinted 1989. First published by George Godwin Ltd 1970)

Verrall, W., (1938) *The Modern Plasterer*, (Republished by Donhead 2000)

14.1 RELEVANT CODES FROM BRITISH STANDARDS INSTITUTE

BS 5492 : 1990 Code of practice for internal plastering, Section 7. Fibrous plasterwork.

BS 1191 : Part 1 : 1973 Specification for gypsum plasters which classified plasters by type: Class A (hemihydrates) plaster of Paris; Class B (retarded hemihydrates); Class C (anhydrous, lightly or moderately burnt), for example, Sirapite; Class D (anhydrous, hard burnt), for example , Keen's cement, Parian cement; Class E (anhydrite).
The current standard is *BS EN 13279-1 : 2008 Gypsum binders and gypsum plasters. Definitions and requirements.* This classifies materials by their use and not by their composition: A Gypsum binders for direct use in further processing; B gypsum plasters; C Gypsum plasters with special purposes.
Gypsum is defined simply as a "*binder consisting of calcium sulphate in its various hydration phases, for example hemihydrate [$CaSO_4 . \frac{1}{2} H_2O$] and anhydrite [$CaSO_4$]*". The specific composition needs to be requested from the manufacturer.[80]

BS EN 13964 : 2004 Suspended ceilings. Requirements and test methods.

BS EN 14118 : 2003 (3 parts) Reinforcement. Specifications for textile glass mats (chopped strand and continuous filament mats)

14.2 [redacted]

[redacted]

14.3 OTHER REFERENCED SUSPENDED CEILING [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[80] The preceding paragraph referring to BS 1191 : 1973 and BS EN 13279-1 : 2008 is reproduced from Stewart, J., Henry, A., (eds.), Ireland, R., – principal contributor, (2012) *Mortars, Renders & Plasters: Practical Building Conservation*, Ashgate Publishing & English Heritage p.582

[redacted]

Westminster Health and Safety Team (Jan 2014) 'Interim advice to theatre owners with suspended ceilings.

Westminster Health and Safety Team (Mar 2014) 'Suspended ceilings – further guidance to theatre owners and other places of entertainment.

14.4 ACKNOWLEDGEMENTS

Alan Baxter & Associates LLP

The Association of British Theatre Technicians

Buildings Research Establishment, Bucknall Lane, Watford, WD25 9XX.

Czar, E., for RAW file photograph of Apollo Theatre auditorium ceiling taken from G9 Stalls taken at 17.20 (US Standard Eastern Time) 14/12/2013

English Heritage Building Research and Conservation Team, Waterhouse Square, London

I am indebted to Dr Anita Quye, previously Principal Conservation Scientist in the Department of Conservation and Analytical Science at the National Museums Scotland, and presently Lecturer in Conservation Science, The Centre for Textile Conservation and Technical Art History, University of Glasgow, for a literature review and summary of scientific papers related to tensile performance and deterioration mechanisms of natural cellulosic textiles.

I am indebted to Mark Ormiston of Ormiston Wire Ltd who operates the family run wire manufacturing firm first established in 1793, for the benefit of his extensive practical and technical knowledge of historic and contemporary wire chemistry and technology. I am also indebted to his testing a section of suspension wire to determine tensile strength.

15.0 APPENDICES

15.1 APPENDIX A

ENGLISH HERITAGE LISTING

List entry Summary

This building is listed under the Planning (Listed Buildings and Conservation Areas) Act 1990 as amended for its special architectural or historic interest.

Name: THE APOLLO THEATRE

List entry Number: 1236173

Location

8, ARCHER STREET W1
THE APOLLO THEATRE, RUPERT STREET W1
THE APOLLO THEATRE, SHAFTESBURY AVENUE W1

The building may lie within the boundary of more than one authority.

County: Greater London Authority
District: City of Westminster
District Type: London Borough
Parish:

National Park: Not applicable to this List entry.

Grade: II
Date first listed: 28-Jun-1972
Date of most recent amendment: Not applicable to this List entry.

Legacy System Information

The contents of this record have been generated from a legacy data system.

Legacy System: LBS

UID: 427104

Asset Groupings

This list entry does not comprise part of an Asset Grouping. Asset Groupings are not part of the official record but are added later for information.

List entry Description

Summary of Building

Legacy Record - This information may be included in the List Entry Details.

Reasons for Designation

Legacy Record - This information may be included in the List Entry Details.

History

Legacy Record - This information may be included in the List Entry Details.

Details

CITY OF WESTMINSTER SHAFTESBURY AVENUE W1 TQ 2980 NE The Apollo Theatre 71/54 (including No 8 Archer 28-6-72 Street) GV II Theatre,1901 by Lewen Sharp with sculptured work by T. Simpson. Stone faced, plain brick to Rupert Street and Denmark Street. Shaftesbury Avenue front in a Free Renaissance style. 3 main storeys and a tall attic. 3 major bays wide, the outer two as pavilions with shallow canted fronts. Arcaded ground floor foyer and gallery-circle entrances, under glass canopy supported on elaborate ornamental iron brackets. 1st floor central loggia and pedimented flanking windows. Attic storey above main entablature, with enriched oeil de boeuf windows and crowning cornice. The pavilion attics are treated as short circular turrets with shallow domes, rather Art Nouveau in character and are enhanced by figure sculpture of heroic scale. Rich interior (slightly simplified by Schaufelberg in 1932) with foyer and ante-room to Royal Box; the auditorium with elaborate plasterwork in "Louis XIV" style. 3 cantilevered balconies flowing into the serpentine fronts of richly ornamental tiers of boxes flanking the proscenium - single box at stage level, pairs at dress and upper circle levels with modelled terms supporting the gallery "box" above; architraved proscenium with figure relief composition to tympanum over. Richly ornamental shallow domed ceiling on pendentives, etc. Lewen Sharp's only theatre, although he also altered the Camberwell Palace of Varieties in 1908.

Listing NGR: TQ2962280839

Selected Sources

Legacy Record - This information may be included in the List Entry Details

National Grid Reference: TQ 29622 80839

Map


PETER STREET
OLD COMPTON STREET
ROMILLY STREET
DEAN STREET
LEXINGTON STREET
BREWER STREET
WARDOUR STREET
SHAFTESBURY AVENUE
ARCHER STREET
SMITHS COURT
HAM YARD
GOLDEN SQUARE
BRIDLE LANE
LOWER JAMES STREET
BREWER STREET
SHERWOOD STREET
GREAT WINDMILL STREET
DENMAN STREET
GLASSHOUSE STREET
RUPERT STREET
COVENTRY STREET
GERRARD STREET
GERRARD PLACE
LISLE STREET
LEICESTER PLACE
LEICESTER STREET
LEICESTER SQUARE

15.2 APPENDIX B

PLASTER HISTORICAL DEVELOPMENT

15.2.1 HISTORIC PLASTERING MATERIALS

Plaster is an incredibly versatile material. Once a cheap and easy means of simply 'ceiling' internal and external architectural surfaces, it was to develop to reach its artistic apotheosis in the eighteenth century across Europe. Applied to all kinds of architectural surfaces, it can be manipulated by skilled modellers to form breathtakingly rich and varied three-dimensional enrichment. It could dramatically frame ceiling and wall paintings or provide the standalone architectural enrichment. Compared with the expense of carving in stone or timber, plaster provided a very economical form of decorative enrichment.

Plastering materials and methods remained largely unchanged over several centuries in Europe. In the UK and Ireland decorative run mouldings, added to the normal flatwork treatment from the early sixteenth century, were generally executed in lime. The greater brilliance and smoothness of plaster of Paris was exploited on occasion for high status use, particularly as a more suitable ground for decorative wallpainting.

The older methods were gradually ousted during the nineteenth century by faster setting alternatives including sand and cement based plasters and latterly 'fibrous plaster' (gypsum). These new technologies were coupled with the use of cast gypsum plaster enrichment which was ushered in during the late eighteenth century for the rapid replication of decorative enrichment from pre-carved moulds.

Two distinctive material types are generically termed 'plaster': lime and gypsum, commonly referred to as 'plaster of Paris'. Broadly, until the latter part of the eighteenth century, it was lime plaster that predominated.

Lime

Lime is produced by the calcination of limestone rock $CaC0_3$ (calcium carbonate) at temperatures in excess of 1,000°C forming quick lime Ca0 (calcium oxide). Slaking with water ($Ca0 + H_20$) produced a non-hydraulic lime putty – that is, a form of lime $Ca(0H)_2$ (calcium hydroxide) which does not set on contact with water. The lime reverts to a chemically identical material as its parent rock by slow absorption of carbon dioxide during carbonation and evaporation of water.

Lime cycle: 1) $CaC0_3 + 1{,}000°C = Ca0 + C0_2$ 2) $Ca0 + H_20 = Ca(0H)_2$ 3) $Ca(0H)_2$ + atmospheric absorption of $C0_2$ & evaporation of $H_20 = CaC0_3$

The addition of set-enhancing pozzolans such as crushed brick to non-hydraulic lime plasters reduces setting time at the expense of malleability, as does the use of naturally hydraulic lime. Lime was common on building sites. It was used for mortar, external renders and for internal plastering. Ultimately artificial cements made pure limes all but redundant in new building construction, and gypsum based plasters emerged as the predominant finish for interior walls and ceilings, but this change was surprisingly late and limes were still commonly used on building sites up until the Second World War.

The unique qualities of lime plasters, when intimately combined with aggregates such as sand, include plasticity and controlled setting. These self-same traits restrict maximum coat thickness to some 3/4in. (18mm) and necessitate several days between applications to allow for shrinkage and development of adequate strength.

The inclusion of differing grades of aggregate and of organic ingredients such as cattle hair, modify and adjust performance to suit the work in hand. The resulting mixture may be used to render walls and ceilings, run mouldings, press ornament and model *in situ*.

A lengthy tending period is required for pure lime/sand plasters to ensure suitable setting conditions and to guard against too rapid drying which could lead to failure through excessive shrinkage, distortion and cracking. This led to the gauging of plasters with gypsum (plaster of Paris or casting plaster) towards the latter part of the eighteenth century. Its purpose was to provide a more rapid set and thus control shrinkage and reduce the excessive care otherwise required.

Gypsum ('Plaster of Paris')

While lime is inherently weather resistant and could be used inside or outside, the same is not true of gypsum ($CaS0_4$, calcium sulphate), otherwise known as 'plaster of Paris' or 'casting plaster'. Mined in England from natural gypsum deposits like alabaster, it is most often referred to as 'plaster of Paris' due to the large deposits found in Montmartre in Paris from where it was imported. Calcined at between 150°C and 160°C forces a reaction which changes it from dihydrate ($Ca\ SO_4.2H_2O$) to hemi-hydrate ($CaSO_4.½\ H_2O$) by driving off 1 ½ of the molecules of water. This produces a plaster that is commonly referred to as plaster of Paris, otherwise referred to as a Class A plaster. Higher calcining temperatures drive off more water and produce harder setting plasters, though they take longer to set. Class D plasters are completely anhydrous forming an especially hard surface such as Keene's.

Production of Class A hemi-hydrate plaster forms a white powder that typically sets rapidly and rigidly within fifteen minutes of mixing with water. This is a material for internal use only: it rapidly loses strength on contact with water. Gypsum was used in England from the sixteenth century and is occasionally mentioned in accounts for a variety of uses. It is not clear how widespread its use was in seventeenth century plasterwork as superficially it looks the same as lime plaster and it is only with chemical testing that the presence of gypsum can be confirmed. However, analysis of eighteenth century plasterwork at Uppark and elsewhere shows that lime plaster predominated. From the latter half of the eighteenth century gypsum was often used as an admixture combined with lime plaster to achieve an earlier physical set and to counteract shrinkage of the ongoing carbonating lime.

Its other chief use was for the casting of decorative ornament like medallions and runs of enrichment such as egg and dart, a practice continuing today.

Harder and denser materials were increasingly employed for internal plastering with the development of various gypsum based patent formulations from the early nineteenth century. These included Martin's Cement, invented 1835 and patented 1840. Others included Keene's Cement (patented 1838) and Parian Cement (patented 1846). Parian and Keene's, which set exceptionally hard, could be polished to form a smooth surface. Such Class D plasters were commonly used where increased impact resistance and strength were required such as dado, skirtings and external angles where the flat work was of lime plaster.

By the twentieth century wall plasters for internal use were increasingly formulated from retarded gypsum mixed with different aggregates from lightweight expanded minerals, such as perlite, or heavier and denser aggregates to suit, from bonding to hardwall finishes. Indeed gypsum plasters so dominated the market that by the second half of the twentieth century very few plasterers had any experience of mixing or working with lime plasters, which had almost entirely disappeared from regular use.

Additives

Numerous historical references are made to the use of organic additives to enhance and modify the performance and characteristics of lime plasters. The most commonly recurring references to additives are milk and cheese, eggs, blood, animal fat, animal glues, oil, beeswax, resin, beer, urine and dung. Some of these are highly questionable, for instance the use and benefits of urine. How frequently they were used is almost impossible to tell from surviving material due to the difficulties of tracing and appropriate chemical analysis.

Aggregates

Aggregates are vital and act as fillers in the plaster mix adding bulk and strength reducing the amount of binder needed, and also help to reduce shrinkage as the plaster dries out. Sand is one of the most common aggregates for plasters, though crushed old lime plaster could also be added. It was usual from the eighteenth century onwards to wash sands, especially for better quality work. Angular sands, referred to as 'sharp', were traditionally used for superior performance and were obtained from quarries and pits. River sands were also good and widely used and were characterised by more rounded particles. Sea sands were also used in the past, though not without problems due to their more rounded particle size and contamination by sea salt that could have a deleterious effect on the finish and durability. In all cases, plastering required a well graded particle size which may not always have been readily obtainable.

Crushed marble was not used extensively in the UK and Ireland. It was an expensive commodity north of the alps where sand was much more readily available and it was not the essential ingredient – a myth that some of the historic literature perpetuated. Other crushed rocks such as limestone and granite were also a regular addition.

16.2.2 HISTORIC PLASTERING METHODS[81]

Materials and methods were widely adapted to suit local circumstances. Accumulation of experience and dissemination of knowledge incorporated and refined local variations. This led to the establishment and adoption of best practice that provides the core of the methods outlined below.

Flatwork

Wattle and daub techniques have been used for at least 6,000 years and predominantly formed the basis of earlier flatwork in the UK and Ireland. Panel grounds were formed from woven thin branches and daubed with mixtures that might include principal binders of clay

[81] Terminology employed in the description of historic methods described above is that of the present date in the interests of clarity and to help avoid confusion. The technical language of earlier periods, understood at the time, was often inadequate to convey critical nuances and detail. Modern usage should not be applied ad hoc to historic terms without research of the appropriate period – which in early work can prove particularly difficult to establish.

and lime with tensile reinforcement provided by materials such as straw and animal hair. From the seventeenth century onwards wattle and daub was ousted by lath and plaster, though could still provide the flatwork base coats, as at Astley Hall, Chorley (1575-1600) retaining earth plaster with straw base coats and lime plaster finish coat in plaster surviving the later c.1650s work. Also haired earth plaster base coats surviving in the stair hall ceiling of c.1660 at Sydenham House, Devon (1600-1612).

Internal flatwork on walls and ceilings in the sixteenth and seventeenth centuries was mostly composed of two layers, with a base coat of coarse stuff keyed into the laths, which was covered with a finer layer and finished with white distemper. By the eighteenth century it was traditionally comprised of three layers: a render or pricking-up coat, floating coat and setting coat. The render or pricking-up coat was applied to solid or lathed backgrounds respectively. Laths would be hand riven sweet chestnut or oak until the introduction of sawn softwood in the mid-nineteenth century. Because the lathwork affected the stability and form of the finished product, plasterers were traditionally responsible for fixing laths to structures provided by the carpenter.

Lime plaster was made with sand and often had hair added. The use of coarse sharp sands reduced the effects of shrinkage whilst the inclusion of hair was typical for internal plastering to lathwork. A physical key for the following coat was formed by scratching the partially set surface with a rake assembled from a fan of three sharpened laths.

The floating coat was usually formulated and applied in the same way as the pricking-up coat but with more attention paid to its 'straightening'. Keying for the next coat was shallower and less vigorous using a devil float formed with three nails projecting 1/8 in. (3mm) or so through the sole.

The setting coat was formulated with much finer softer sands using a higher ratio of lime to sand and could exceed 1:1. Where hair was included it was finer and shorter – often goat hair or wool. Applied only to a maximum thickness of 1/8 in. (3 mm), considerable skill and attention was required to form fine surfaces.

External rendering was usually carried out without hair and a coarser finish left on the surface usually by rubbing up with a wooden float. The final coats would have a similar ratio of binder to aggregate as internal render and float till the nineteenth century. Subsequently experimentation led to the common use of very dense hard finishes often over softer coarser textured base coats.

Development of methods to increase productivity during the nineteenth century led to the invention and use of Expanded Metal Lath (EML). The use of EML became particularly popular in the construction of public buildings and the quest for fireproof solutions.

By the last quarter of the nineteenth century, fibrous plaster casting of large flat and curved plain-faced sections became increasingly economical and heralded today's extensive use of the techniques from domestic interiors through to the largest shopping malls. Cast slabs include woven hessian and sawn timber laths to enable lightweight sections and provide a strong internal framework for fixing to the desired structures as has been used for the Walter Crane panels in the Saloon at Combe Bank, Sevenoaks, Kent (1880). Plain flat plasterboard developed from its invention in 1894 by Augustine Sackett, marketed as 'Sackett Board', before it evolved into 'Gypsum Board' around 1910 and subsequently further developed into the plasterboard in use today.

Run-Mouldings

Architectural topography such as changes of plane, downstands and ribs would typically be reflected in the underlying structure to minimise the weight and thickness of plaster required to form a feature. Run-mouldings (current terminology) are so called because they are formed by the craftsman repeatedly passing a pre-cut profile (originally wooden and later metal) of the desired shape across a surface whilst adding plaster. The profile was mounted on a timber frame known as a horse and was run against timber rails or rules temporarily affixed, as appropriate, to the flatwork. By this means, continuous constant profile features, such as ribs, were formed *in situ* following the existing surface undulations. Features were built up layer by layer in the same manner as flatwork. Depressions and quirks would be run and incorporated in the profile, if desired, which allowed for the subsequent planting of separately formed units of decorative enrichment. These might take the form of small tiles of intertwining leaves, egg and dart or indeed, all manner of low relief enrichment.

'Press-Moulding'

'Press-moulded' enrichment is a technique quite distinct from the later pouring of gypsum casting plaster into moulds that started in the late eighteenth century and continues today. In the early press-moulding technique, shallow low relief decorative elements were produced by the 'pressing' (beating) of a stiff, near dry lime plaster mix into reverse carved timber impressions. This was especially popular as a method to form decorative elements, 'tiles' and 'plates' commonly employed as enrichment in the sixteenth and seventeenth centuries.

Flat-backed press-moulded enrichment would be used from simple embellishments and decorative relief applied to run moulded ribs or would be set into ceiling flatwork or wall panels as at Ormond Castle, Carrick-on-Suir, Co. Tipperary (1575), Gawthorpe Hall, Lancashire (1600-1605) and Sydenham House, Devon (c.1660). This method was also used to form entire elaborate low relief 'tiled' ceilings such as found, for instance, in the barrel-vaulted gallery at Chastleton, Buckinghamshire (1607-12), and window soffits and friezes of Dorton House, Buckinghamshire (1626).

The constraints of a solid and unyielding and inflexible timber mould resulted in the production of enrichment of characteristically low relief without undercut. Lime plaster press-moulded enrichment is also characterised by warping and unevenness resulting from shrinkage of the lime as it dried. The method was not particularly efficient though appears to have been a common enough practice for repetitive embellishment in the sixteenth and seventeenth centuries.

In the eighteenth century, the method continued to be used for the pressing of elements such as modillions and paterae, which were typically affixed by a combination of plaster and a large nail securing the ornament to the timber sub-structure. This was observed in the 1750s decorative plasterwork at Uppark for modillions, sections of egg and dart and paterae.

Freehand Modelling

Modelling of lime plaster is an additive process by which material is gradually added and built up from the surface by the craftsman. It is important to distinguish this method from that of other sculptural materials as it is fundamental to the methods and techniques of its creation. Lime is not carved like the subtractive process used for carving timber or stone where material is progressively removed by the craftsman to reveal the piece within. Nor is lime as pliant a medium as clay, which benefits from both additive and subtractive methods. The modelling of lime requires the individual hand-working of each element from the surface outwards. The introduction of small corrections and surface indentations are only possible as the material is actually applied. The nature of the lime does not allow for a later return to create recesses, indentations and undercut, for instance. Instead, the craftsman must work up and introduce detail as he adds new material a little at a time. It is by this means that the freehand lime plaster modeller is able produced the deep undercut and layering which has so enriched the many buildings of the late seventeenth and eighteenth century. It is this characteristic, in particular, that distinguishes such vibrant and individual work from the minimal undercut of the later technically and precise mechanical repetition of cast plaster produced from rigid moulds.

In the British Isles, freehand modelling predominantly used slow-setting mixtures of non-hydraulic lime plaster. This meant that the modelling of a highly decorative ceiling might be measured in several months. This circumstance is quite different to the speed of some continental work, where the incorporation of gypsum plaster with its rapid setting qualities vastly accelerated production, and enabled several rooms to be completed in a few months.

Lime, without set enhancing additives, carbonates and hardens only very slowly and over many weeks. It remains malleable and soft for a considerable amount of time and thus requires some degree of support where great thickness or relief is required. Large projections such as limbs, wings, foliage or instruments required the use of a supporting armature. These could be ferrous: typically wrought iron wire, nails and lead, or organic: such as wood, leather and bone – indeed anything capable of providing suitable support for the carbonating plaster was used and often became a significant element in later deterioration.

Highly-skilled labour intensive hand modelling and press moulding of lime common up to the end of the eighteenth century, was gradually superseded by the 'mechanical' casting of ornament, poured in gypsum plaster, as the quest for economy and taste for less symmetrical voluptuous high relief was supplanted by the new wave of taste and economy of repetition.

Casting

The shrinkage of lime plaster and comparatively slow set could be exploited to create flat surfaces, beaten into shallow reverse cut moulds to form 'press-moulded' enrichment and manipulated or modelled in situ by those adept in the 'plastic art'.

However, the rapid setting time of gypsum (around fifteen minutes from mixing with clean water) lent itself to the more efficient casting of low relief repetitive architectural ornament. This typically used reverse carved hardwood moulds for durability and higher volume replication as well as less durable wax and clay moulds for comparatively small runs of enrichment. These methods became obsolete with the introduction of flexible moulding materials which were introduced and developed from the mid nineteenth century. To cast 'in the round' or with any degree of undercut, required complex piece moulds prior to flexible mould making technology. However, reverse carved timber or well-hardened plaster master moulds were sufficient for gypsum poured models without undercut. Artists' studios used more technical moulding and casting techniques to form complex models in the round using interlocking piece moulds that located in a larger case for the production of cast statuary and similarly complicated subjects.

Mixed on its own with water to a creamy consistency, gypsum is particularly suited to pouring into low relief moulds with an absence of undercut. Exploitation of these attributes in the late eighteenth century, together with the rise in popularity of the Neoclassical style, enabled large quantities of repetitive low relief ornament to be churned out in a fraction of the time taken to model lime *in situ*. This led to the rapid decline of the lime plaster modeller as artist craftsman and ushered in the decorative plasterer as more of a technician. However, *in situ* freehand modelling of enrichment enhancing cast principal elements of the decorative plaster ceilings was observed at Kiddington Hall, Oxfordshire as part of its wholesale remodelling by Barry in the 1850s. By the mid-nineteenth century, flexible gelatine moulding materials allowed a degree of undercut to be achieved in a single cast.

Moulds today are generally formed from cold cure silicone rubber supplanting mouldable thermoplastics in use post 1950 such as Vinamold.

Pourable moulding materials are initially applied in a thin layer over a model typically of clay, timber or plaster and left until set. A hard cased backing is then formed over the rubber in plaster or glass reinforced plastic (G.R.P.) to give structural support when stripped from the model. Once stripped, and placed in its hard case, liquid plaster of Paris is poured into the mould and allowed to set – an operation of around half an hour. The mould is stripped off the set plaster to reveal the cast copy.

Fibrous Plaster

Fibrous plaster is a form of lightweight construction using cast gypsum plaster generally found incorporating timber laths and hessian scrim for reinforcement. It was introduced into Britain from France in the mid-nineteenth century by Leonard Alexander Desachy who took out a patent in 1856 for "producing architectural mouldings, ornaments, and other works of art formed with surfaces of plaster." Desachy introduced the manufacture of fibrous plaster decorations into London employing a large number of workers.

Casts could be large or small, plain faced or decorative. Techniques followed similar basic processes for the manufacture of both plain faced plaster sheets as well as for decorative sheets incorporating decorative enrichment. A thin initial pouring of plaster would be allowed to firm up to ensure a consistent even face of the cast, before the addition of loose woven hessian (jute) to provide tensile reinforcement of the cast. Typically, narrow timber laths were also added at this stage of the process before fresh plaster of Paris was poured into the mould incorporating and sandwiching the added reinforcement till the desired thickness of the cast was achieved. Skilled and experienced plaster manufacturers achieve a thickness of cast no greater than required for the structural integrity of that element and its purpose saving excessive weight and cost. Additional reinforcement could be added to the rear of a cast if required at installation. The completed and installed cast piece may be made up of several smaller items if a large degree of undercut for the completed enrichment was required. Finished cast sections were then affixed to a latticework of timber joists or metal struts by means of composite ties of hessian soaked with plaster of Paris referred to as wadding ties. Wadding ties are sometimes wrapped around a wire tie enclosing and consolidating the wire preventing corrosion and untwisting of the wire.

This form of decorative plaster work is not to be confused with the freehand in-situ modelling of lime plaster that characterises the outstanding undercut and relief of plaster decoration typical up until the late eighteenth century and surviving beyond in local areas.

15.3 APPENDIX C

CELLULOSIC FIBRE PERFORMANCE PROPERTIES

15.3.1 Summary Of Mechanical Behaviour Of Cellulosic Fibres In Plaster

Cellulosic fibres to reinforce plaster are bast fibres. They include sisal, hemp, jute and ramie. They all have 10% moisture content and different levels of lignin and cellulose and hemi-cellulose. The stiffness differences between fibres reflect their differences in crystallinity of the cellulose

The properties of flax that most influence its mechanical properties are

- the ratio of crystalline to amorphous polymer character
- fibre thickness
- fibre length
- surface deformations (e.g. nodes)
- degree of polymer crystallinity
- volume of the lumen (central void in the fibre)
- porosity
- angle of fibrils

Effect of moisture on bast fibres

Moisture appears to be the most significant factor in the mechanical strength properties of bast fibres used for reinforcement. Although Conclusions from this Publication that mention this include:

Baley, C. (2002). Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase. *Composites: Part A* 33:939-948.

- Strength of fibres increases with moisture content (H-binding) and decreases with temperature (T_g), and Young's modulus (stress/load against strain/elongation) decreases with moisture.
- Hemicellulose is hydrophilic, so a fibre with a high hemicellulose content will absorb more water than one with lower content. Implication for the ceilings – the type of fibre used (see table of different properties in Daniels' paper). Ca. 11-17% compared to Ca. 65-75% cellulose.
- Moisture in pores and amorphous regions reduce internal strain through a plasticising effect by essentially reducing T_g.
- Moisture changes in the crystalline regions are minimal and have little influence on the fibres' mechanical properties.
- Deformation affects the Young's modulus, and load release then repeated loading. There is some plastic deformation after the first release, i.e. the fibre relaxes without permanent deformation before re-elongation. The fibre becomes stiffer with repeated strain and load because of internal polymer chain reorganisation – reorientation.
- Young's modulus decreases with fibre diameter – thicker fibres break more easily than finer ones.

Summerscales, John, Nilmini P.J. Dissanayake, Amandeep S. Virk, and Wayne Hall. 2010. A review of bast fibres and their composites. Part 1 - Fibres as reinforcements *Composites Part A: Applied Science and Manufacturing* 41 (10):1329-1335.
Stiffness of cellulose reduces by a factor of 2 to 4 when wet and moisture penetrates the amorphous regions due to less hydrogen bonding

This paper addresses moisture of gypsum:

> Karni, Joseph, and E'Yal Karni. 1995. Gypsum in construction: origin and properties. *Materials and Structures* 28:92-100.
> Increasing moisture content = decreasing strength. Measurement of hardened plaster of Paris exposed to moist air at 65% RH lost 2% compressive strength. However, they say that:
> "It was also found that, under moisture conditions common in residential buildings, there is no significant effect, particularly since dried gypsum is capable of regaining strength."

Effect of the plaster chemistry on bast fibre reinforcement

I found no papers specifically on the effect of lime plaster on the chemical and mechanical properties of natural bast fibre reinforcement. There was one paper which alluded to a possible uptake of calcium ions from gypsum plaster by flax, but this was a hypothesis still under debate.

> Dalmay, P., Smith, A., Chotard, T., Sahay-Turner, P., Gloaguen, V., and Krausz, P., 2010. Properties of cellulosic fibre reinforced plaster: influence of hemp or flax fibres on the properties of set gypsum. *Journal of Materials Science* 45 (3):793-803.
> Factors influencing strength of fibre-reinforced gypsum include fibre length.
> Hypothesis that Ca is absorbed/chelated by pectin

There were no obvious publications on the effect of pH, specifically alkalinity, of the plaster on bast fibres in reinforced plaster.

Conclusion
Under load and with moisture uptake, bast fibres can become stiffer and less elastic.

15.4 APPENDIX D

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

15.5 APPENDIX E

15.6 APPENDIX F

15.7 APPENDIX G

SELECTIVE EXTRACTS

HEALTH AND SAFETY AT WORK ETC. ACT 1974

The extracts below are from the Health and Safety at Work etc. Act 1974 (HWSA)

The full legal text is available on line: http://www.legislation.gov.uk/

15.7.1 SECTION 2

General duties of employers to their employees.

(1) It shall be the duty of every employer to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all his employees.

(2) Without prejudice to the generality of an employer's duty under the preceding subsection, the matters to which that duty extends include in particular —

(a) the provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risks to health;

(b) arrangements for ensuring, so far as is reasonably practicable, safety and absence of risks to health in connection with the use, handling, storage and transport of articles and substances;

(c) the provision of such information, instruction, training and supervision as is necessary to ensure, so far as is reasonably practicable, the health and safety at work of his employees;

(d) so far as is reasonably practicable as regards any place of work under the employer's control, the maintenance of it in a condition that is safe and without risks to health and the provision and maintenance of means of access to and egress from it that are safe and without such risks;

(e) the provision and maintenance of a working environment for his employees that is, so far as is reasonably practicable, safe, without risks to health, and adequate as regards facilities and arrangements for their welfare at work.

(3) Except in such cases as may be prescribed, it shall be the duty of every employer to prepare and as often as may be appropriate revise a written statement of his general policy with respect to the health and safety at work of his employees and the organisation and arrangements for the time being in force for carrying out that policy, and to bring the statement and any revision of it to the notice of all of his employees.

(4) Regulations made by the Secretary of State may provide for the appointment in prescribed cases by recognised trade unions (within the meaning of the regulations) of safety representatives from amongst the employees, and those representatives shall represent the employees in consultations with the employers under subsection (6) below and shall have such other functions as may be prescribed.

F1 (5)...

(6) It shall be the duty of every employer to consult any such representatives with a view to the making and maintenance of arrangements which will enable him and his employees to co-operate effectively in promoting and developing measures to ensure the health and safety at work of the employees, and in checking the effectiveness of such measures.

(7) In such cases as may be prescribed it shall be the duty of every employer, if requested to do so by the safety representatives mentioned in [F2subsection (4)] above, to establish, in accordance with regulations made by the Secretary of State, a safety committee having the function of keeping under review the measures taken to ensure the health and safety at work of his employees and such other functions as may be prescribed.

Annotations are used to give authority for changes and other effects on the legislation you are viewing and to convey editorial information. They appear at the foot of the relevant provision or under the associated heading. Annotations are categorised by annotation type, such as F-notes for textual amendments and I-notes for commencement information (a full list can be found in the Editorial Practice Guide). Each annotation is identified by a sequential reference number. For F-notes, M-notes and X-notes, the number also appears in bold superscript at the relevant location in the text. All annotations contain links to the affecting legislation.

15.7.2 SECTION 3

General duties of employers and self-employed to persons other than their employees.

(1) It shall be the duty of every employer to conduct his undertaking in such a way as to ensure, so far as is reasonably practicable, that persons not in his employment who may be affected thereby are not thereby exposed to risks to their health or safety.

(2) It shall be the duty of every self-employed person to conduct his undertaking in such a way as to ensure, so far as is reasonably practicable, that he and other persons (not being his employees) who may be affected thereby are not thereby exposed to risks to their health or safety.

(3) In such cases as may be prescribed, it shall be the duty of every employer and every self-employed person, in the prescribed circumstances and in the prescribed manner, to give to persons (not being his employees) who may be affected by the way in which he conducts his undertaking the prescribed information about such aspects of the way in which he conducts his undertaking as might affect their health or safety.

15.8 APPENDIX H

FIBROUS PLASTER DEVELOPMENT

ILLUSTRATIONS

PLASTERING

PLAIN AND DECORATIVE.

A PRACTICAL TREATISE ON THE ART & CRAFT OF PLASTERING AND MODELLING.

INCLUDING FULL DESCRIPTIONS OF THE VARIOUS TOOLS, MATERIALS, PROCESSES, AND APPLIANCES EMPLOYED; ALSO OF MOULDED OR "FINE" CONCRETE AS USED FOR FIREPROOF STAIRS AND FLOORS, PAVING, ARCHITECTURAL DRESSINGS, &c. &c.

TOGETHER WITH AN ACCOUNT OF

HISTORICAL PLASTERING IN ENGLAND, SCOTLAND, AND IRELAND,

ACCOMPANIED BY NUMEROUS EXAMPLES.

BY

WILLIAM MILLAR,

PLASTERER AND MODELLER.

WITH AN INTRODUCTORY CHAPTER ENTITLED "A GLIMPSE OF ITS HISTORY,"

BY G. T. ROBINSON, ESQ., F.S.A.

THE WHOLE FULLY ILLUSTRATED WITH FIFTY-TWO FULL-PAGE PLATES, AND TWO HUNDRED AND THIRTY-ONE SMALLER ILLUSTRATIONS (comprising over Five Hundred Figures) IN THE TEXT.

LONDON:

B. T. BATSFORD, 94 HIGH HOLBORN.

1897.

Plate 1 Frontispiece of Millar, 1st Edition 1897.

Millar was a Scottish plasterer active during the second half of the nineteenth century and spent the latter part in and around London. He came from a long family tradition in plastering stretching back generations.

At over 600 pages covering all aspects of the craft, the first edition was closely followed by a second edition in 1899. Whilst revising for the third edition in 1903, Millar was stricken with an illness and died in 1904. The third edition was published 1905 with revisions and additions by others. A fourth edition was published in 1927 considerably edited and revised by George P Bankart omitting large sections and adding chapters of his own.[82]

[82] Introduction to the facsimile reprint of the 1st edition of 1897 by Donhead, (1998)

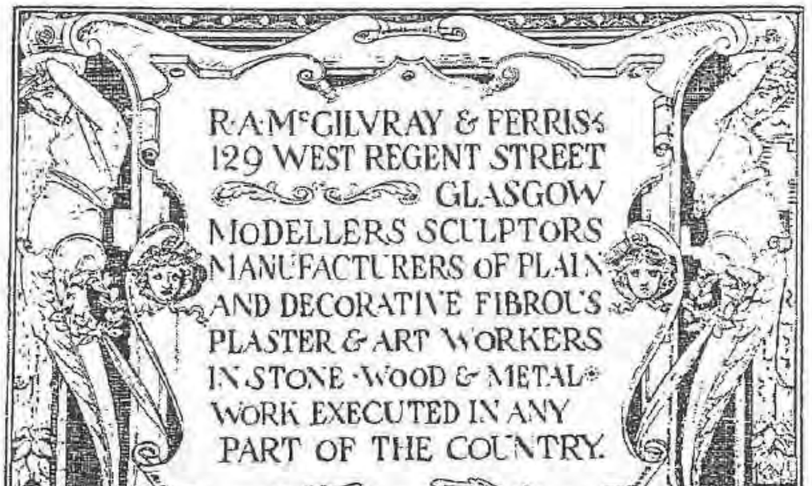


Plate 2 Adverts for fibrous plaster from across the country reproduced in Millar 1897

25

A. F. LATTO & CO.

10, Coleman Street, London, E.C.

JUTE, HEMP, AND FLAX MERCHANTS.

SPECIALTY—CANVAS

Of all Descriptions for Fibrous-Plastering, Building, Paper-Hanging, &c.

Samples and Price Lists on Application.

Telegraphic Address—"Yarnless, London."

Plate 3 Canvas "scrim" 'chiefly supplied by A.F. Latto & Co. advert in Millar 1897

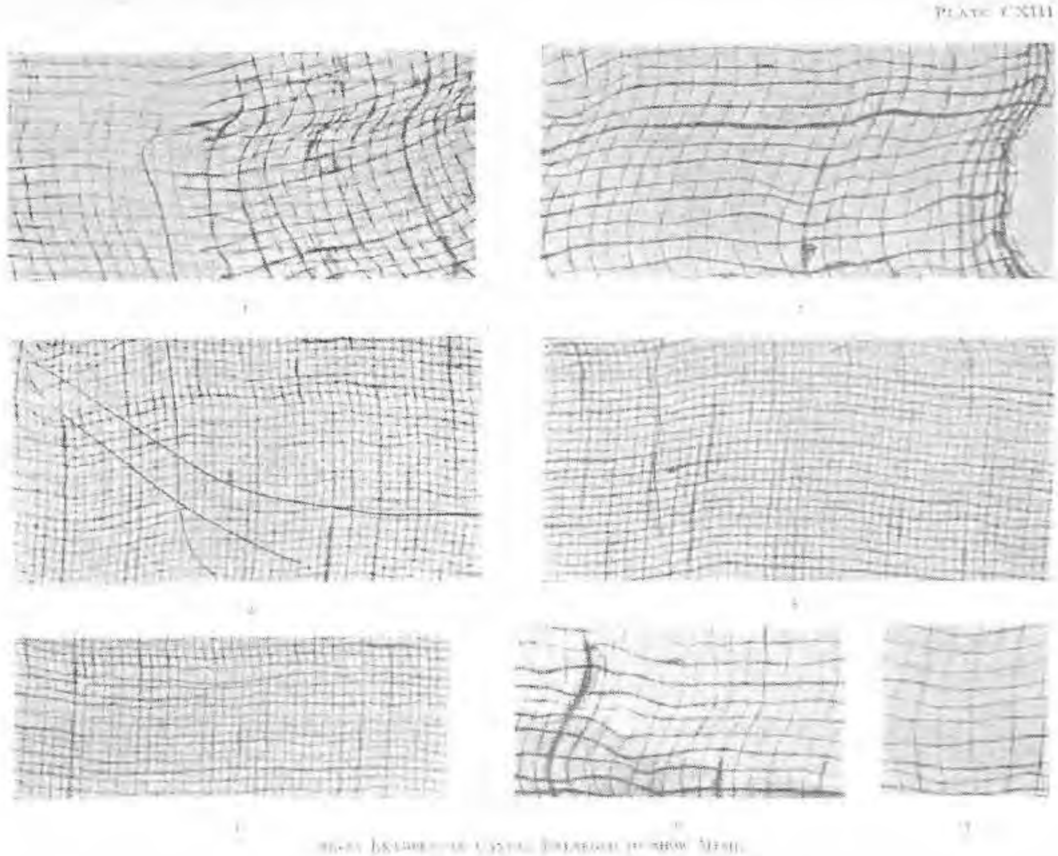


Plate 4 Seven examples of canvas (hessian scrim) in Millar 4th Ed (1927) p.248 Plate CXIII

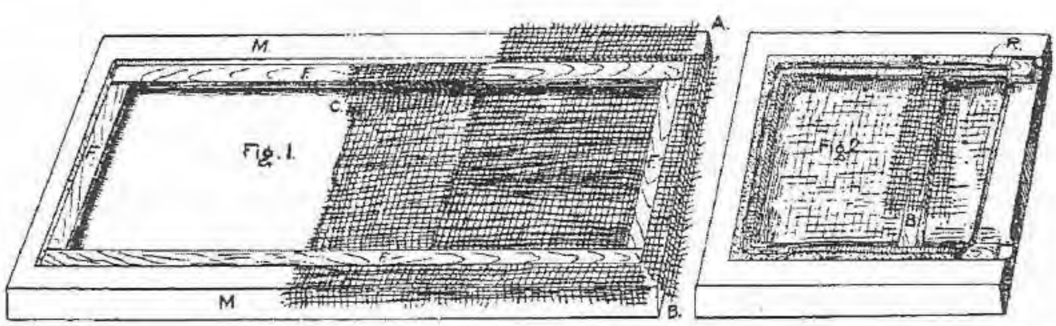
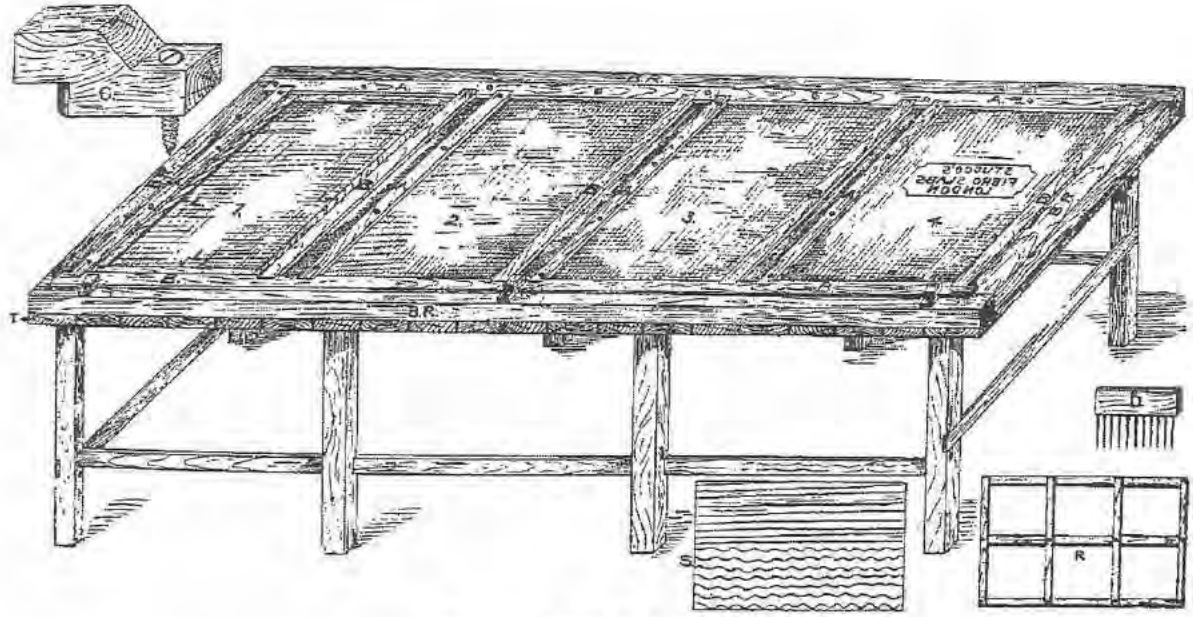


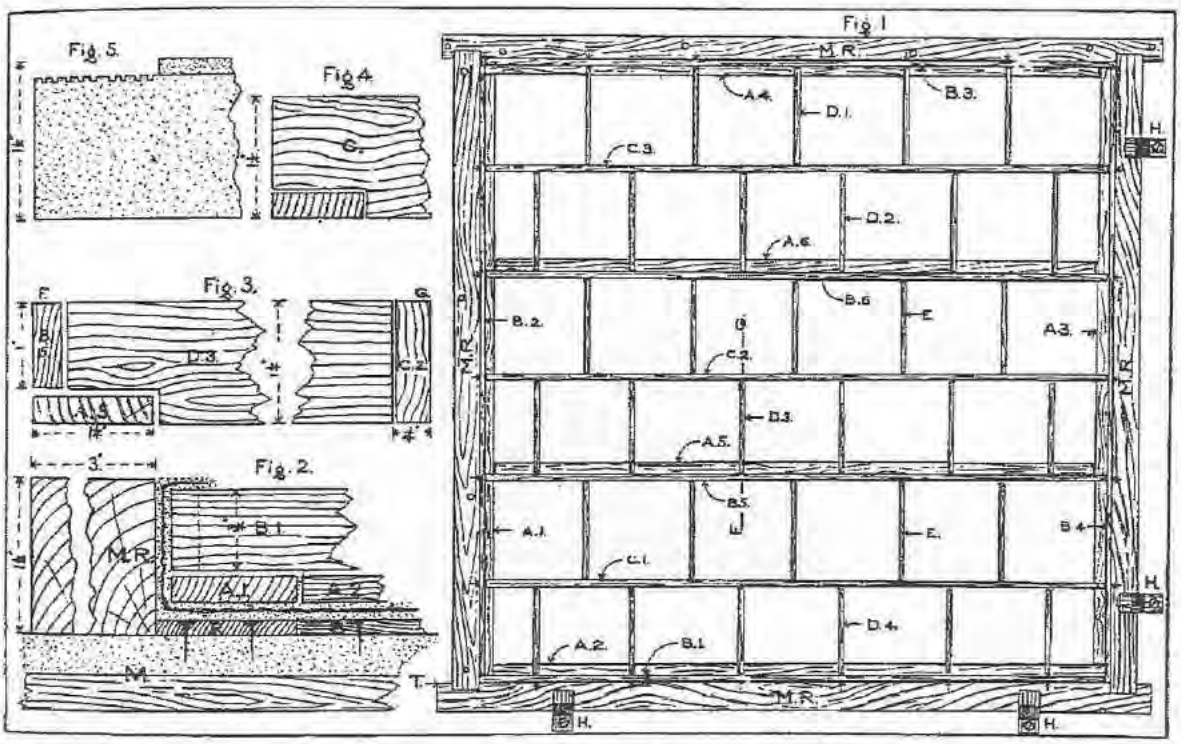
FIG. 104.—(1) Panel Mould, showing Filling in of a Fibrous Plaster Cast; (2) Portion of Mould with Cast nearly Finished.

Plate 5 Illustration of the method of laying and folding the edges of hessian and inserting timber reinforcement in casting flat faced plaster panels in Millar 1st Ed (1897) p.348



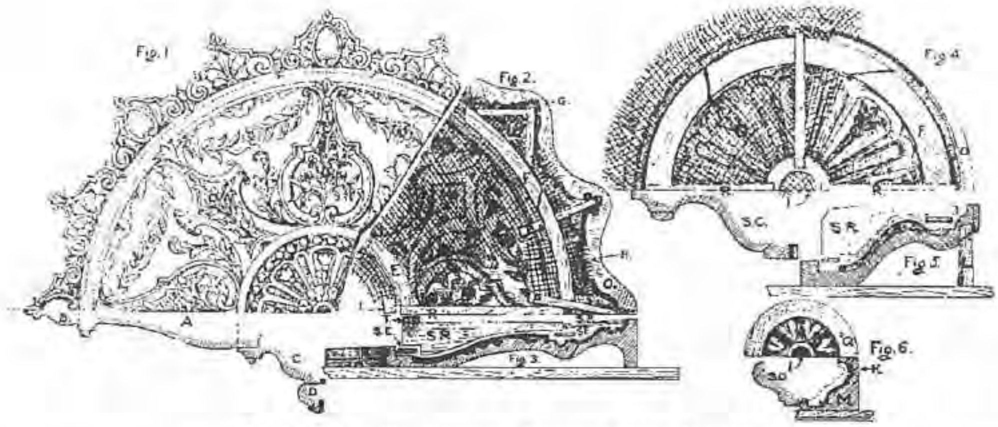
No. 140.—Bench Slab Mould.

Plate 6 Creating a large slab mould of plain faced plaster in Millar 1st Ed (1897) p.369



No. 141.—Finished Face Slab Mould, showing Slab during the Process of Making.

Plate 7 Typical reinforcement of flat faced ceiling panels contemporary with those employed in the ceiling fabrication and construction at the Apollo Theatre in Millar 1st Ed (1897) p.375.



No. 136.—Casting a Fibrous Plaster Centre Flower.

Fig. 1.—Part Plan, with Section of Centre Flower. Fig. 2.—Part of Wax Mould, with Cast partly filled in. Fig. 3.—Section of Body Mould and Cast. Fig. 4.—Half Plan and Section of Centre. Fig. 5.—Section of Centre Mould and Cast. Fig. 6.—Half Plan and Section of Seed Mould.

Plate 8 Casting a fibrous plaster centre flower in Millar 1st Ed (1897) p.351

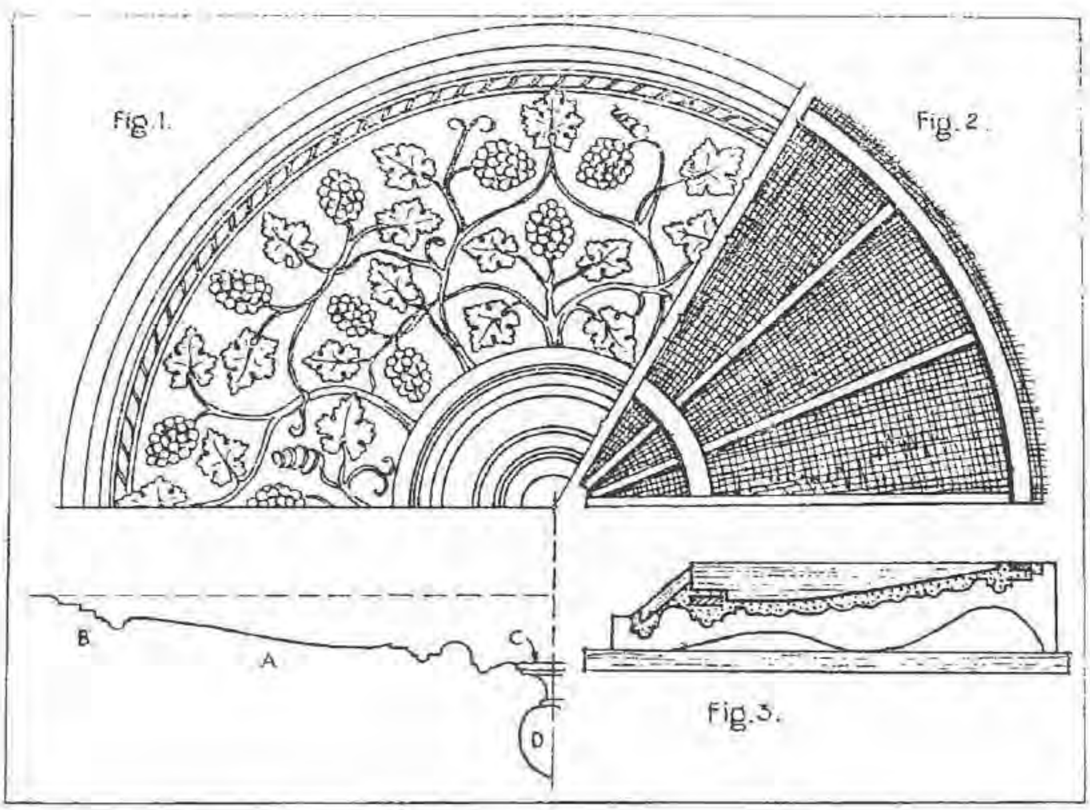


Fig. 167.—Casting a Fibrous Plaster Centre Flower.

Plate 9 Simplified illustration of same process in Millar 4th Ed (1927) p.250

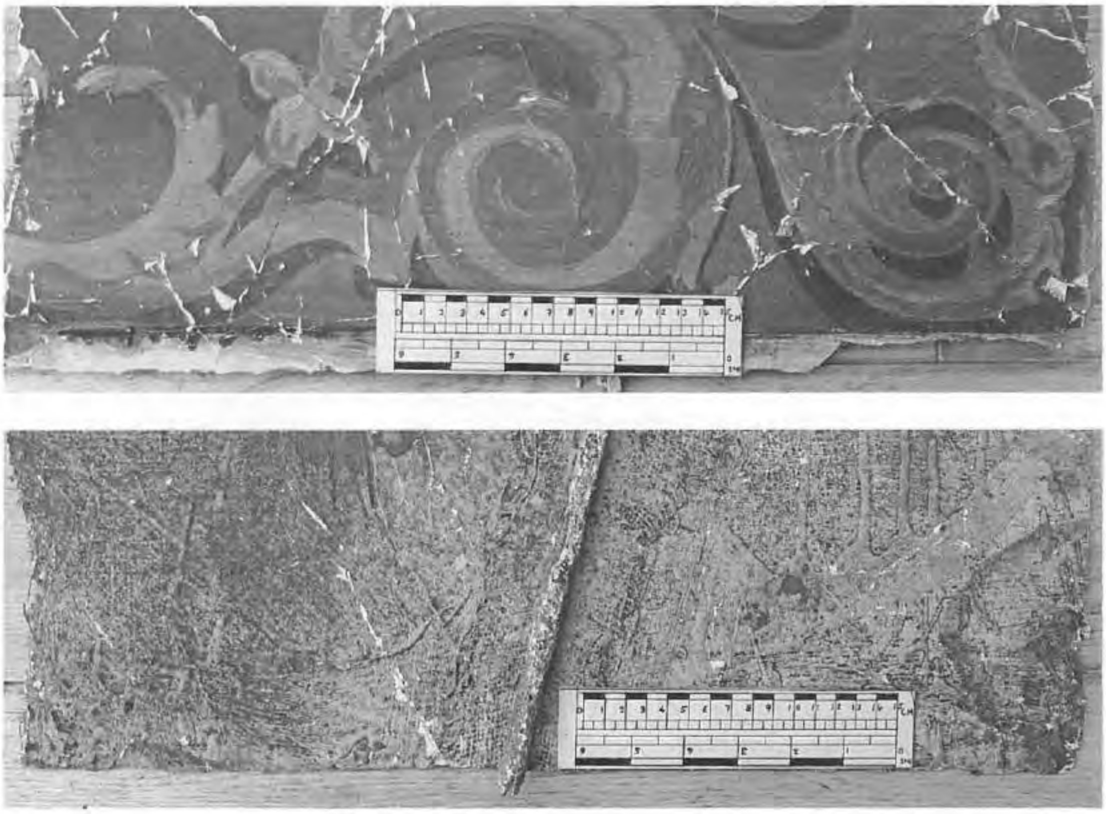


Plate 10 Front and back of typical fibrous plaster section from the Palace Theatre London, (opened 1891) showing the use of lath to provide additional reinforcement to a flat panel

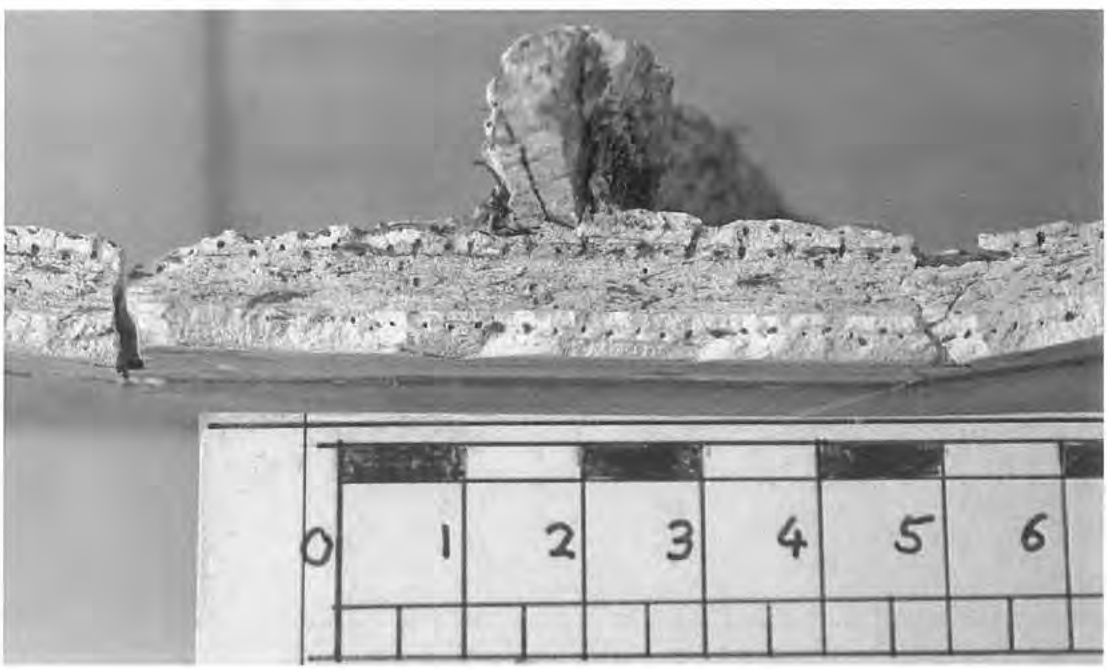


Plate 11 Detail of Plate 10 (above) giving edge on view of plaster section showing exposed hessian scrim incorporated in plaster and lath on edge for additional panel support and with whiter 'firsts' layer distinct from the subsequent greyer 'seconds' layer of plaster

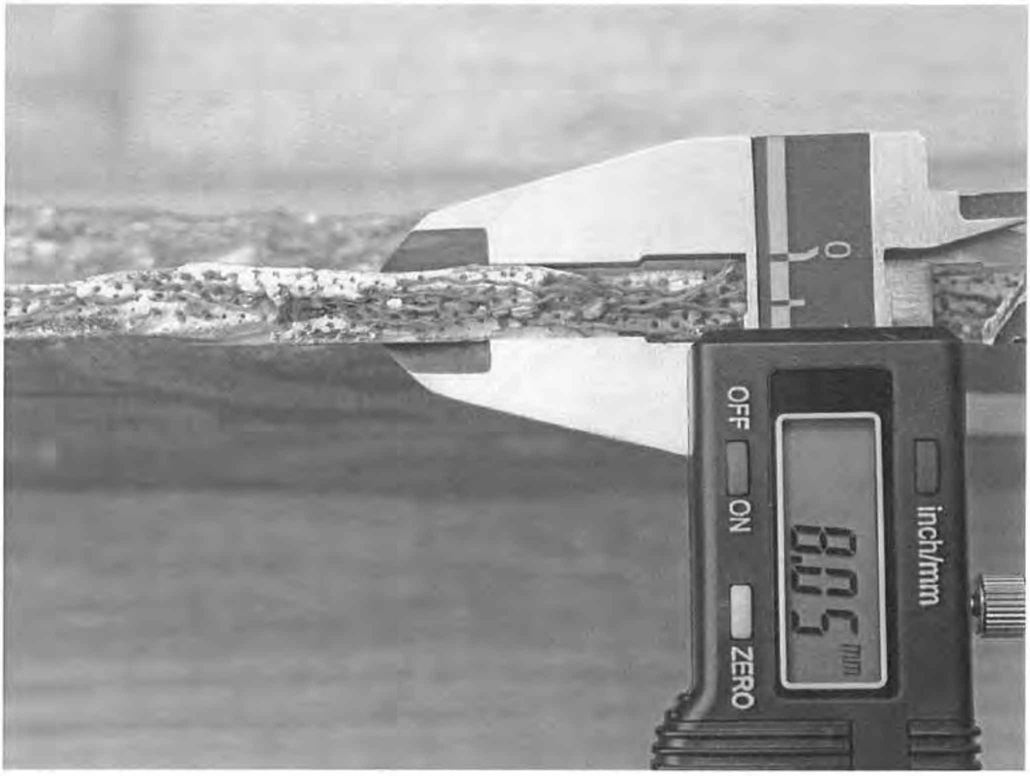


Plate 12 Digital caliper indicating the thickness of the Palace Theatre panel at just 8.05mm

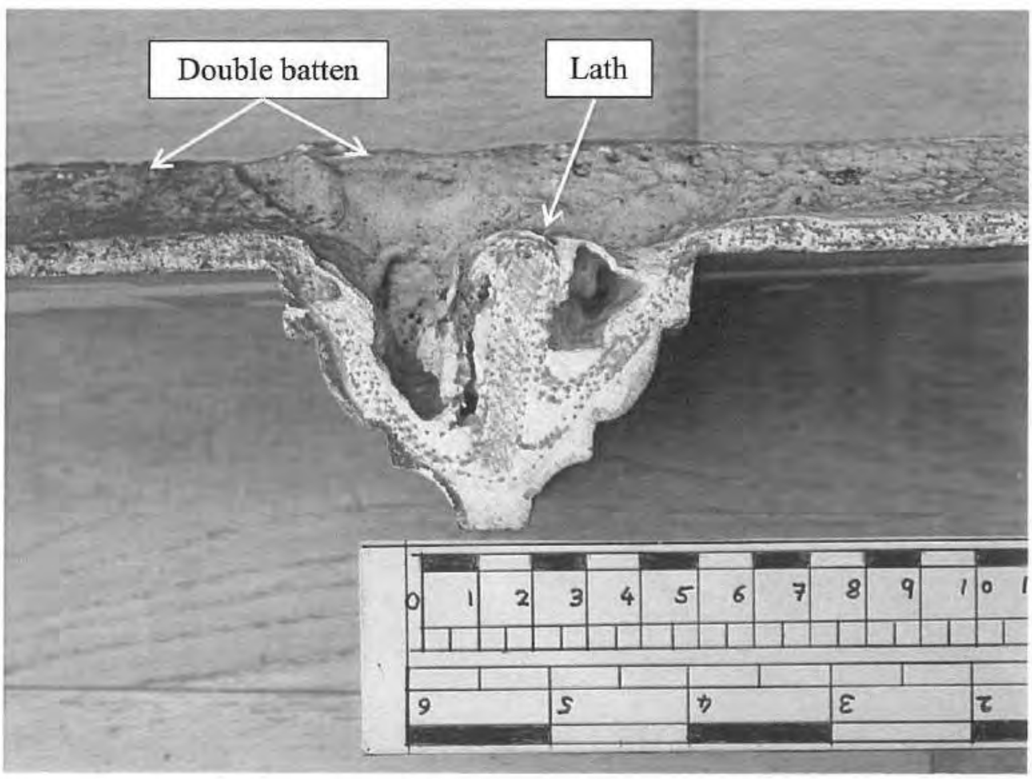


Plate 13 A larger rib from the Palace Theatre panel incorporating a lath on edge taking up the depth of the rib with the horizontal hump along the upper edge covering a double batten

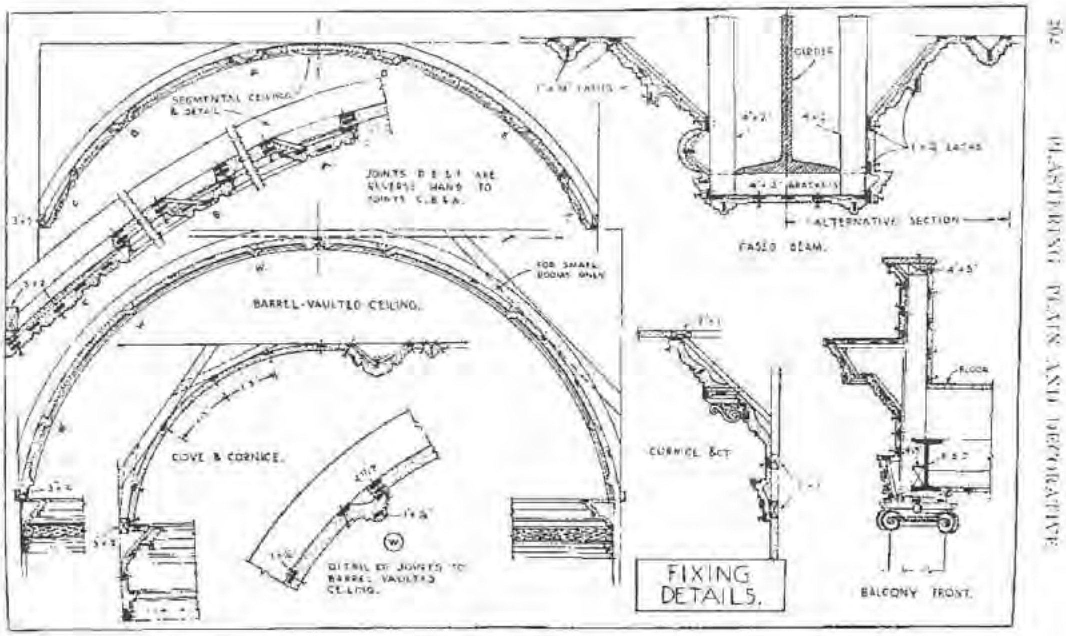


Plate 14 Fixing detail for a vaulted fibrous plaster ceiling in Millar 4th Ed (1927) p.262

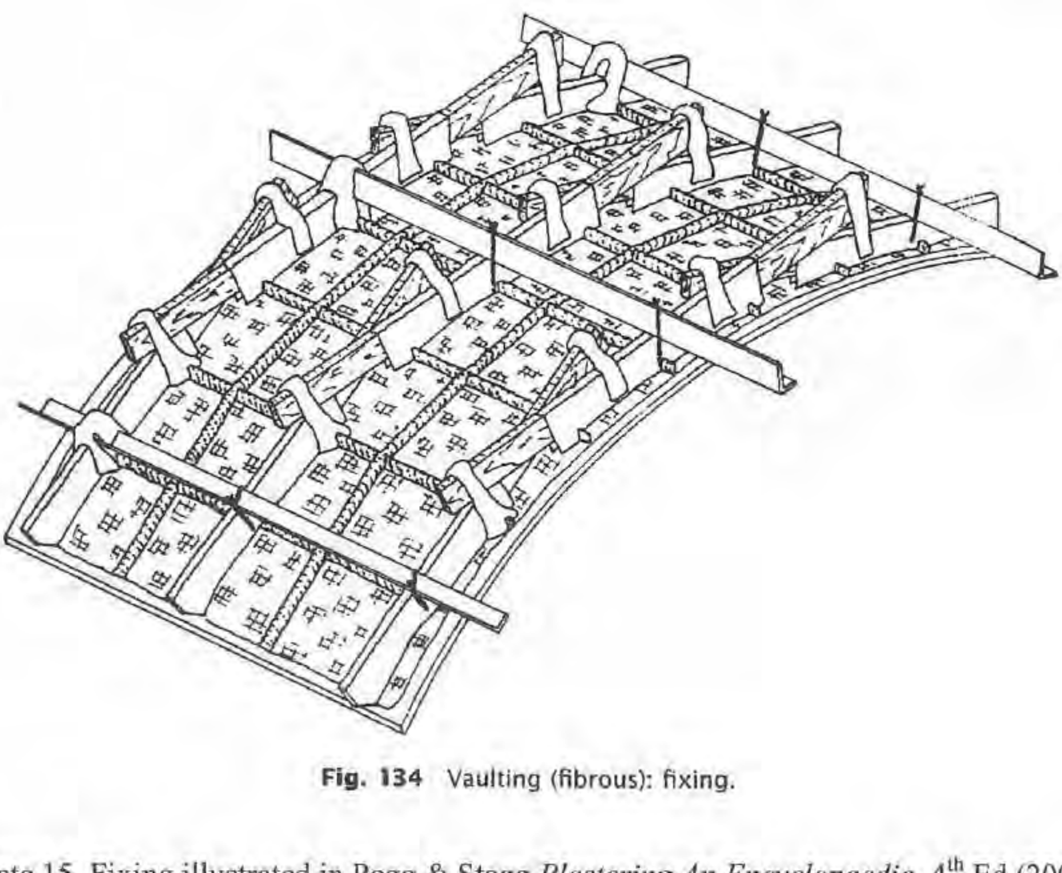


Fig. 134 Vaulting (fibrous): fixing.

Plate 15 Fixing illustrated in Pegg & Stagg *Plastering An Encyclopaedia*, 4th Ed (2007) p.285 written for students for The Advanced Apprenticeship in Plastering NVQ Level 3.

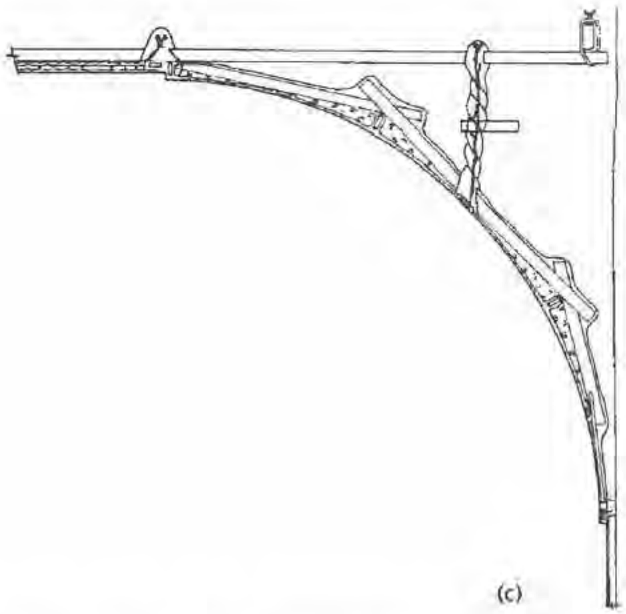


Plate 16 Cornice and coving fixing illustration in Pegg & Stagg 4th Ed (2007) p.55

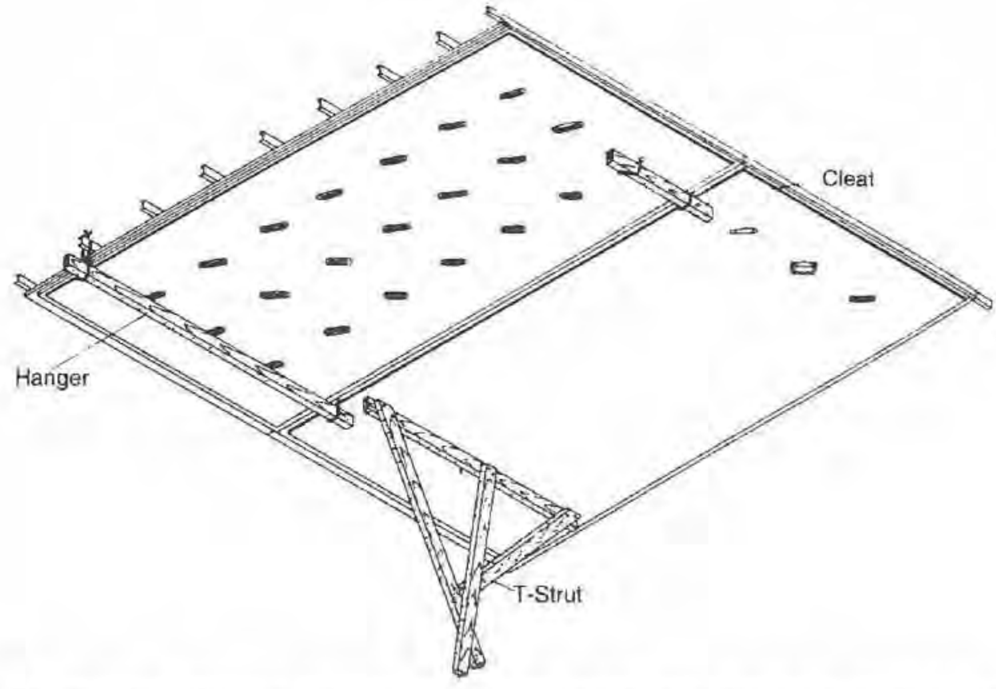


Fig. 93 Plainface (fibrous): hanging plainface for wiring and wadding to metal fixings.

Plate 17 Plainface panel fixing illustration in Pegg & Stagg 4th Ed (2007) p.197

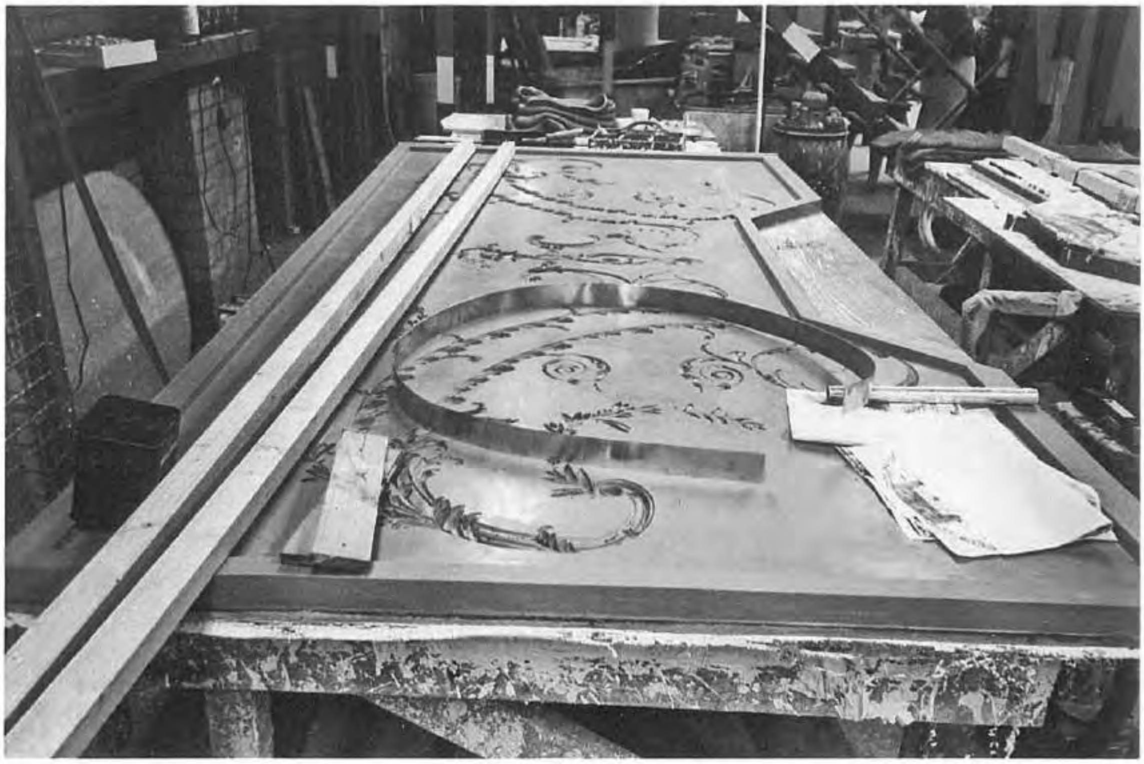


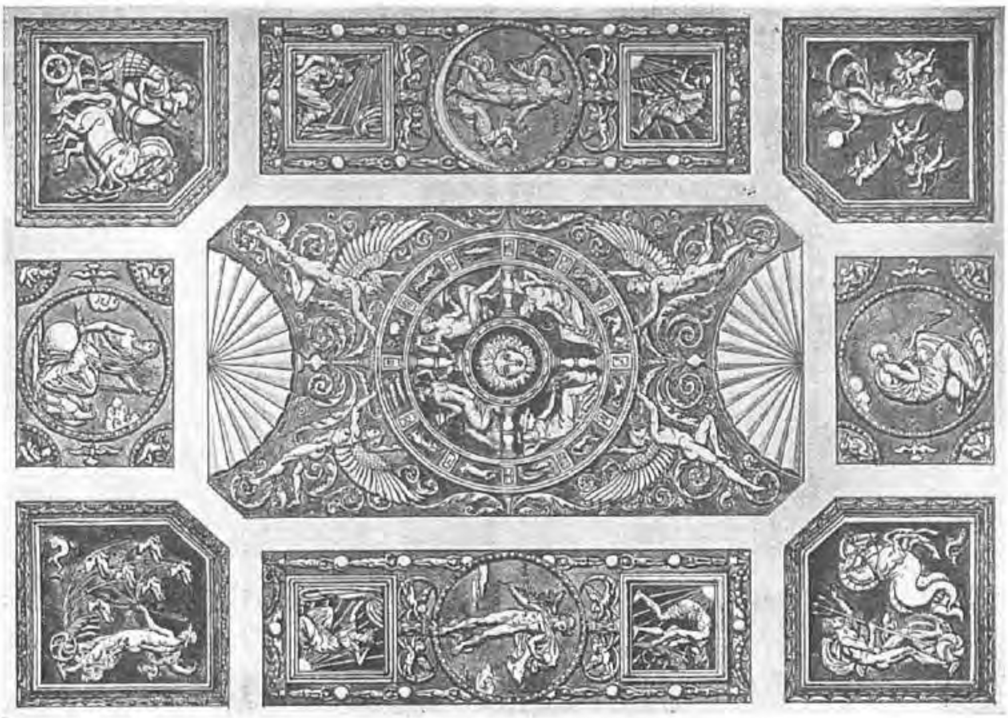
Plate 18 Silicone rubber mould ready for casting of fibrous plaster ceiling panel 2003

Plate 19 Cast fibrous plaster ceiling panel section forming part of a new ceiling installation

Plate 20 Suspension and making good of modern 24 panel fibrous plaster ceiling bed 2012

Plate 21 A plaster workshop in London late nineteenth or early twentieth century

PLATE XLIV.



CEILING IN GESSO, IN THE SALOON AT COOMBE PARK, SEVENOAKS, DESIGNED AND MODELLED BY WALTER CRANE, 1880.

Plate 22 fibrous plaster and gesso fabricated ceiling design by Walter Crane for Combe Bank Sevenoaks designed in 1880 and illustrated in Millar 1st Ed (1897) p.402 Plate XLIV

Plate 23 Walter Crane ceiling installation at Combe Bank Sevenoaks

Plate 24 Typical wadding tie suspension system using hessian soaked in plaster of Paris. Photo courtesy of English Heritage in *Mortars Renders & Plasters* (2012) p.109

Plate 25 Wyndham's Theatre, London c.1898 one of the many period fibrous plaster ceilings Photo courtesy of English Heritage in *Mortars Renders & Plasters* (2012) p.109

15.9 APPENDIX I

APOLLO AUDITORIUM ILLUSTRATIONS

Fig 01 The Apollo Theatre Shaftesbury Avenue London opened 1901

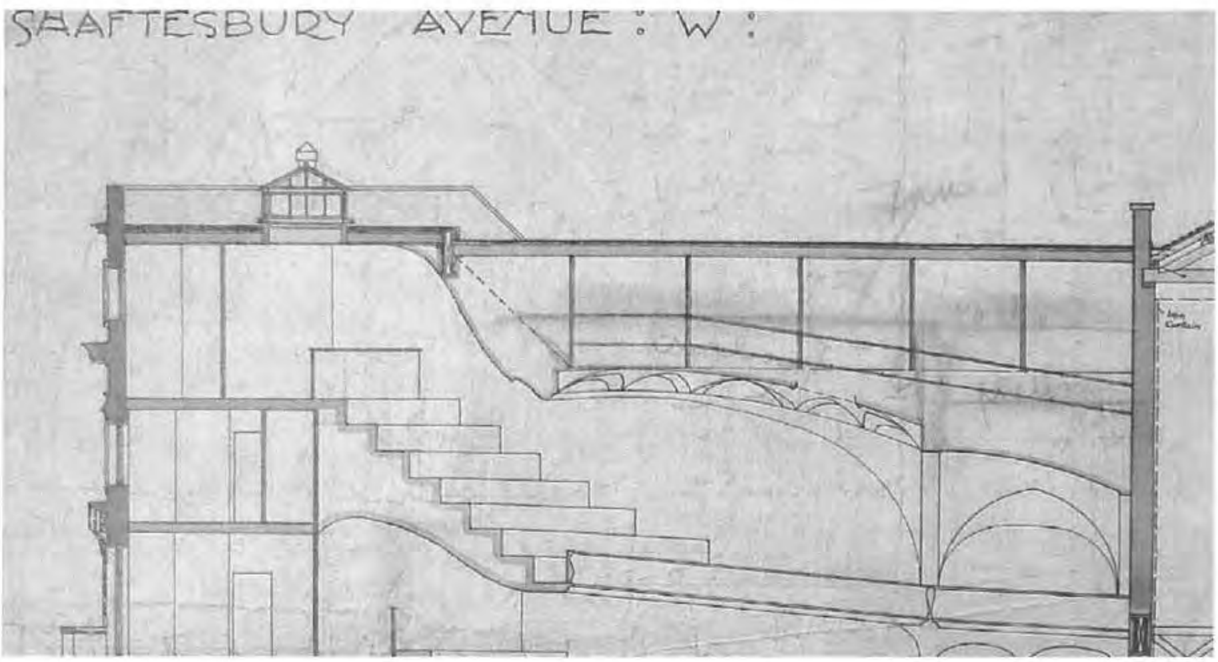


Fig 02 Detail of cross section of Apollo Theatre design by Lewen Sharp 1900 showing upper gallery and ceiling arrangement. Reproduced courtesy of Alan Baxter & Associates, retrieved from the London Metropolitan Archive.

Fig 03-52 REDACTED