CONSERVATION TECHNICAL HANDBOOK

A GUIDE FOR BEST PRACTICES

Volume 4 | Structure

ICOMOS SINGAPORE

URBAN REDEVELOPMENT AUTHORITY

Conservation Technical Handbook
Volume 4 | Structure

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Project Team

ICOMOS SINGAPORE
Ho Weng Hin
Tan Kar Lin
Wong Chung Wan
Yeo Kang Shua
Meranda Tang Ying Zi
Ryanne Tang Hui Shan
Foo Chin Peng
Margherita Pedroni
Jaclyn Chua Xin Hua
Nimmy Namrata
Rachel Lim Wan Shuen

GUEST CONTRIBUTORS
Ian Tan Yuk Hong
Yeo Sok Yee

URA
Chou Mei
Teh Lai Yip
Tan Huey Jiun
Kelvin Ang
Lee Yan Chang

Book Design
Achates360

Book Template
Meranda Tang Ying Zi

Cover photography by Jeremy San Tzer Ning, courtesy of Singapore Heritage Society: Ticketing foyer below reinforced concrete raked seating structural frame, National Stadium (1973–2010)

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Preface

Urban Redevelopment Authority, as the national land use planning and conservation authority, is pleased to present this series of conservation handbook. Through judicious planning, Singapore has conserved more than 7,000 buildings and structures since 1989. They cover different building types, architectural styles, scales and genres. They are our precious legacy that must be protected for current and future generations of Singaporeans.

This series is a culmination of URA's collaboration with ICOMOS Singapore, our local chapter of the International Council on Monuments and Sites. This worldwide non-government organization is the official Advisory Body to UNESCO, advising the latter on heritage, conservation and preservation matters and issues. It taps on the technical expertise and experience of ICOMOS Singapore members to take the protection of our heritage gems to a higher level.

The eight volumes in the series are designed as step-by-step guides to carry out best practices in conservation. They will aid those undertaking works on heritage buildings. They contain a wealth of insights gleaned from projects in and around Singapore, taking into account climatic conditions, materials available in the market, new techniques brought by technological advances, and the types of skills offered by the industry.

I hope building owners, developers, professionals in the industry, builders and others who are interested in this field will find this series rewarding. I believe we can foster a strong partnership to protect our heritage. Together, we can make Singapore not just a distinctive liveable city, but also a home that holds meaning for us all.

Chou Mei (Ms)
Group Director (Conservation & Urban Design)
Urban Redevelopment Authority

About This Series

Since the 1970s, when historic monuments were first granted legal protection and the first shophouses were rehabilitated, architectural conservation has evolved and taken root in Singapore. Heritage buildings form a significant part of our urban landscape today, as brick-and-mortar repositories of memories straddling generations and as treasured focal points for diverse communities.

In the early days, the main challenge was overcoming the prevailing perception of these historic buildings as crumbling, unsanitary and inefficient structures worthy only of demolition (though in need of rehabilitation, they are embodiments of artisanship, history and urban character). Another uphill battle was the polarized view that conservation is a zero-sum game in terms of economic growth and urban development (it is an indispensable component in all creative, dynamic, well-loved, liveable and competitive cities).

With growing appreciation and awareness of heritage, many have since come around to the idea that conservation is not about fighting change but about how it is managed. Across the city, historic neighbourhoods have found a new lease of life as places to live, work and play, and a growing number of national monuments have been carefully restored in recent years.

While much progress has been made and lessons learned in the past four decades, there is still much room for improvement in skills and knowledge of best conservation practices. This guide is intended to help bridge this gap by laying out the ways to identify and appreciate heritage attributes, understand historic materials and assess their condition, as well as the methods and principles of restoration and long-term maintenance.

Built heritage can be seen as a public good, and every stakeholder – including the owner, developer, authority, building professional, builder and user – serves as a custodian of these precious assets. There is shared responsibility to safeguard each historic structure and ensure its safe passage onwards to the next generation. This series is conceived to provide guidance along the way.

Dr Kevin Y.L. Tan
President
ICOMOS Singapore

About This Volume

Look out for margin notes such as this one, which will give you further advice or link you to other parts of the book.

What do the icons mean?

- General tips and advice
- Concepts covered in other chapters or volumes in the series
- Worksheets are available
- External references
- Further reading and topical notes

Volume 4: Structure is the fourth book in a series of eight **Conservation Technical Handbooks**. It provides an introductory overview of the key historic structure types found in Singapore's historic buildings, highlighting key challenges, principles and approaches for their protection, repair and rehabilitation.

Chapter 1 Introduction presents important principles, issues, approaches and concepts to take into account in the structural rehabilitation of historic buildings, including protection works and instrumentation.

Chapters 2 to 6 are organized according to the broad types of structural systems by material for easy reference: **Masonry** (bricks and stones), **Timber**, **Metal**, **Reinforced Concrete** and **Composite Structures**. Except for the last chapter, which covers more general concepts and notes, the contents of each chapter are organised under three key headings:

Overview: This section provides a historical background of the particular structural system, its local production, and particular uses in Singapore's past building practice.

Issues and Diagnostics: This section highlights common local structural deterioration issues and possible causes, and introduces the range of possible methods for inspection and diagnosis. Visual and tactile methods of diagnosis, as well as methods that require equipment and laboratory analysis, are provided.

Repair and Rehabilitation: This section outlines steps that are commonly taken to address causes of deterioration, as well as to restore and protect dilapidated historic materials.

While specialist consultants or builders are required for many of the technical investigations and works mentioned, having a basic understanding and overall idea of what constitutes a good conservation/maintenance regime would inform better management and works planning of the historic property.

Do look out also for **box stories** and **helpful tips** in the margins for more in-depth discussion of the material or element at hand.

1 INTRODUCTION

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Overview

Refer to Volume 1 Introduction for more information on historic building types and construction, planning for conservation works, and maintenance care.

Also refer to Volume 2 Roofs for more specific information on the various common roof systems.

Structures refer to the load-bearing elements of a building, such as columns, beams, floor slabs, load-bearing walls, roof trusses and foundations. Secondary structural elements may include corbels, struts, lintels, etc. In combination, these elements form a structural system to carry the weight of the building itself or 'dead load', and 'live load' – the users, fixtures, furniture and so on occupying the building – as well as environmental stresses such as wind load. Structures are generally designed according to the specific **building types**, catering for the maximum load associated with the particular building use – such as residence, office, warehouse, car park and so on.

Left: *Timber roof structure on massive masonry columns at former Tanglin Barracks (late 19th century).* ***Right:*** *Reinforced concrete structural frame as an integral part of architectural expression, Kampong Arang Housing Development Board flats (1960s).*

Current-day fire safety regulations may also require fire protection treatments to be done for historic timber and steel structural elements. This may impact on the building's heritage character, especially if these elements were also exposed architectural features. *Volume 8 Building Environment* will cover the possible mitigation strategies for heritage features impacted by regulatory compliance.

Assessment of and designing for historic structures is a specialized field that conventional engineers working only with current-day construction may not be familiar with, nor able to design for. For more information on the topic, refer to *ICOMOS International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage* (ISCARSAH).

A change in building use or **building regulations** may change the loading capacity required for a conserved building. General decay and usage wear of historic structures affecting their performance may also need to be addressed in a conservation project. A detailed heritage survey and structural investigation by qualified specialists should be carried out to assess the existing condition and capacity. A **professional engineer (PE) with conservation design expertise** and knowledge of historic structural systems should be engaged to oversee the structural investigation and undertake the design of any interventions.

Structural systems deployed in historic buildings provide material evidence of construction practices, applied building material and technology, and even product trade and supply network, for the particular period and context. Although a major contributor of heritage value in terms of material authenticity and scientific significance, structures are usually not the most visible aspect in a historic building and often overlooked in conservation considerations.

This volume provides an overview of the main structural systems found in local historic buildings, common issues encountered, and key considerations for repair and intervention works.

Flared mushroom columns and cantilevered flat slab roof in reinforced concrete, former Yan Kit Swimming Complex (1952).

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Principles for Conservation and Intervention

The degrees of intervention on historic buildings range from simple maintenance to deep rehabilitation, with two broad categories of work:

- **Repair** – to simply restore the load-bearing capacity of the building elements that have been compromised by cracks, loss of section and material degradation
- **Strengthening** – to increase the load-bearing capacity as a counter to general decay or due to change in building use

Structural systems form the basis of scale and spatial character of historic buildings. These qualities should be taken into consideration when devising conservation interventions. The five-foot ways along prewar shophouses with masonry and early reinforced concrete (RC) structure have a more intimate sense of scale to the colonnade ***(left)****, as compared to the openness of space along a postwar building with slender and long-spanning RC members* ***(right)****.*

A structural intervention approach that does not take into consideration non-structural heritage features may end up in severe loss of historic fabric and material authenticity. For example, fibre-wrap structural strengthening calls for plaster removal, which may severely damage historic stuccowork. As such, structural interventions of historic buildings should be **closely tailored solutions** designed by qualified engineers with conservation experience and sensibility.

It is pertinent to note that due to multiple considerations such as heritage value, potential collateral damage from intervention approach (e.g., in situ or off-site), or site constraints, the **optimal solution may not be the most structurally efficient**. Instead, the objective is to achieve the necessary structural performance while optimizing retention of historic material and minimizing heritage impact. Five key principles should be respected when considering structural interventions on historic buildings:

1. **Conserve as found**
   Each intervention should as far as possible respect the concept, techniques and heritage value of the existing historic structural design, and be marked or designed as evidently new for future reference. Deteriorated structures should be repaired rather than replaced, whenever possible.
2. **Minimum intervention**
   The removal or alteration of any historic material of distinctive architectural features should be avoided whenever possible.
3. **Like-for-like repairs**
   The characteristics of materials used in conservation repairs should fully match and be compatible with existing historic materials.
4. **Repairs should be reversible**
   Where possible, any measures should be reversible so that they can be removed and replaced with more suitable measures when new knowledge is acquired. Where they are not reversible, the interventions should not limit future interventions.
5. **Repairs should be sympathetic**
   The choice between traditional and innovative techniques should be evaluated on a case-by-case basis, and preference should be given to those that are least invasive and most compatible with the historic. Checks and monitoring during and after the interventions should be carried out to ascertain the efficacy of the results.

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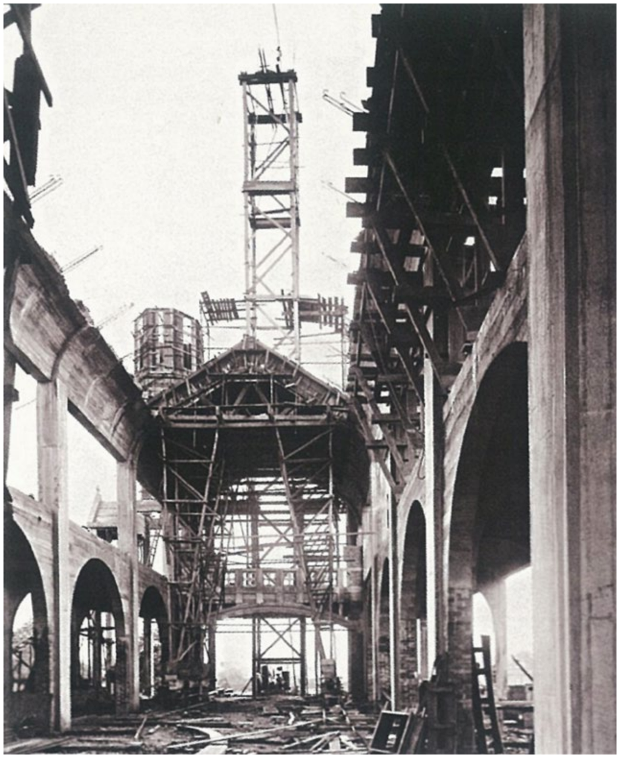
General Notes on Investigation and Diagnostics

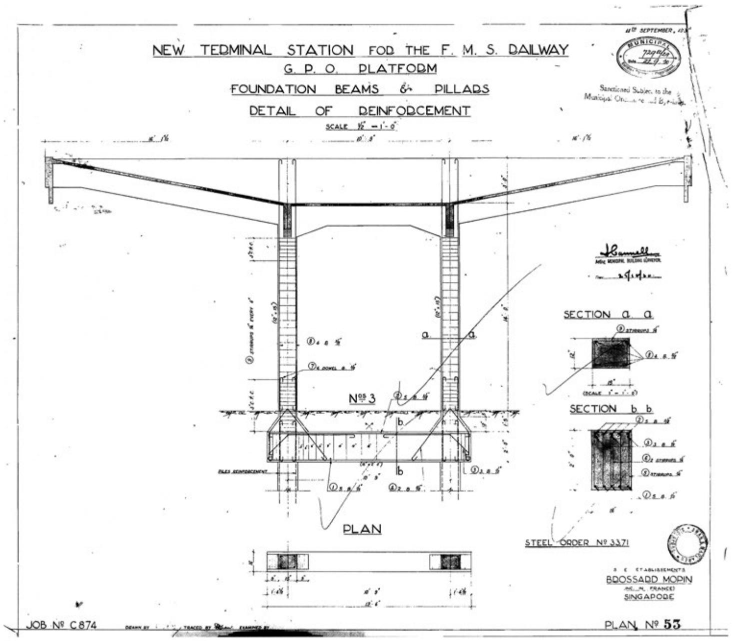
A necessary groundwork preceding any intervention design, the assessment of historic structures for safety and performance is a complex task, especially if there is scarce documentation of the original design provision, materials, and alterations undertaken. Conventional structural investigation caters mainly to current building practices using standardized industrial materials and methods, and should not be simplistically applied to historic construction that may vary widely in structural attributes and behaviour. The investigation of historic structures requires an **interdisciplinary approach** involving the skills and expertise of structural engineers, architects, conservation specialists, material scientists, geologists and structural testing specialists.



1927 archival photo of Church of St. Teresa being built sheds light on early reinforced concrete construction.

Beyond technical investigations, historical research often yields critical findings that inform building structural behaviour, such as construction phasing, historic material palette and building systems. A thorough understanding of the heritage structure's attributes and history will facilitate the impact assessment and sensitive design of any proposed works. The investigation process should cover the following aspects:-

- **Archival Research** to retrieve historical drawings, images, publications and documents that may contain the following information:
  - Architect, engineer, builder and client
  - Original intended design
  - Construction system and techniques
  - Material palette
  - Past building phases and transformations such as extensions, additions and alterations, structural modifications, restoration and reconstructions, and changes of use
  - Past environmental factors or events such as flooding, or accidental impact, that may have caused dilapidation, damage and failures



1930 archival building plan of Tanjong Pagar Railway Station shows structural details and name of the builder-engineer firm, Brossard Mopin.

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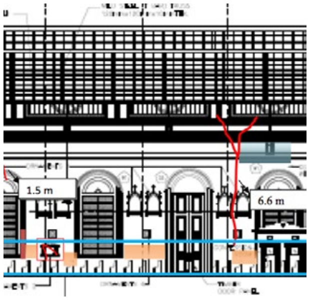

Mapping cracks and other dilapidation systematically will provide a more holistic understanding of the building's structural problems.

- **Dilapidation and Heritage Survey** to be carried out by a team of qualified conservation specialists to assess the structure's current state and material intactness:
  - Identify and document the material palette, construction, structural system and any observable alterations
  - Identify the type and extent of dilapidation, mapping their pattern and distribution
  - Determine the progression of dilapidation – whether it is worsening or has stabilized
  - Establish the current risks and whether there is a need for urgent measures
  - Identify any environmental factors impacting the building

Specialist equipment, such as the Drill Resistance Measurement System for brick masonry, is deployed to evaluate the strength and condition of existing structures to establish the conservation rehabilitation workscope.

- **Specialist Tests, Sampling and Laboratory Analysis** to be carried out by qualified specialists experienced in and capable of conducting these tests and evaluating the results according to the specific parameters of historic material and structures. In addition, for structural investigation, the test methods and final evaluation must be endorsed by a professional engineer. These investigations are required to determine the following attributes:
  - Mechanical (strength, elastic modulus, etc.), physical (e.g., porosity, density and dimensional stability) and chemical (composition, salt content, etc.) characteristics of the historic materials
  - Stress and deformation of the structure
  - Extent and nature of deterioration, such as corrosion, sectional or volume loss etc.
  - Presence of any discontinuity such as cavity, void, honeycomb, delamination within the structure

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General Notes on Maintenance

In general, the maintenance guidelines and programme of historic structures should take into account the following:

- Decay and deterioration tendencies of particular historic materials
- Past and impending interventions, changes to the use and/or environment of the historic building that may subject it to stresses
- Past and impending alterations to the historic structural scheme that may modify the load paths
- Changes in climate and microclimate such as urbanization, pollution, etc.

Monitoring devices -
***Top:** A crack gauge monitors the changes in width of a crack over time. Widening cracks are a cause for concern and should be addressed with the help of structural and building conservation specialists.*
***Above:** High-precision instrumentation using laser technology to monitor building settlement.*

The maintenance programme should include:

- Periodic inspection of the building for signs of decay and deterioration such as cracks, distortion, corrosion, wet rot, termite infestation, choked drainage
- Regular appropriate maintenance treatments, such as repainting with suitable paint, cleaning, removal of plant growths, etc.
- Preventing water ingress and condensation
- Proper ventilation when the building or part of the building is left unoccupied for a prolonged period

Where signs of distress or damage cannot be addressed immediately, these should be closely monitored either visually or with the help of common **monitoring devices**. Any sign of progressive deterioration should be noted and brought to the attention of structural engineers and conservation specialists.

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General Notes on Conservation and Intervention

LOAD PATHS AND MATERIAL COMPATIBILITY

First and foremost, any structural intervention should consider the original and current load paths. These should not be altered in any way that causes **undesired stress concentration**. For instance, the continuity of the wood grains or fibres in the same direction must be ensured in any replacement or partial replacement of timber members. Only mortar of similar composition and strength of the existing – and weaker than the bricks – should be used in the repointing of load-bearing masonry. Patching mortar for concrete should be of compatible modulus and strength as the parent historic concrete.

It is a common misconception that using a stronger material than the existing is better for structural repair – for example, the use of industrial bricks to repair a historic masonry wall of underfired hand-formed bricks. In fact, this will result in uneven stress concentration at the stronger new bricks, instead of the load being evenly distributed across the wall, creating potential weak points at the interface between old and new bricks.

HERITAGE IMPACT OF INTERVENTION

The impact of the proposed structural repairs or strengthening on significant historical elements and finishes should also be considered. Care should be taken to ensure that these are not damaged or adversely affected by the structural intervention works. Where damage or removal of significant architectural or historical features to facilitate the structural intervention is unavoidable, provision should be made for detailed prior documentation to allow such features to be restored or reinstated using the traditional and original methods and materials. In the restoration of traditional Chinese timber structures, the ***luojiadaxiu*** approach, involving complete dismantling of the roof structural frame, should only be adopted in cases of severe and extensive damage, as it would result in the collateral loss of significant historic features on the roof ridge such as the ceramic shardwork, stuccowork and murals.

Refer to Chapter 3 Timber Structures, box story on *luojiadaxiu* for more details on this traditional method of repairing timber structures.

STRUCTURAL RESTORATION AND REPAIR

Generally, the repair of degraded building material is achieved through restoring the geometry of structural elements. When the loss of a section is not very significant, it will be sufficient to adopt protective measures of the existing materials without having to restore the geometry.

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When restoring the geometry, materials identical to the original ones should be used. Should new materials be used, their compatibility with the original material in terms of strength, modulus, dimensional stability and vapour permeability should be looked into to avoid incompatibility issues. Repair of masonry, for example, may be obtained through repointing, injection of appropriate grout, and sometimes reconstruction or replacement of deteriorated masonry units. For timber, it may include splicing repair of degraded or lost segments, the use of inserted or external fasteners, aside from prosthetic repair, injection and consolidation with synthetic resin. Where there is a significant reduction in their sections, structures could be augmented with added members, with replacement only considered as a last resort.

Timber members that are otherwise intact but displaced due to impact or movement may be dismantled and reassembled to restore structural connectivity and load paths.

STRUCTURAL STRENGTHENING AND ADDITION

In the case of structural damage such as from ground settlement, or increased loading from change of building use, the additive approach is to repair the historic structure and introduce new structural elements to partially or entirely bear the required new load. For example, new steel I-beams could be inserted between original joists to increase the structural capacity of the historic timber floor.

__Right: Structural Restoration__ – Restoring the geometry and structural integrity of a timber column through whole-section 'timber-to-timber' partial replacement of the decayed lower portion. __Far Right: Structural Addition__ – Historic steel roof trusses were restored with new I-section portal frames sensitively inserted in between to meet increased roof loading needs, in the adaptive reuse of a former oil mill into a hotel. New structures could be easily distinguished from the old by a discreet difference in design without detracting from the heritage presentation.

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Where there is a need to restore or increase the strength of the historic structural element itself, it usually requires the introduction of new components:

- **Masonry walls** – Cracks and damage can be addressed by the installation of anchorages, bed reinforcement such as helix bars, and grout injection. To counter the effects of lateral loads the wall can be strengthened with metallic reinforcement or composites like carbon fibres and glass fibres with epoxy, i.e., fibre-reinforced polymer (FRP). Mesh reinforcement may be applied over a damaged masonry wall followed by suitable plaster – this method should, however, be carefully designed to retain the breathability of the wall.

- **Timber columns and beams** – Solutions include injection with consolidant, augmenting with steel or fibre reinforcement, and external reinforcement with FRP or steel plates. However, these techniques should be sparingly used, with the design and installation customized to the particular situation of each building.

FOUNDATION STRENGTHENING

Upgrading of foundations can be carried out by underpinning with micropiles or through improvement of the soil through jet grouting or with hydro-active grout. However, these types of measures should be extended to the entire building to avoid differential deformation of the building. An alternative solution to upgrade the foundation is the widening or enlargement of the footing, usually with additional reinforced concrete, or converting the isolated footing to strip footing.

Right: Foundation Strengthening – *Underpinning works to strengthen masonry building foundation.* ***Far right: Temporary Support*** *– Protective bracing of façade structural masonry wall while foundation underpinning was carried out at the Cathedral of the Good Shepherd.*

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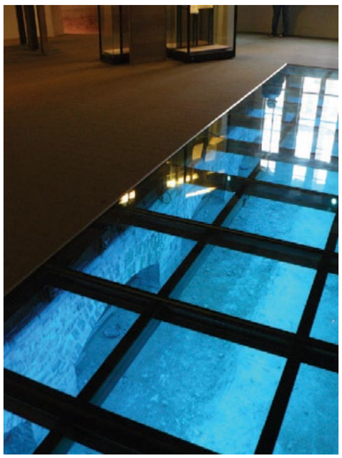
PROTECTION, TEMPORARY SUPPORT AND MONITORING

Pre-construction investigations and surveys of historic buildings should identify both structural and non-structural heritage elements that may be adversely impacted by intervention works. For example, damage could be caused by settlement and vibrations resulting from underpinning works, or accidental impact from proximity to heavy machinery access paths. An adequate protection, temporary support and instrument monitoring system should be catered for and put in place prior, to ensure the building's structural stability and prevent damage to the heritage elements throughout the construction stage.

HERITAGE PRESENTATION

Structures are often not highly ornamental or even visible parts of a historic building. Yet their material composition and construction present a rich depository of knowledge encompassing craftsmanship, local geology and resources, past trading activities, building traditions, and historic technologies. In the adaptive reuse and fitting out of a historic building, box-ups, false ceilings and partitions are often used to conceal new services, covering up originally exposed structures such as walls, columns, trusses, ceiling beams and joists. These new elements should instead be carefully planned and sensitively designed such that the historic features are not obstructed, or at least strategic parts of the original structures are left visible.



***Heritage Presentation** – Even originally hidden parts of the building structure may be showcased as part of the heritage presentation, to showcase a richer narrative. **Right:** The brick vault foundation of the former Tainan Prefecture Hall (1916) as seen through a glass floor panel. **Far right:** The panel of exposed structural masonry wall of Cathedral of the Good Shepherd shows how the two building phases (1845 and 1888) used bricks of different manufacturing processes.*

2 MASONRY STRUCTURES

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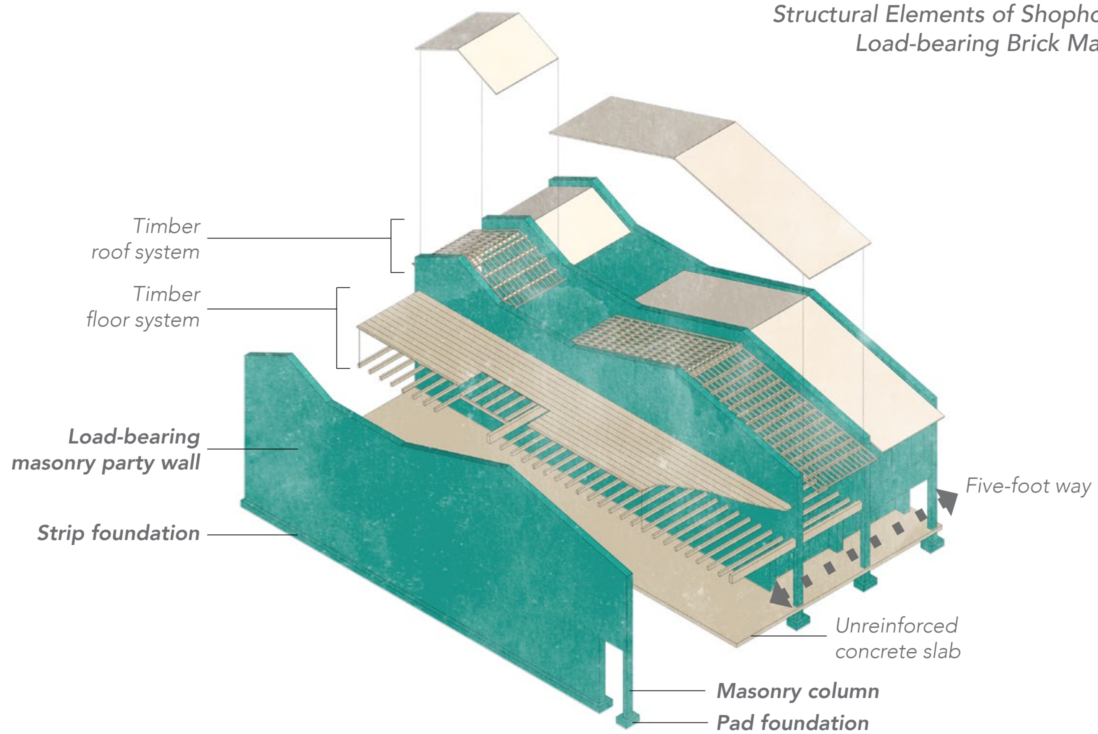
Overview

Refer to Volume 3 Facades, *Chapter 3 Masonry*, for more information on fairfaced masonry facades (that may or may not be load-bearing structures) as well as mortar joints, pointing and repairs.

Masonry structures refer to load-bearing building components constructed of individual units laid and bound together by mortar. Masonry structures are high in compressive strength but have low tensile strength. To counter flexing and provide lateral stability, this is usually compensated for by creating massive construction, introducing stiffeners (such as vertical 'ribs' along walls), or embedding reinforcements in the masonry.

The most common historic masonry material used locally is brick, with rare examples in building stone such as granite. The typical shophouse/ townhouse party wall is one of the most common major structural masonry elements found in Singapore's historic buildings, usually in combination with timber floor and roof systems. As stipulated by early colonial planning regulations following fire incidents, party walls extended all the way from the front to the back facades and above the roofs to act as firebreaks separating the terraced units.

Structural Elements of Shophouse – Load-bearing Brick Masonry



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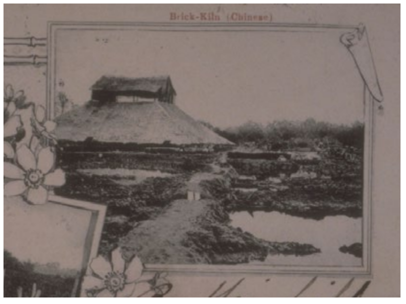
Refer to *Volume 3 Facades Chapter 3 Masonry* for more information on the history of brickmaking in Singapore as well as a discussion of mortar joints.

BRICK MASONRY

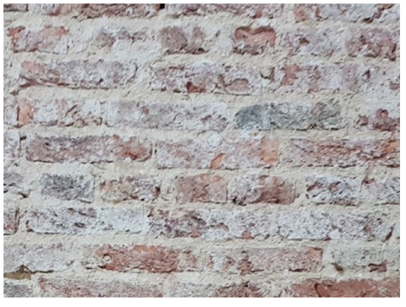
In essence, brickmaking refers to iron-rich clay being moulded, pressed and then baked at a certain temperature to create robust fireproof masonry units. Archaeological findings at Fort Canning included brick buildings – and, by implication, **brickmaking** – dating back centuries to precolonial times.

Small-scale Chinese-operated brick kilns produced affordable hand-made bricks from the early colonial period, found in most prewar privately developed shophouses or townhouses where they were used to construct party walls. Being irregular in size and underfired/unevenly fired (thus lower in strength and unevenly coloured), most **pre-industrial hand-formed bricks** were usually not meant to be exposed but concealed and protected under plaster and paint (or limewash). These private kilns later on competed against government-run brickfields from the mid-19th century onwards that supplied public works with their better quality-controlled products.

Local geology presented clay that was wellsuited for brickmaking, such as along Serangoon Road, where a large-scale government brickfield was started in 1858, and at Pasir Panjang, where the industrial production first took place at Alexandra Brickworks in 1899.



Left: *1904 postcard showing a privately operated Chinese brick kiln.*
Right: *Workers stacking bricks for firing at Alexandra Brickworks, 1953.*



Left: *Pre-industrial hand-formed brick masonry found at Raffles Hotel (1887).*
Right: *Larger standardized industrial bricks from Alexandra Brickworks, seen at the former Traffic Police Headquarters (1929).*

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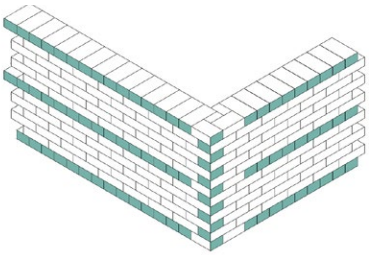
The labour-intensive early kilns were eventually phased out with the arrival of **industrial brickmaking** at the turn of the century, where machinery and high-powered kilns produced high-strength standardized bricks.

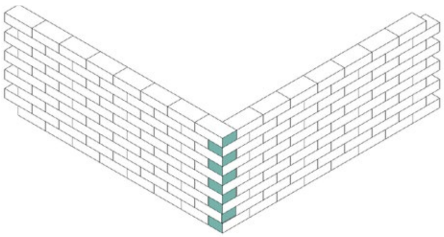
Historically, load-bearing brick walls were constructed by lime-based mortar binding irregular hand-formed bricks, the masonry held together largely by friction and gravity. The arrangement technique later developed into interlocking patterns that would tie the mass of the wall together and distribute the load evenly. Known as **brick bond patterns**, most are variations of the basic Stretcher, English and Flemish bonds, which enhance the structural performance as well as the visual appearance if the brickwork is exposed or fairfaced.

Other than shophouses, common uses of load-bearing brick masonry include first storey columns and walls of black-and-white bungalows supporting the timber-frame upper storey, brick piers of raised Anglo-Malay bungalows, and so on. More expressive forms of brick structures include arches and vaults that allow for spanning across openings or spaces, as well as buttresses. Brick masonry superstructures would usually extend below ground as strip or pad foundations.

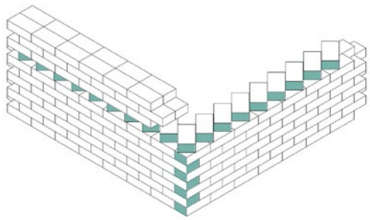
Brick Bond Patterns



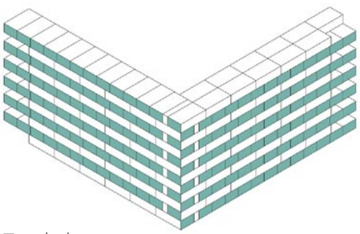
American



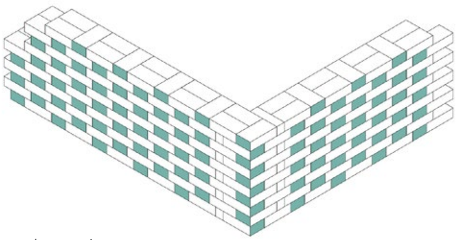
Common



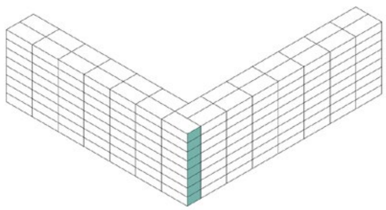
Dogtooth



English



Flemish



Stacked

***Top row and left:** Fairfaced load-bearing brick walls in English bond, and brick arches at St. George's Church (1913). **Right:** Buttressed brick wall at Tanjong Pagar Railway Yard staff quarters.*

***Far left:** The shophouse/ townhouse landscape, characterized by the series of party walls rising above the clay tile roofs as firestops between units. **Left:** Historic brick foundation of Victoria Concert Hall (flanked by new micropiles for strengthening).*

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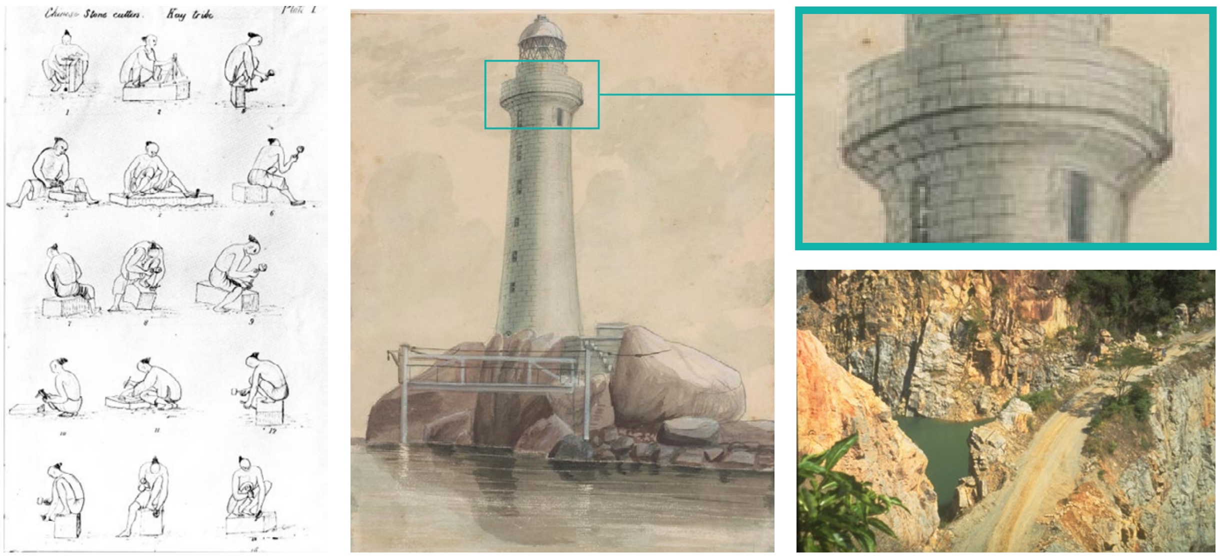
Refer to *Volume 3 Facades Chapter 3 Masonry* for more information on the history of stone masonry in Singapore.

STONE MASONRY

Load-bearing stone masonry is one of the oldest building construction techniques known and used by man. The earliest form of stone masonry construction was random rubble dry masonry, using various sizes of stones randomly stacked on top of each other to build a wall without using any mortar. This construction was further developed into the use of chiselled uniform stone pieces stacked in horizontal beds with mortar, also known as **ashlar masonry**, of which local examples can be found.

The Pulau Ubin quarries supplied their light blue-grey granite to colonial Singapore's early developmental works, including the Horsburgh (1851) and Raffles (1855) Lighthouses. The early government-run quarries on the island as well as Bukit Timah deployed Indian convict labour. Sketches by engineer and surveyor J.T. Thomson documented skilled Chinese stonecutters at Pulau Ubin working granite blocks for the construction of Horsburgh Lighthouse, which he designed.



*Drawings by J.T. Thomson - **Left:** Sketches of Hakka ('Kay Tribe') Chinese stonecutters at work on Pulau Ubin, mid-19th century. **Middle and top right:** 1851 painting of the Horsburgh Lighthouse a year after its completion, showing its stone masonry construction. **Bottom right:** View of an active Pulau Ubin granite quarry in the 1990s. The light blue-grey stone was still being quarried till recent decades for construction use.*

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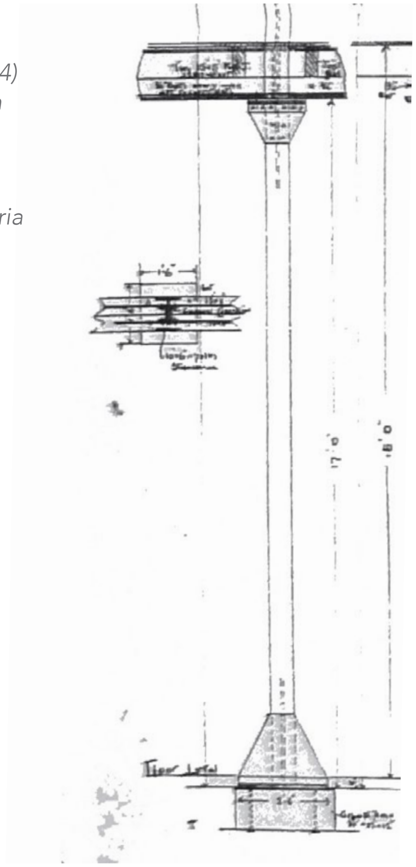
Given the costly and resource-intensive process of quarrying, working and building with the material in Singapore, entire stone buildings were uncommon. Instead, structural stonework was often used in combination with other types of structures such as brick masonry, timber and iron, usually taking the form of sparingly applied **carved stone structural features**. These include high key elements such as grand granite columns at the Victoria Concert Hall foyers, or strategic reinforcements where exceptional compression strength and durability are called for, such as corbels, column bases and capitals, lintels, plinths, etc. Stone may also be incorporated as part of the foundation system – for example, in the historic steel frame structural scheme of Stamford House (1904), rolled steel joist stanchions were bolted onto massive granite pads to form the substructure.

__Right:__ Archival drawing of Stamford House (1904) showing steel stanchion on granite pad footing foundation. __Far right:__ Granite columns at the grand staircase of Victoria Concert Hall (1909).



***Left:** Granite elements commonly appear in shophouses/townhouses as corbels supporting timber structures (top), and more rarely, as ornamental column bases (above). **Right:** As seen on the innerleaf facade of the former Jinriksha Building, granite keystone and impost are positioned where the compressive load is concentrated along an arch.*

*Examples of fairfaced masonry columns designed with an interplay of stones and bricks that showcase artisanal construction and fine workmanship at **(right)** House No. 1 on Pulau Ubin, and **(far right)** postwar government housing bungalows at Stevens Road (c.1948).*

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Structural Issues and Diagnostics

Refer to Chapter 1, General Notes on Investigation and Diagnostics for important concepts and issues to be aware of at the outset of planning for structural rehabilitation.

MAIN CAUSES OF STRUCTURAL ISSUES

In the local context, key root causes of structural damage to historic masonry structures can be classified broadly into three categories:

Ground movement and settlement can arise from changes to the groundwater and soil condition, often brought about by neighbouring construction activities like excavation, tunnelling works, roadworks and so on. Pre-World War II historic buildings are often constructed on shallow footings. Those with rigid structures such as masonry, with little tolerance for displacement, are especially vulnerable to ground movements. Surrounding vegetation, especially trees, can cause ground settlement or heaving, for example by the growth of roots. Such changes in the ground will cause the building to experience uneven physical stresses, resulting in cracks and structural instability.

Overloading can occur when the loading capacity limits and load paths that the building is designed for are altered. This can happen if there are ill-conceived changes to the structural scheme, for instance the ad hoc addition of a floor, removal of a load-bearing member, or unauthorized installation of services. Damage to a load-bearing element such as cracks and deteriorated bricks of a wall can result in a reduction of its loading capacity, leading to overloading stresses.

__Right:__ Brick masonry columns damaged by ground settlement caused by tunnelling works. Temporary bracing was put in place until structural repairs could be carried out. __Far right:__ Excessive chasing of services into the wall results in a loss of mass and compromised strength of the load-bearing brick structure.

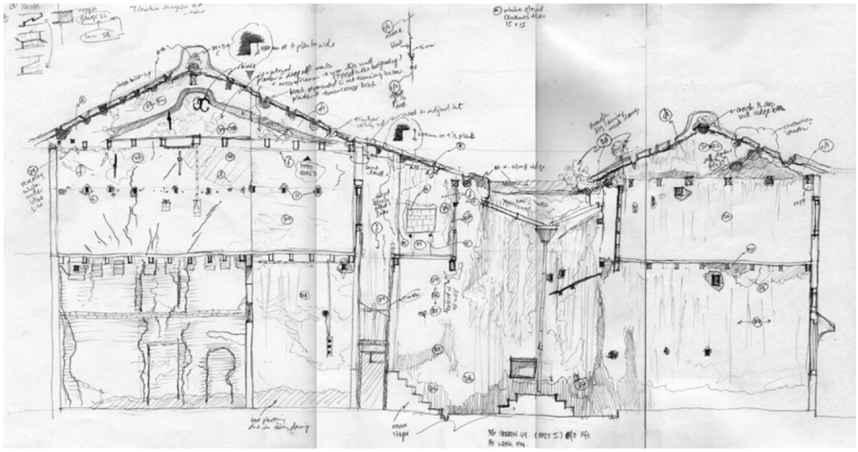
Refer to *Volume 3 Facades*, *Chapter 3 Masonry* for information on conservation treatment of rising damp and salt attack.

Restraint to dimensional changes refers to stresses and strains at the component level resulting from swelling or shrinkage of individual structural components. These can occur, for example, due to hygroscopic swelling of the clay bricks, and salt attack of the brickworks from rising damp. Where the masonry is reinforced, dimensional changes could arise from the corrosion of embedded steel, wet rot or termite damage of encased timber members, and so on.

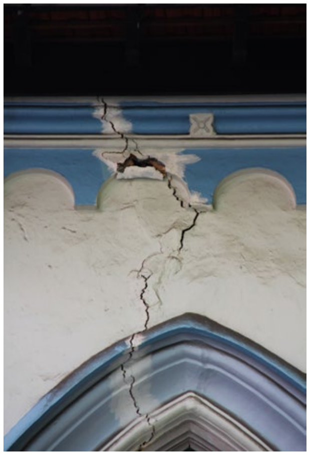
Rising damp caused by incompatible latter-day paint resulted in salt attack that eroded the brick substrate at the base of the columns and load-bearing walls. Plaster along the base has to be removed as part of conservation treatment.

VISUAL AND TACTILE SURVEY

Visible signs of dilapidation and the general structural scheme should be carefully identified, mapped and documented by a visual and tactile survey as the first step in assessing structural condition and issues.



Visual dilapidation mapping field sketch of a historic townhouse brick masonry party wall.



Visible sign of structural defect – crack through arch structure.

Visible symptoms suggesting possible masonry structural distress include the following:

- Crack - pattern, displacement, widths and their variation over length, changes to crack over time
- Deformation and tilt
- Misalignment of masonry units
- Deterioration or disconnection of joint between masonry element and other structural members
- Surface disintegration of masonry units or mortar joints
- Plant growth
- Dampness and water ingress
- Efflorescence indicating possible salt attack
- Delaminated or hollow-sounding plaster (for plastered walls, indicating possible issues with masonry substrate)

Any detected movement of the building during the survey should be monitored with instrumentation to determine the rate, severity, and risks of any structural damage.

For more details, refer to *Chapter 1, General Notes on Maintenance.*

NON-DESTRUCTIVE TESTS

The visual survey can be supplemented by on-site non-destructive tests that may reveal construction details and conditions concealed by the plaster finish or embedded within the masonry. These include the following:

- **Ground-/surface-penetrating radar** uses radar pulses to image the subsurface, revealing hidden construction details and elements, voids or cavities, thickness of walls, presence of moisture and salt, and so on.
- **Ultrasonic pulse velocity measurement** is used for assessing the soundness of the masonry units and wall.
- **Infrared thermography** detects the temperature distribution along a surface. Different temperature readings may indicate building defects, especially trapped moisture (cold spot) or the presence of different hidden elements (with varying degrees of heat retention).
- **Borescope or videoprobe** allows the visual inspection of hidden construction details at unreachable spots such as cavities and the insides of walls.

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SAMPLING AND LABORATORY ANALYSIS

In situ investigation methods that are more invasive include **breakouts** to reveal subsurface details such as masonry substrate, and **Drill Resistance Measuremen**t mainly for the evaluation of a brick masonry structure for its strength, extent of deterioration due to weathering, hydrolysis and salt attack that can reduce the load capacity. These methods may include the extraction of samples for laboratory analysis.

For an assessment of the soundness and strength of the masonry members, it is common to extract samples of the bricks and mortar joints for laboratory tests. These include the following:

- **Compressive Strength** test of the bricks or brick-mortar composite
- **Modulus Elasticity** test of brick-mortar composite
- **Mix Composition** test of mortar joint
- **Splitting Tensile Strength** test on brick core and brick-mortar joint composite core

Given the limitations of sample extraction and laboratory testing, other in situ techniques for strength assessment may be used, such as the following:

- **Single Flat Jack** test to measure the in-situ strain or stress within a wall
- **Double Flat Jack** test to determine the load capacity and modulus of elasticity of the wall
- **Brick-Mortar Shear Bond Strength** test to assess the adhesion bond of the brick to the mortar

__Right:__ A breakout revealing the structural brick masonry substrate under the plaster. __Far right:__ Drill resistance measurement being carried out on a load-bearing brick masonry wall, with real-time results represented in graphical form on a laptop connected to the equipment.

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Structural Repair and Rehabilitation

Refer to *Chapter 1, Principles and General Notes on Conservation and Intervention* for important issues to consider when planning for structural rehabilitation.

Refer to *Volume 3 Facades* for conservation treatment of surface defects and restoration of finishes found on facade structural masonry; in particular *Chapter 3 Masonry* for more details on conserving stone and brick masonry, including repointing, rising damp and salt treatment.

Restoring integrity and strength to masonry structures may be broadly grouped as repair of localized defects – such as addressing mortar bedding and pointing, or individual masonry units – and reinforcement and addition to the structural scheme. Less invasive repair options should always be considered and exhausted before looking into scaling up the intervention. Care should be taken for repairs to fairfaced masonry. Some common methods for structural repair are briefly described below, listed according to increasing degree of intervention.

LOCALIZED REPAIR AND REPLACEMENT

Repointing – The outermost 10–15mm of the mortar is known as 'pointing mortar', which is generally designed to be weaker than the wall substrate. Once this becomes loose or eroded by weathering, the loss of material may affect the structural integrity, especially for members with a large surface-to-mass ratio such as columns. Replacement with compatible mortars – known as 'repointing' – will be required. Friable or incompatible mortar joints should be removed and replaced with new compatible mortar.

Grouting and anchoring – Grouting is used to repair several defects in stone and brick masonry, most extensively to treat cracks along mortar joints. Typically, a compatible grout mix is inserted into the cracks and allowed to set until it binds the masonry together.

Repointing trial for fairfaced brick masonry wall.

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This procedure is generally carried out by gravity grouting, pressure pumping or vacuum grouting. In the case of historic masonry, the grout mix is usually based in hydraulic or non-hydraulic lime.

Alternatively, a hollow stainless steel anchor is inserted through brickwork and a grout mix is injected through the anchor under low pressure, which sets to bind the masonry units together.

Tying and stitching – Structural cracks in masonry are also commonly repaired by tying the masonry together through stitching with steel. Reinforced stitching is done in walls with wider mortar joints. The crack is filled with repair mortar and masonry, incorporating proprietary stainless steel bed joint reinforcement. In areas of finishes or lining, the cracks are stitched through a helical stainless steel reinforcement bar embedded in a proprietary polymer modified grout injected into slots cut into mortar joints.

Wall ties can also be installed across the thickness of a masonry wall, with anchor plates on both ends. This is to counter compressive bulging or buckling, especially for thick load-bearing masonry walls.

Localized reconstruction ('cuci-scuci') – Structural integrity can also be restored by highly localized replacement and relaying of masonry units and mortar using original and compatible materials. While there is some loss in historic materiality, the method nonetheless allows for retention of most of the unaffected masonry structure, instead of rebuilding entirely.

Left: Grouting — *Brick masonry crack repair by injecting compatible grout.* ***Middle: Tie and stitch —*** *Helical spiral bar reinforcement provides stitching repair for masonry walls that have large cracks through several bricks. Pointing mortar underneath the affected areas of masonry is chiselled and raked out. Stitching is then done by embedding stainless steel anchors into the mortar directly underneath the brick units before sealing with an appropriate mortar.* ***Right: 'Cuci-scuci' —*** *Localized brick replacement.*

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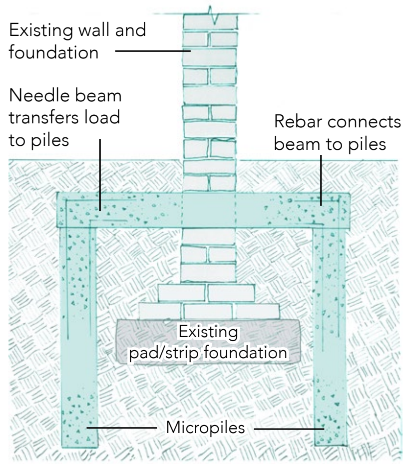
STRENGTHENING AND ADDITION

Structural strengthening and addition involves design enhancement to the existing structural scheme to upgrade its loading capacities, for example, to cater to adaptive-reuse new functions with higher loading requirements. Similarly, strengthening design should be premised on minimal intervention to reduce impact on the historic building, incrementally stepping up to more invasive alternatives only when needed, and only as much as necessary. For the strengthening of foundations, the current geotechnical characteristics of the subsoil should be thoroughly assessed through investigation. Following are some of the key strengthening and addition methods for masonry structures.

Underpinning and micropiling – Underpinning refers to the strengthening of foundations of existing buildings, typically in pad or strip form. The objective is to spread the load or transfer it to deeper soil or bedrock with higher bearing capacity. In particular, the micropiling method, which uses small-diameter piles (usually reinforced concrete) driven by compact-size piling rigs, is wellsuited for historic buildings where access and headroom may be restricted. To minimise impact on existing historic floor slab and floor finish, micropiles could be installed on the exterior and the load transfered via cantilevered needle beams. Where this is not feasible, affected historic elements such as floor tiles may be carefully dismantled and reinstalled after strengthening. The historic foundation should be properly documented prior.



Left: *Compact piling rig that could be accommodated beneath the porch of the Cathedral of the Good Shepherd.* ***Middle:*** *Micropiles are installed next to existing column bases to strengthen the masonry strip foundation and address severe structural damage caused by ground settlement.* ***Right:*** *Diagram of brick foundation strengthening by micropiles.*

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__Right:__ Steel tie rods anchored on the outer sides of facing walls to ensure the structural integrity of the load-bearing wall configuration in case of ground movement.
__Far right:__ Steel plate jacketing of interior load-bearing brick masonry wall as part of temporary seismic strengthening measure prior to long-term rehabilitation works. This will, however, result in loss of historic ornamental plasterwork.

Addition of structural members – New structural members may be added to the existing structural scheme as reinforcement or to address structural distress, usually transferring load to the new foundation piles. Buttressing or addition of piers to the loadbearing wall may be deployed to negate the outward thrust caused by compressive load bearing down on the wall. New structural arches or frames may be installed to offload the stress on existing loadbearing masonry, or as independent structural systems for building additions such as new floors or stairs. These new structures may or may not be in masonry; reinforced concrete and steel usually offer a more compact footprint relative to masonry, minimizing visual and spatial obstruction to the historic building. The dimensions and locations of structural additions should be sensitively coordinated to complement the existing structural datum, heritage elements, elevations and spaces. Steel tie rods may also be installed in line with cross walls on facing walls to ensure they remain in position to counter anticipated ground movement such as earthquakes or tunnelling vibrations.

Jacketing – This method involves the enlargement of the structural element by encasing it in a layer of new material, usually reinforced concrete or steel plates. While the historic member is retained, its original profile, proportion, finishes, and any ornamentation such as column capitals or wall cornices will be adversely affected. This may contravene heritage presentation and conservation requirements. Jacketing may be selectively applied at less sensitive areas, and for elements of less heritage significance.

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Fibre-reinforced polymer (FRP) strips – Based on principles of structural containment, in this method the structural member is 'wrapped' or applied with layers of FRP strips and epoxy grout to restore structural integrity or for added strength. The key concern is with the incompatibility of the unbreathable FRP and epoxy material, especially with soft clay historic brickwork and friable stonework, which may result in masonry damage in the long run. This method should be considered a last resort, and only applied to the historic fabric following thorough material investigations to verify its long-term performance, and with closely tailored design to minimize adverse effects. In addition, while this method does not add as much bulk as jacketing, it needs to be applied directly onto the masonry substrate, affecting any existing finishes. As such, this method should not be applied on elements with significant ornamental features or fairfaced finishes.

Deployed as a last resort, here the severely compromised brick masonry column is strengthened with carbon fibre-reinforced polymer strips. Gaps are designed to allow for some degree of breathability for the historic brick substrate.

3 TIMBER STRUCTURES

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Overview: Structural Timber

Refer also to *Volume 2 Roofs*, *Chapter 2 Roof Structures*, for more information on roof structural timber elements.

Tropical hardwood is one of the most prized natural resources in Southeast Asia, with timber processing historically being one of the region's major industries.

The earliest industrial timber supplies for Singapore came from **Johore Saw Mills**, founded in 1859 by Scottish entrepreneur James Meldrum. The sawmill supplied timber to many key projects in early colonial Singapore, its nearest market, including the Government House, as well as for 'Railway, House, Shipbuilding and general purposes', as advertised in the 1890s.

The first significant modern development in Johor, the Johore Saw Mills was strategically sited on the banks of Sungei Segget, so that logs harvested in the jungles upstream could be floated down to the steam sawmill. Small ships could also berth and transport the processed timber, to be exported worldwide. Similarly, sawmills built in Singapore later on were located near waterways such as Kallang River. In the late 1960s, the foreshore of Kranji was reclaimed for the purpose of relocating these sawmills.

With the growing timber industry, local sawmills were established to process logs typically imported from Sumatra and Peninsular Malaysia. Until the 1960s, local conventional practice still had logs stored for long periods in the lumber yard as part of the **wood drying process**. Industrial wood-drying kilns that speed up the process do not seem to have been adopted until more recent decades. There are three basic methods of sawing logs, i.e., **plain sawn**, **quarter sawn** and **rift sawn**. Plain sawn yields the most lumber and is therefore the most cost-effective.


HONOURABLE MENTION, EXHIBITION
LONDON, 1862.

SILVER MEDAL AND FIRST CLASS CERTIFICATE
CALCUTTA EXHIBITION, 1883.

GOLD MEDAL,
INTERNATIONAL FORESTRY EXHIBITION,
EDINBURGH, 1884.

BRONZE MEDAL,
ADELAIDE JUBILEE INTERNATIONAL
EXHIBITION 1887.

JOHOR STEAM SAW MILLS Co.
Timber for Railway, House, Shipbuilding and general purposes.
Johore, near Singapore.
J. MELDRUM,
Manager

Left: *1890 news advertisement of Johore Saw Mills.* ***Right:*** *A black-and-white bungalow (1900s) with profiled timber joist ends exposed as a design feature and an articulated second-storey timber frame verandah.*

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A historic kampong house at Pulau Ubin featuring timber post-and-beam main structure with timber siding infill and lattice balustrades.

Timber species are generally graded for different building uses as follows:

1. **Structural timbers**, further classified as
    - Heavy construction, such as bridges and beams
    - Medium construction, such as trusses and joists
    - Light construction, such as fenestration frames
2. **Panelling timber**
3. **Flooring timber**
4. **Furniture timber** (for fine joinery works)

Structural Timber			Panelling Timber	Flooring Timber
Heavy	**Medium**	**Light**		
Balau	Chengal	Bintangor	Kempas	Bintangor
Belian	Kapur	Kapur	Merbau	Chengal
Chengal	Kempas	Keruing	Nyatoh	Merbau
Kempas	Keruing	Nyatoh	Ramin	Red/White & Yellow Meranti
Keranji	Merbau	Red/White & Yellow Meranti	Red/White & Yellow Meranti	Teak
Red Balau	Nyatoh	Teak	Teak	
Tempinis	Teak			

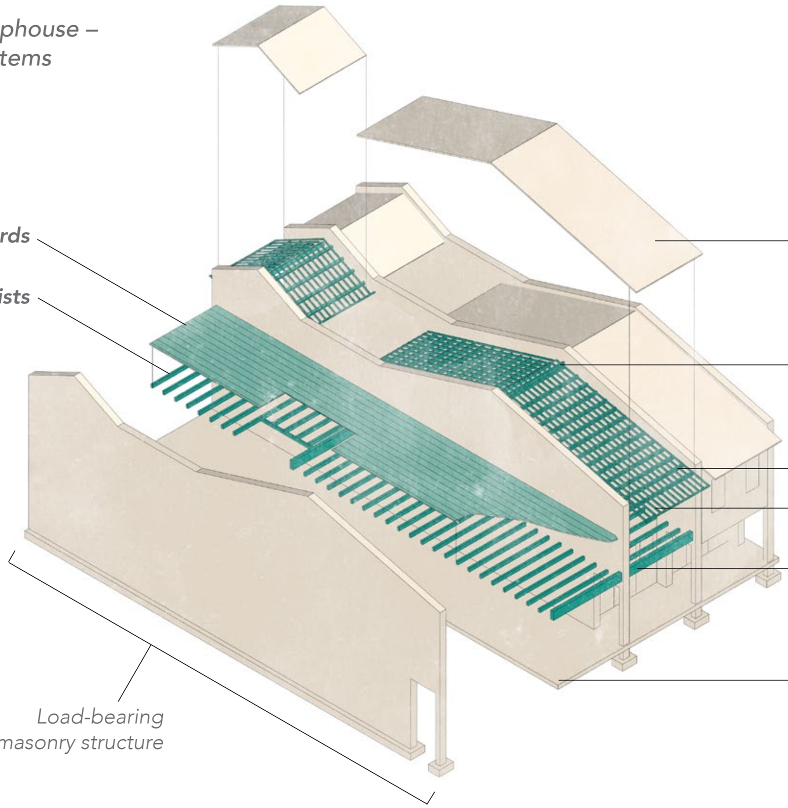
For the building of Chinese traditional structures, **master carpenters** and artisans from China had to adapt to working on tropical hardwood from the region, which was more challenging to work with relative to the timber used in China. Even for carved timber, tropical camphor, a softer hardwood, and occasionally teak would be used, likely for better resistance to the warm and humid local climate.

Commonly seen historic timber structures in Singapore include traditional Chinese constructions (temples, courtyard houses), vernacular kampong structures, as well as the roof and floor systems of colonial period buildings including bungalows, shophouses/townhouses and churches.

These present varying timber building traditions and construction techniques. In general, Chinese traditional timber structures are connected using hidden **dowel and mortise-and-tenon joints**, while colonial-introduced practices tend to include the use of external and embedded **metallic connections**, such as nuts and bolts, metal plates and tension rods, working alongside timber joinery to achieve structural performance.

Traditional Chinese timber construction with elaborate carved and painted structural members at Thian Hock Keng temple.

Structural Elements of Shophouse – Timber Floor and Roof Systems



Timber structural features that contribute to the interior spatial quality of historic shophouses/townhouses should be retained and exposed. ***Left:*** *The upper-storey timber floor system comprises beams and joists that span the party walls, reinforced with stone or timber corbels. Timber floorboards are laid across the joists, with tongue-in-groove joints.* ***Middle:*** *The timber main beam spanning over the five-foot way becomes a key facade feature.* ***Right:*** *Given the narrow span, the roof system could do without trusses or rafters, featuring timber purlins directly spanning across party walls, with battens laid closely along the slope of the pitched roof to receive unglazed V-shape clay tiles.*

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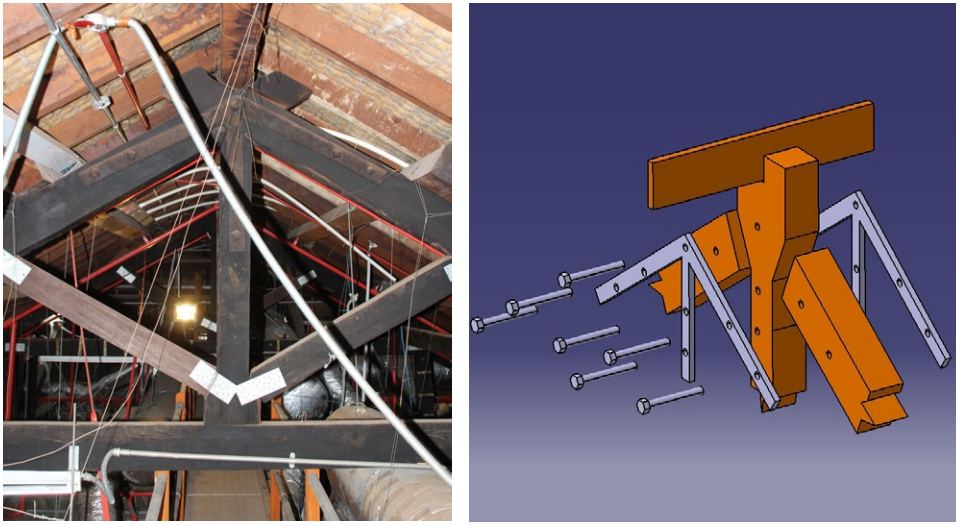
Structural Issues and Diagnostics

Refer to *Chapter 1, General Notes on Investigation and Diagnostics* for information on the prior investigation and documentation to establish a sound diagnostic basis, as well as important concepts and issues to be aware of at the outset of planning for structural rehabilitation.

Timber structures and components can be durable if they are properly designed, constructed and maintained. Conversely, poorly seasoned timber members or those that are unprotected from vastly changing environmental conditions (e.g., fluctuating between wet and dry) tend to be more susceptible to biological decay and stress-induced defects.

Each member of the historic timber structure should be carefully studied and examined by skilled and experienced timber experts such as a master carpenter or timber specialist prior to developing the conservation approach. Construction details and the condition of the existing timber members should be systematically documented. Timber members are then classified according to damage level, and whether they are repairable. Non-destructive and semi-destructive techniques can be deployed to clarify cases that cannot be determined by visual and tactile examination alone.



Study of timber roof truss construction details, including joinery and fastening types.

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VISUAL AND TACTILE SURVEY

The visual condition survey to be carried out by skilled, experienced inspectors should cover the following aspects for all timber members:

- **Naturally occurring features** (e.g., knots and seasoning checks)
- **Construction and design features** (e.g., joinery type, fasteners, carved ornamentation)
- **Biotic deterioration** (e.g., damage from infestation of insects such as termite or carpenter bee, bacterial or fungal decay)
- **Weathering- and stress-induced degradation and structural deformation** (e.g., transverse cracks across grains, severe embedment, shrinkage, creep or misalignment, deterioration of joints like ends splitting, corrosion of metal connectors)
- Any protective **coating or preservative** treatment
- **Exposure condition** of the timber members, classified as follows:
    - Timber is under cover and fully protected from the weather
    - Timber is under cover and fully protected from the direct effects of the weather, but high humidity can lead to occasional but not persistent wetting
    - Timber is not covered and not in contact with the ground. It is either continuously exposed to the weather or is protected from the weather but exposed to frequent wetting
    - Timber is in contact with the ground or water and thus is permanently exposed to wetting

***From top: Dilapidation** – displaced timber truss joint; termite trails along timber beam and wall around beam end; rafter damaged by carpenter bee infestation.*

In the case of **traditional Chinese timber-framed buildings**, qualified master carpenters should be engaged for thorough inspections. Being familiar with the types of wood species used and traditional carpentry, they will be able to provide further insights on the historic construction techniques and other observations.

Master carpenter conducting visual and tactile survey on the traditional timber structures at Shuang Lin Monastery.

Tactile surveys are commonly done by master carpenters and trained specialists during visual inspection as they provide economical and quick 'frontline' identification of non-visible serious or potential deterioration within timber members. This method involves tapping the entire surface of each timber member gently with a hammer – the specific variation in sound thus generated enables trained ears to rapidly screen and make inferences on the condition of the members.

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Historically, most structural timber would have been finished with some form of preservative or protective coating, ranging from a bitumen (tar) coat to oil-based paints. In such cases, pigment composition analysis and other investigation of the coatings, and detailed documentation if needed, should be carried out prior to any interventions.

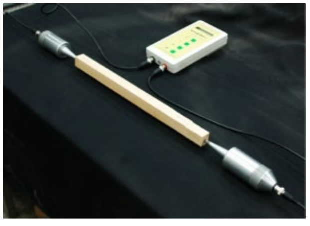
Refer to *Volume 7 Paints and Coatings* for more information on this topic.

NON-DESTRUCTIVE AND SEMI-DESTRUCTIVE TECHNIQUES

Although the tactile survey method may detect potential deterioration 'hotspots', it cannot quantify the extent of the issue. Results may also vary between inspectors with differing skills. Equipment-based non-destructive techniques (NDT) may then be deployed as a supplementary frontline procedure to affirm, quantify or derive more information on the condition of timber members. At times, semi-destructive methods may also be used as they provide more direct and accurate information on the internal condition of timber members. These techniques also allow for subsurface studies of hidden construction details.

As non-destructive and semi-destructive techniques usually require more expert knowledge in conducting on-site testing and subsequent analysis, the overall cost tends to be higher than for visual and tactile surveys. Common methods include the following.

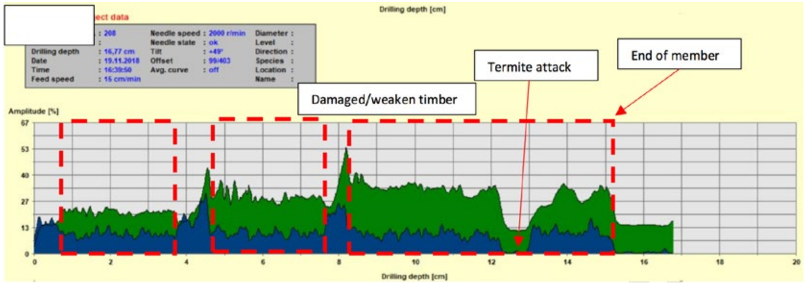
- **Stress wave** technique involves the transmittal of sonic or ultrasonic sound wave through the target member, with the resulting variation in corresponding velocity used to detect interior voids or deteriorations, providing a global, or overall, condition assessment of the timber member.




Stress wave technique – calibration of the equipment prior to measurement of a horizontal timber structural member.

- **Pulse echo** and **Radiography** make use of ultrasonic and electromagnetic waves for digital imaging of different angles of the interior of the timber member, and are able to identify internal connection methods, deterioration and defects. They may reveal potential hidden internal materials and flaws that are undetectable by other investigation methods.
- **Moisture content** can be derived by measuring electrical resistance across a common two-pin. This method may be deployed where timber deteriorations are encountered to help determine the cause and existing timber condition.

- **Resistance drilling** is a semi-destructive technique where a small needle-like drill (diameter: 1.5–3 mm) is used to bore the timber member at a constant speed, with the resistance encountered by the drill bit at different penetration depths recorded and plotted into a graph. The peaks and dips in the drilling log correspond to its respective high and low resistance and density within the drill sample; hence the result can be used to locate and estimate the size of cavities or extent of deteriorated fibre in the timber members.

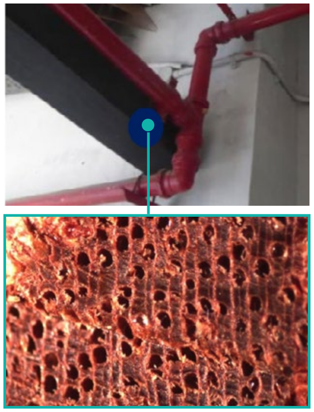


Above: *Specialist carrying out resistance drilling measurement on a timber structural member.*
Right: *Example of a resistance drill graph, revealing interior conditions.*

- **Wood density** method measures timber density and hardness by measuring the penetration depth of a plunger pin that is driven into the specimen with controlled impact.

SAMPLING AND LABORATORY ANALYSIS

- **Wood species identification** is an indispensable step in the conservation of historic timber structures. 1cm x 1cm x 1cm cube blocks are extracted from the timber members and undergo microtomy, where transverse, radial longitudinal and tangential longitudinal sections of 15–20μm thickness are prepared for microscopic study. The timber anatomical characteristics are then analyzed to identify the species.
- **Dendrochronology** is a highly precise dating method providing material evidence of building history or historic construction phasing. The date on which the parent tree of the historic timber member was felled can be traced by matching tree-ring patterns against an existing database. In the process, cores of diameter 10–15 mm are extracted from the timber member cross-section and subject to analytical studies. However, the method is not applicable to all timber species – for example, historic timber species that are no longer commercially available may be under-represented in existing databases. Wood species identification needs to be carried out prior to determine the feasibility of the timber member for dendrochronological sampling.



Wood species identification by microscopic anatomy study of a timber sample extracted from a historic beam.

Structural Repair and Rehabilitation

Refer to *Chapter 1, Principles and General Notes On Conservation and Intervention* for important concepts and issues to be aware of at the outset of planning for structural rehabilitation, including protection and temporary bracing.

Depending on the complexity of the timber structural system, a **criteria matrix** may be developed to objectively determine the degree of intervention based on the structural role, damage level and heritage significance of individual members. For example, damaged members dated as very historic, with unusual joinery work or carved ornamentation, should be prioritized for repair and retention.

The extent of timber structural damage can be broadly classified into three levels – (1) slight damage, (2) moderate damage and (3) severe damage. Timber members that fall under levels 1 and 2 are considered repairable cases, whilst Level 3 is usually beyond repair and thus recommended for disposal and refabrication, or, if retained, to have the load transferred to new structural additions. Disposed structural timber may be recycled for repair of smaller timber members, or considered for upcycling as furniture, landscape features and so on.

<table>
<tr><th></th><th>Scenarios</th><th colspan="2">Extent of Damage</th><th>Damage Level</th><th>Direction</th></tr>
<tr><td rowspan="9">Internal Damage</td><td rowspan="2">Primary Structural Members</td><td colspan="2">Overall section damaged area ≤ 1/3</td><td>1 or 2</td><td>Repair</td></tr>
<tr><td colspan="2">Overall section damaged area > 1/3 & more than 2 areas damaged</td><td>3</td><td>Discard</td></tr>
<tr><td rowspan="3">Secondary Structural Members</td><td>High value</td><td>Overall section damaged area ≤ 2/3</td><td>2</td><td>Repair</td></tr>
<tr><td rowspan="2">Low value</td><td>Overall section damaged area ≤ 1/2</td><td>1 or 2</td><td>Repair</td></tr>
<tr><td>Overall section damaged area > 1/2</td><td>3</td><td>Discard</td></tr>
<tr><td rowspan="2">Fungal Damage</td><td colspan="2">Overall section damaged area < 1/2</td><td>1 or 2</td><td>Repair</td></tr>
<tr><td colspan="2">Overall section damaged area ≥ 1/2</td><td>3</td><td>Discard</td></tr>
<tr><td rowspan="2">Horizontal Cracks</td><td colspan="2">Cracks extend < 1/2 of total length</td><td>1 or 2</td><td>Repair</td></tr>
<tr><td colspan="2">Cracks extend ≥ 1/2 of total length</td><td>3</td><td>Discard</td></tr>
<tr><td rowspan="2">External Damage</td><td rowspan="2">Surface of All Timber Members</td><td colspan="2">Overall surface damage ≤ 1/2</td><td>1 or 2</td><td>Repair</td></tr>
<tr><td colspan="2">Either overall section damaged area > 1/3 or overall surface damage > 1/2 ; & more than 2 areas damaged</td><td>3</td><td>Discard</td></tr>
</table>

Example of a criteria matrix for the assessment and conservation recommendation for historic traditional Chinese timber structural members.

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Where new timber material is introduced in conservation structural interventions, it is important to ensure that it is of a similar wood species and grain to the historic, and that it has been certified to be within acceptable moisture content, adequately kiln-dried, and has undergone appropriate preservative treatment.

Repairs using epoxy resin should be carefully designed and skillfully applied, including trials and mock-ups to test different mix calibrations and techniques, to ensure minimal visual impact and effectiveness of the intervention.

LOCALIZED REPAIR AND REPLACEMENT

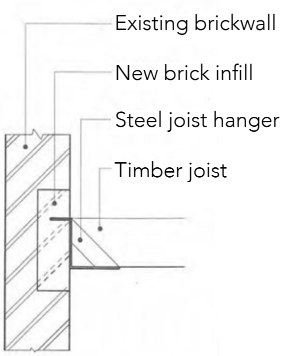
Following are the basic steps of the four broad **localized repair** approaches, in increasing degrees of intervention.

Minor repair with epoxy resin-sawdust mix should be sufficient for slight damage such as fine or shallow cracks.

From left: *Clearing of debris within fine cracks; fill the cracks with epoxy-cum-wood sawdust mixture; level or sand down surfaces, and air-dry upon completion.*

Mechanical restraints may be introduced as a temporary or long-term repair measure, for example to prevent existing cracks from widening or introduce resistance to joints to address known stresses such as tunnelling vibrations.

Reinforcing the existing half-lap dovetail jointed purlins with new bolted steel plates – the steel connectors will subsequently be concealed by patching with timber of similar species and grain to mitigate the visual impact of this intervention.



Far left: *Detail drawing of reinforcement of the joint between timber floor joist and load-bearing masonry wall by introduction of steel joist hanger brackets – this will also protect the joist ends from moisture ingress due to rising damp in the wall.* ***Left:*** *Historic purlin restrained with steel clamps to prevent the split from widening – a method with high visual impact only for temporary application, or when concealed from view.*

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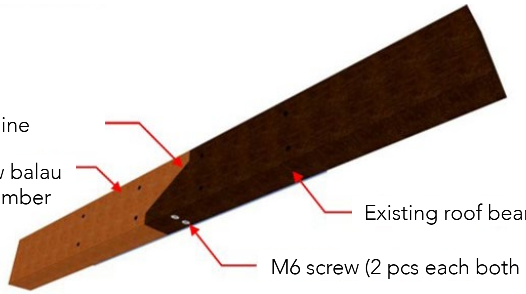
Timber-to-timber repair addresses moderate partial damage such as by termite or fungal attack, or deep seasoning checks. The two main categories are patch or face repair that addresses surface damage, and whole-section repair where a complete cross-section is replaced. New or recycled wood material of the same or similar wood species is used for repair. New fastenings – often steel – may be introduced where historically there were none. Epoxy-resin may also be deployed as an adhesive.

From left: *Removal of damaged regions with tools leaving clean, straight surfaces to receive new wood material; new or recycled wood are tooled to the right dimensions and scarfed onto the existing timber - epoxy mix may be used as an adhesive; level or sand down surfaces, and air-dry upon completion.*

Whole-Section Repair Using Splayed Scarf Joint



Like-for-like localized replacement using similar wood species and grain may be considered if structural members are damaged to an extent that they can no longer function structurally and are beyond feasible repair.

From left: *Setting out the dimensions for the refabrication of the roof short post member (gua-tong 瓜筒) of a traditional Chinese timber roof structure; tooling of the new gua-tong; trial-assembly of the completed gua-tong with the rest of the retained historic timber roof structure members.*

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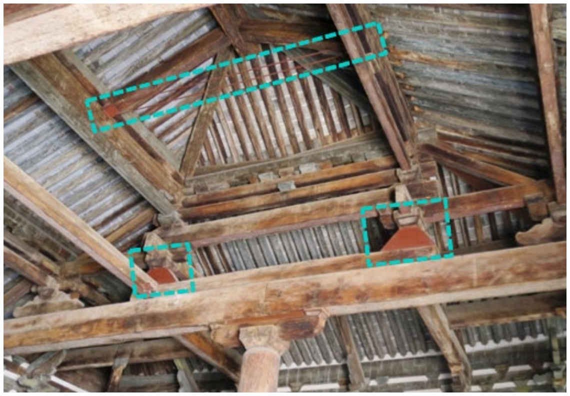
STRENGTHENING AND ADDITION

In some cases where seriously damaged members are nonetheless recommended for retention due to their heritage or artistic significance, strengthening or addition methods may be used. These interventions may also be deployed where increased loading or stress resistance is called for, such as in adaptive reuse projects, or as a result of building regulation changes.

Timber construction is no longer mainstream in the local building industry. As such, many practitioners do not have working knowledge of timber structural behaviour or traditional construction. It is thus critical to engage a professional engineer with relevant experience and expertise in historic timber buildings to design for and supervise any modification, strengthening of, and addition to conserved timber structures.

In general, strengthening and addition involve the introduction of new material, usually timber or steel, to the historic timber frame system. In designing any intervention, the visual and material impact of these methods should be considered in relation to the location (concealed or exposed) and heritage significance of the target structural member. Especially for exposed structures in key spaces, interventions should be sensitively designed to be visually compatible in scale and appearance.



Addition of steel tension cable and brackets (highlighted) that enables the retention of the ancient timber frame of Kai Shan Temple (1033), China.

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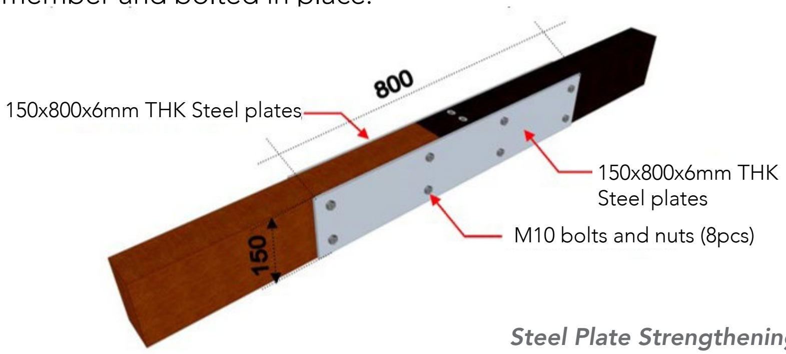
Strengthening generally refers to the attachment or embedding of reinforcement material to the existing timber member for added loadbearing capacity. A partnering or supplementary timber component could be fixed to the existing member, for example alongside the damaged section of a roof beam. Examples includes plates bolted to the sides, or steel flitch inserted via a blind slot cut into the existing timber member and bolted in place.



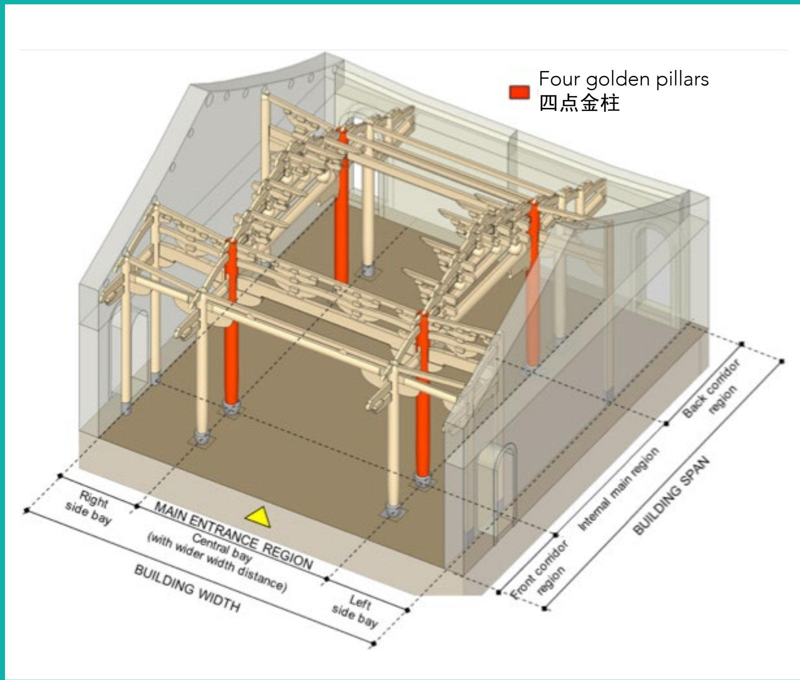
Steel Plate Strengthening of Whole-Section Repaired Timber Beam

Addition involves introducing new members to the existing structural frame, for example adding new joists between existing ones. The Professional Engineer should ensure that the existing structure is able to support the increased loading; alternatively the new members may be designed as self-supporting frames – this may be done to lighten the load borne by historic timber members, enabling them to be retained in situ without compromising the overall building structural performance.

__Right:__ Addition of steel cross-ties (highlighted) to improve the stiffness of historic timber frames, on the walls and roof of the barn house at Hokkaido University. __Far right:__ Addition of steel I-beams (highlighted) to the original timber floor system, likely to accommodate the added weight of the extended organ at the Cathedral of the Good Shepherd.

LUOJIADAXIU
落架大修

Luojiadaxiu literally refers to the complete dismantling and rehabilitation of traditional Chinese timber frame. This major traditional intervention method is undertaken when a high number of main timber structural members are severely damaged by termite infestation, fungal attack, or major ground settlement, with signs of impending structural failure and thus require immediate action. The work can only be carried out by master carpenters and skilled artisans. In Singapore, the building and maintenance of Chinese traditional timber buildings were particularly affected during the 1960s–80s Cultural Revolution period when skilled artisans were banned from travelling or practising abroad.



Schematic drawing of traditional Chinese timber frame structure.

Luojiadaxiu evolved as part of a long-term cyclical building maintenance process focusing mainly on the timber structure. Nonetheless, in recent years when applied to historic traditional Chinese buildings, the practice has been adopting a more encompassing approach, taking into account other elements of historic and artistic value that may otherwise be adversely impacted, such as roof finishes and ridge ornaments.

Luojiadaxiu is traditionally done via the top-down approach, where the entire roof (including roof ridge decorations, roof tiles, and all interlayers beneath roof tiles and rafters) is first removed, followed by the systematic dismantling of timber frames. Beginning from an inner zone within the central bay demarcated by the four 'gold pillars' (四点金柱), timber members are dismantled starting from the top, and gradually moving down and out towards the front corridor frames, before those at the two side bays and inner corridor are finally taken down.

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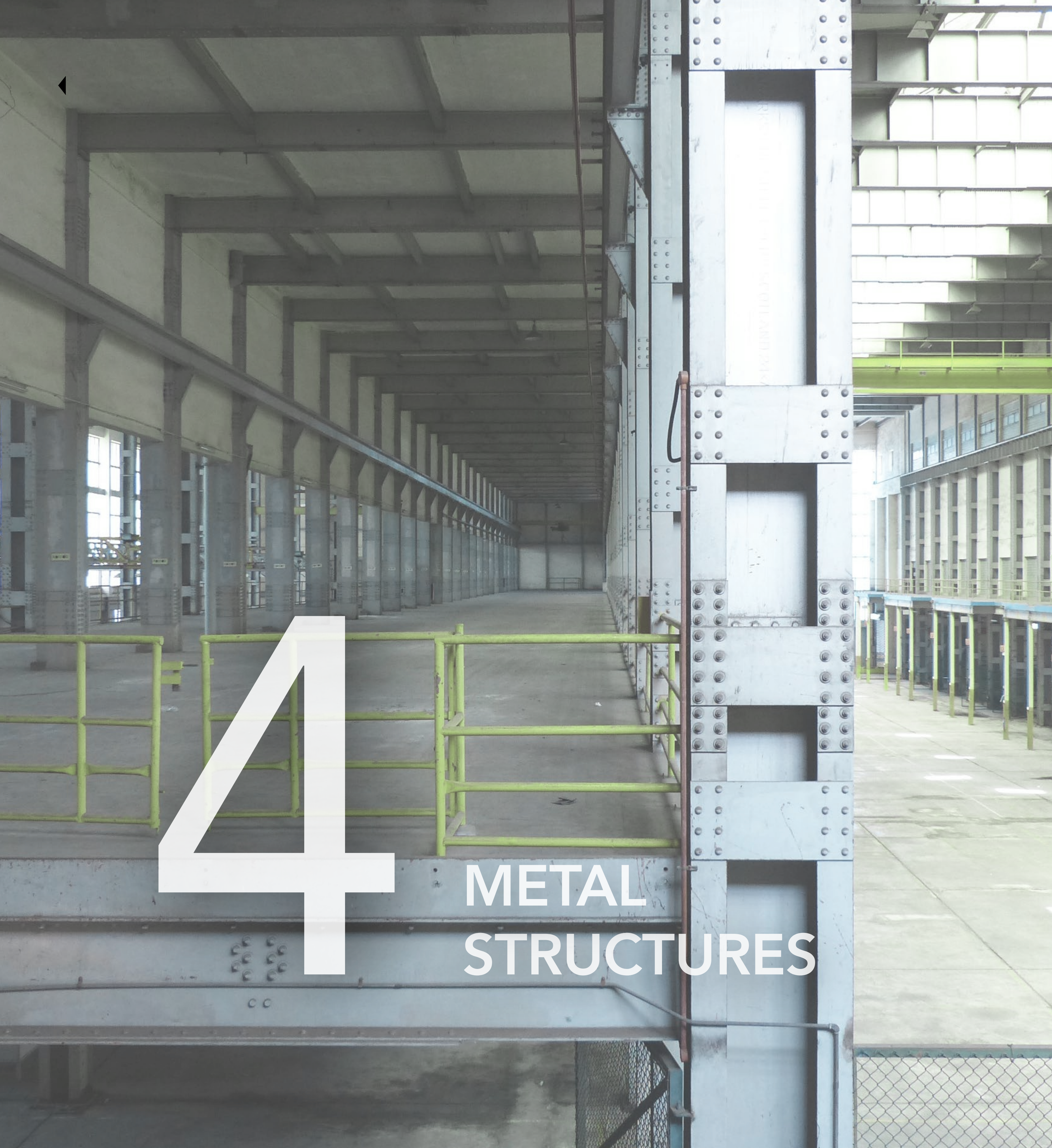
Left: ***Each timber member is identity-tagged with cloth strips before dismantling.*** *Below left:* ***In Taiwan, ornamented roof ridges of high heritage and artistic value are recommended for conservation. Instead of being dismantled, they are retained in situ during*** **luojiadaxiu** ***using suspended steel plate supports hung from a temporary shelter structure.***

Although it ensures a thorough rehabilitation, given the great time and cost involved in *luojiadaxiu*, interim structural issues that surface tend to be deferred, with temporary supports put in place for long periods. Another possible 'middleground' measure would be a **partial dismantling and repair approach** (*jubuzhengxiu* 局部整修) that has been recently developed in Taiwan. Temporary supporting systems are carefully designed around the affected region to allow for the replacement of the target member(s). Although the preparations for executing this approach may be more complex compared to the traditional dismantling procedure, the overall repair time is significantly shortened and impact on the historic fabric minimized.

Partial repair of timber column base section:

Above from left: ***Temporary structural support in place around repair region; marking out the truncated lower region and master carpenter working on the cross-shaped joint in situ; removal of lower column base and temporary supporting of the original column with a newly shaped cross-joint; fabrication of a new cross-jointed column base with the same wood species.*** *Right:* ***Joining of the new and old column on-site with mechanical fastening and epoxy.***



4 METAL STRUCTURES

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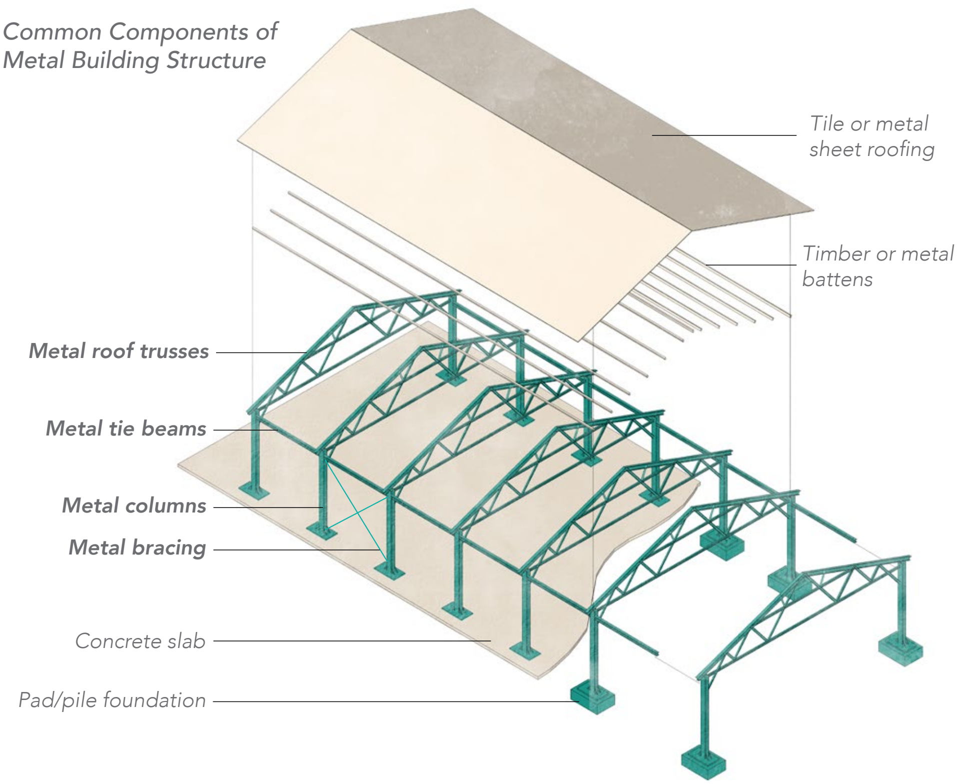
Overview: Structural Iron

Refer also to *Volume 2 Roofs, Chapter 2 Roof Structures* for more information on structural iron roofs.

Cast iron was the first structural iron material manufactured, followed by wrought iron, with both eventually replaced by steel. A material born of the Industrial Age, structural iron could be easily worked and produced in a variety of sizes and forms – such as sheets, plates, I-beams, angles, channels. **Standardized units** could be combined and assembled in different configurations depending on the function, such as roof trusses or bridges. Compared to masonry and timber construction, much taller structures of wider spans and higher load-bearing capacities could be achieved with less material, within a much shorter erection time frame.

Made from mould casting, **cast iron** can form complex shapes and is usually designed to be decorative, with the ornaments presented as bas relief. Commonly used as compression elements such as feature columns, cast iron requires a minimum thickness of 1–1.5 inches to prevent twisting.

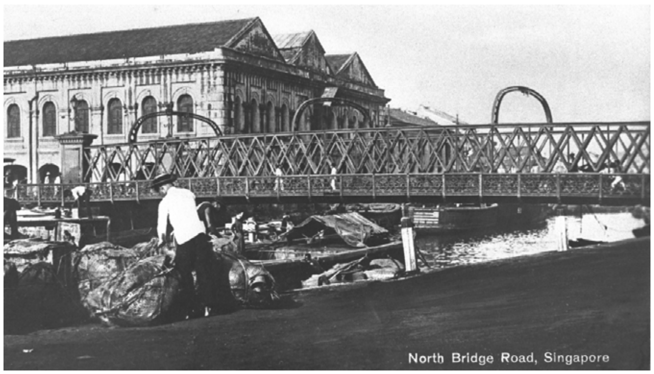
Common Components of Metal Building Structure



Both **wrought iron** and **mild steel** have strong tensile strength as much of the inherent carbon in the iron is removed by oxidization, and they can be used as beams. Wrought iron is forged by hand, while mild steel is machine made. Due to the manufacturing processes, wrought iron can be forged into elaborate three-dimensional shapes by hand; however, the maximum size of each structure is limited. When deployed as beams, short sections have to be joined using plates and rivets.

Structural iron probably first appeared in Singapore as infrastructure. Prefabricated structural components were imported from **iron foundries** in India or Britain to Singapore and reassembled on-site by skilled workmen. Built in 1862 from parts shipped from Calcutta, the original Elgin Bridge was the "first Iron Bridge erected in Singapore" as reported in the news then. Early piers such as Dalhousie Pier (1850–1890s) and Johnston Pier (1856–1929) were also constructed in a combination of cast iron and timber.

Telok Ayer Market, better known as Lau Pa Sat and erected in 1894, is the oldest existing cast iron building in Singapore. The design comprised an assemblage of pre-designed building parts selected from the catalogue of Scottish foundry Walter MacFarlane & Co. The components, from the columns and beams to the elaborate clock tower, were all cast in the firm's foundry in Glasgow and shipped to Singapore for assembly. Iron structural elements were also found in domestic buildings. Shophouses and townhouses, especially those built in the early 1900s, often contained ornamental cast iron columns supporting rooms overlooking the internal airwell.



***Left:** 1920s view of Elgin Bridge (1862), designed with high tensile strength to support heavy vehicles over a single span across the busy Singapore River, so as to allow boats to pass under.* ***Right:** Telok Ayer Market (1894), assembled from parts chosen from a MacFarlane & Co. catalogue of cast iron components.*

The early 20th century saw the erection of increasingly large-scale steel frame buildings, from Stamford House (1904), St. James Power Station (1926), and the streamline moderne Kallang Airport and its hangars (1937) to the Supreme Court (1939), whose appearance, complete with a dome and massive corinthian columns supporting a pediment, was ironically styled to suggest a masonry structure.

By the mid-20th century, steel and reinforced concrete were the preferred structures for major construction. Examples include office towers such as Asia Insurance Building (1955), and industrial buildings such as Pasir Panjang Power Station (1953).

Left: Cast iron columns, spandrel beams and decorative brackets at Chong Wen Ge (1850s) within the compound of Thian Hock Keng Temple. **Right:** Cast iron columns fronting the house entrance at 11 Keppel Hill (ca. 1890s).

Advertisement by the steel supplier for the former Supreme Court (1939, now National Gallery).

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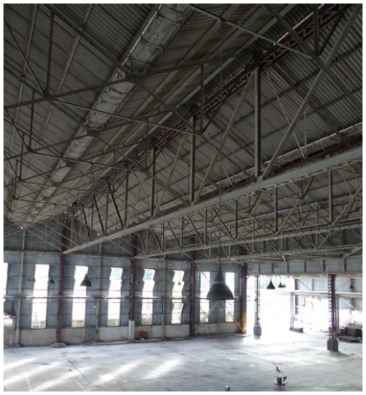

Left: *Anderson Bridge (1910).* ***Middle from top:*** *Singapore Civil Aerodrome hangars (aka Kallang Airport, 1939); Dairy Farm cowshed (1930s).* ***Right:*** *St James Power Station (1926).*




Left from top: *Singapore Badminton Hall (1952); Institute of Health (1958).* ***Middle:*** *Factory at Alexandra (1960s–70s).* ***Right:*** *Pasir Panjang Power Station (1953).*

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Structural Issues and Diagnostics

Refer to *Chapter 1, General Notes on Investigation and Diagnostics* for information on the prior investigation and documentation to establish a sound diagnostic basis.

Characterizing and identifying the type of historic structural iron, and its dilapidation tendencies, may begin with desktop research and study into the provenance of the structural members, as well as the building's history and past alterations, and on-site investigation to be carried out by experienced expert investigators. Visual clues may provide insights into the material, such as foundry name imprints or corrosion patterns. For example, wrought iron is prone to delamination or 'flaking' of the surface during corrosion, due to residual carbon slag left in the folds during its forging process.

The main deterioration of metal structure is **corrosion** in the presence of water (liquid or vapour) and oxygen. Rising damp is a known cause of corrosion of steel columns on the ground floor, and the problem can be aggravated by the presence of chloride salt from the ground. Interior steel structures are less likely to corrode since they are usually protected from the elements.

Brand imprint found on historic steel structural member in Pasir Panjang Power Station (1953) indicating provenance from Lanarkshire & Co., Scotland.

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Traditionally, corrosion protection was provided by paint but the effective lifespan of the coating is less than that of the metal itself. Regular maintenance is required to check the condition of the paint and reapply paint as necessary. In practice, this is often neglected, leading to premature corrosion.

Refer to *Volume 7 Paints and Coatings* for more information on this topic.

VISUAL AND TACTILE SURVEY

A condition survey of any steel structure should include the following:

- **Types of structural steel members** (I-beams, L-sections, plates, C-channels, hollow sections, etc.)
- **Types of connections/joints** (welded, bolted, riveted, etc.)
- **Other construction details** (e.g., interface with other materials)
- **Corrosion pattern, location, and type** (uniform, pitting, crevice – e.g., pitting may indicate chloride-induced corrosion)
- **Signs of deformation and distortion**
- **Exposure condition** (exposed, coated, exterior, interior)
- **Remaining thickness of intact steel member** should be measured by removing rust at corrosion spots, especially in the case of uniform corrosion.

Equipment- and lab-based investigations may be conducted for metal structures to complement, verify and extract more information for a more comprehensive condition assessment and to inform the conservation approach.

Left: *Corrosion of steel column base due to rising damp.* ***Middle:*** *Joint between steel beams and column.* ***Right:*** *Connection details of a steel roof truss with jack roof.*

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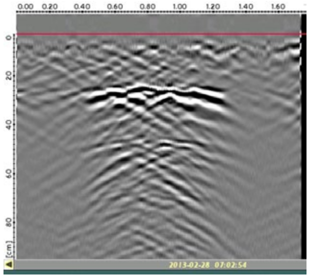


Radargram revealing hidden steel section.

NON-DESTRUCTIVE AND SEMI-DESTRUCTIVE TECHNIQUES

- **Videoprobe** allows for extended visual access to tight spaces
- **Surface-penetrating radar** or **metal detector** to locate the presence of hidden steel structures
- **Surface hardness test** may be used as a qualitative check on the strength of the steel provided a correlation between the hardness and the strength of the steel has been established
- **Ultrasound** technique to detect thickness of remaining intact steel member hidden under corrosion and other materials, and to check the integrity of bolts or rivets
- **Dye penetrant** or **magnetic particle inspection** methods may be used to test the integrity of welds.

Breakout of a latter-day concrete encasement to reveal the historic steel structure originally designed to be exposed.

SAMPLING AND LABORATORY ANALYSIS

Breakouts and sample extraction for laboratory analyses should only be undertaken when necessary, and if structural integrity would not be affected. The location for such destructive procedures should be carefully chosen – it should be away from highly visible areas, and sensitive parts such as delicately ornamented segments should be avoided.

- **Localized breakout inspection** may be carried out at a less visible area to examine structures hidden behind claddings
- **Tensile strength test** can be conducted if a sample can be extracted from the steel structure.
- **Chemical composition analysis** of collected rust residue can verify whether it is chloride-induced corrosion, and inform the treatment method to be applied.
- **Metallurgical examination** of the material microstructure, in situ or on an extracted sample, is usually for identification of the metal type (e.g., to distinguish between cast iron, mild steel and wrought iron) where other methods may not have yielded clear results.

Structural Repair and Rehabilitation

Refer to Chapter 1, Principles and General Notes on Conservation and Intervention for important concepts and issues to be aware of at the outset of planning for structural rehabilitation, including protection and temporary bracing.

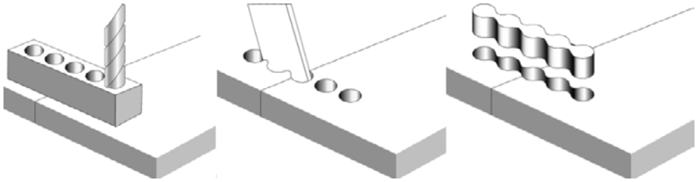
Refer also to Volume 3 Facades, Chapter 6 Cladding for similar conservation treatment for iron surface defects and coatings that may be carried out as finishing works for metal structures following structural repair and rehabilitation.

Telok Ayer Market was dismantled and reassembled in 1988 during restoration works.

Entire buildings in exposed structural iron, such as the cast iron Telok Ayer Market or standalone garden pavilions, could potentially be dismantled for comprehensive restoration or even relocation, not unlike timber frame structures. In most cases, however, steel structures are used in combination with other types of structural systems or integrated with other parts of the historic building, and dismantling may impact on these elements or finishes. Instead, conservation interventions are carried out in situ.

Any structural repair should always go hand in hand with the removal or prevention of deterioration causes, such as rising damp or salts.

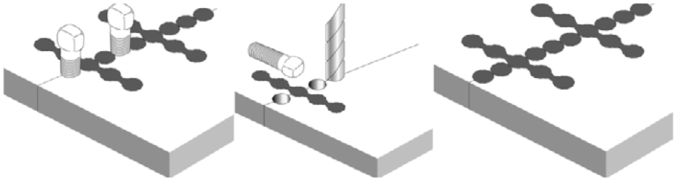
Steps of Cold Stitching Metal Repair



Groups of holes are drilled across the line of fracture to the tool depth of the casing.

The holes are then joined to conform to the shape of the keys.

Keys are inserted into the aperture.



Holes are then drilled along the line of fracture.

The holes are filled with studs, each stud biting into its predecessor, resulting in a pressure-tight joint.

The studs and keys are then ground down to a polished finish.

LOCALIZED REPAIR

In general, cold stitching and welding are the preferred localized repair methods given their minimal visual impact, especially if the repaired or strengthened area is painted over.

Welding repair of steel column base.

Cold stitching may be applied on cracked cast iron. It is carried out without the use of high heat which may cause distortion, and for sites where heat treatment is not feasible. A locking material, usually steel or brass, is driven into a row of holes pre-drilled across the crack, to seal it.

Welding, where the base metal is melted by high heat and cooled to fuse, usually with an added filler, is used for repairing cracks on wrought iron, cast iron and steel structures.

STRENGTHENING AND ADDITION

Strengthening refers to the application of reinforcement material to the existing metal member for restoring or adding on load-bearing capacity. However, this approach usually has significant visual and physical impact on historic structures and may not be suitable as a long-term solution for exposed members in feature spaces or historically and artistically significant historic metal structures.

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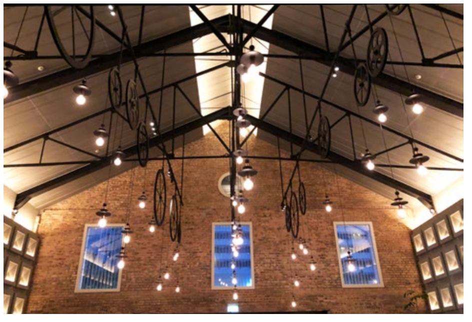
Strengthening by steel – One method of strengthening is by bolting steel plates or flanges to the historic cast iron, wrought iron or steel beams. This process is reversible and is suitable for cast iron, wrought iron and steel structures. Holes are drilled on original structures and aligned with those on strengthening steel flanges or plates. High-strength grip bolts are then inserted to lock the two elements together.

Strengthening steel plates can also be welded directly to a historic steel structural member. However welding a steel plate to wrought iron or cast iron is not advised. The high temperature during the welding could cause the wrought iron surface to delaminate, while cast iron melts at a lower temperature compared to steel and will not form a proper bond with the welding alloy and steel.

Strengthening by fibre-reinforced polymer (FRP) – Adhesive-bonded composite is another viable strengthening method that is generally reversible. It comes in sheet rolls and is applied directly onto historic metal structures.

Addition involves introducing new members to the existing structural frame, for example adding new steel floor joists or roof trusses between existing ones. The professional engineer should ensure that the existing structure is able to support the increased loading; alternatively the new members may be designed as self-supporting frames, in steel or reinforced concrete – this would lighten the load borne by the historic metal structural members, enabling them to be conserved in situ without compromising the overall building structural performance. Additional structures should nonetheless be sensitively designed and located to avoid any impact on other historic elements or creation of visual clutter in historic spaces.



Right: *Strengthening of steel beam by bolting steel plates to the bottom flange.* ***Far right:*** *Sensitive addition of steel portal frame between historic roof trusses allowing for distinction between old and new without detracting from heritage presentation.*

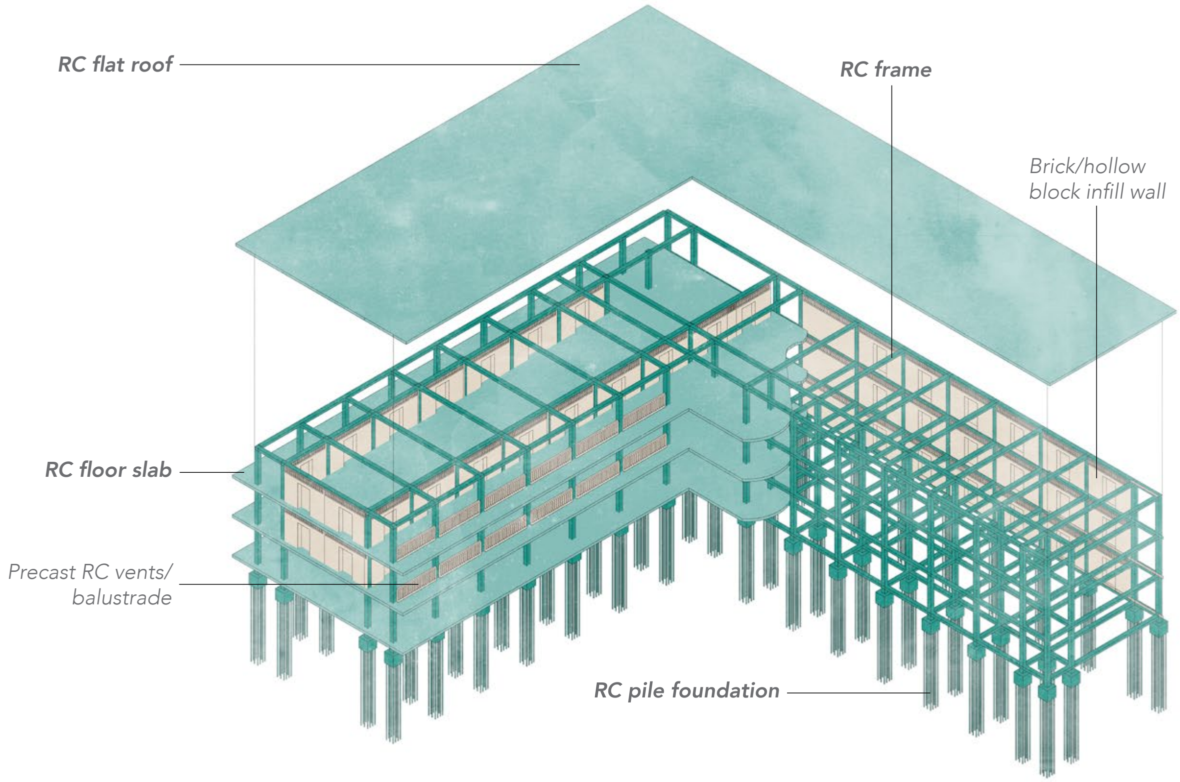
5 REINFORCED CONCRETE STRUCTURES

Overview: Reinforced Concrete

Refer also to *Volume 2 Roofs*, *Chapter 2 Roof Structures* and *Chapter 5 RC Roof Cover* for more information on the history, diagnostics and rehabilitation of RC roofs.

Reinforced concrete (RC) construction was developed in Europe and North America in the 19th century. The composite material combines the **compressive strength** of concrete with the high **tensile strength** of embedded steel reinforcement, and can be made into almost any shape and size. It was introduced into Singapore in the early 20th century, employing mainly imported patented technologies such as the Hennebique, Coignet and Kahn systems. Early **ferro-concrete** construction encased I-sections with clinker concrete, which evolved later to the use of more flexible steel reinforcement bars or **rebars**.

Common Components of Reinforced Concrete (RC) Structure



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In the beginning RC was employed mainly for bridges and hydraulic engineering projects. The technology offered clear advantages especially in the tropical climate, being fireproof, rustproof, and able to withstand both compressive and tensile stresses when compared to steel. Pioneered by specialist builders such as **Riley Hargreaves and Co. Ltd** (predecessor of United Engineers) and French builders **Brossard and Mopin**, the use of RC proliferated quickly in colonial Singapore. From selective application as roofs, columns or slabs, by the 1910s commercial buildings designed entirely in RC were being erected and touted for their premier qualities.

It was in the interwar period that the potential of RC inspired architects and engineers in search of new architectural forms and structural expressions, achieving **unprecedented construction spans and heights** that are the hallmarks of modernism. Architects such as local pioneer Ho Kwong Yew and Singapore Improvement Trust's (SIT) Lincoln Page created works that were proudly expressive of the versatile RC construction and its associated **modernist aesthetics**: flat roofs, cantilevered balconies, pilotis, accented by wafer-thin precast sunshading fins. This culminated in the Cathay Building (1939) designed by Frank Brewer, the first skyscraper in Singapore and tallest building in Southeast Asia at the time, housing the first local air-conditioned cinema, and the headquarters for the British Malaya Broadcasting Corporation.

Right: *1913 advertisement for types of steel reinforcement, 'rib bars' likely being an early precursor to the rebars that became ubiquitous.*
Far right: *The Cathay Building (1939), Art Deco urban landmark and first skyscraper in Singapore.*

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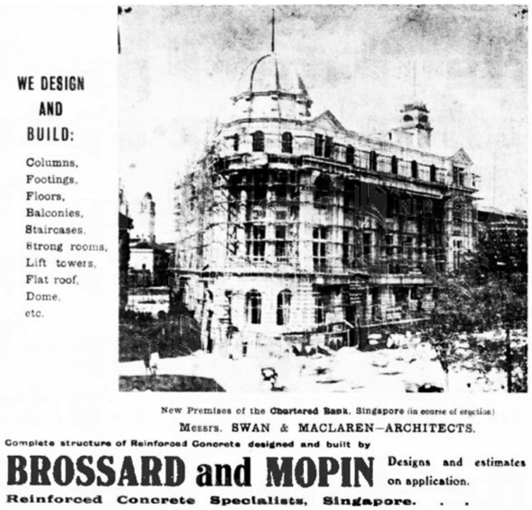
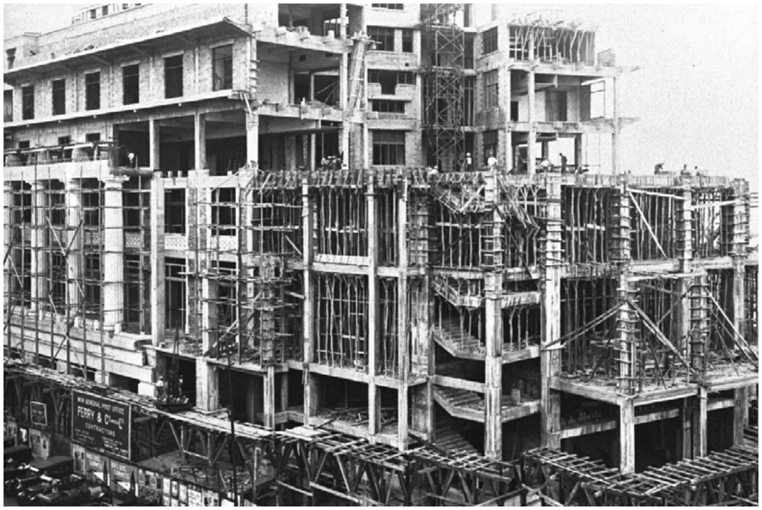
Reinforced concrete can be manufactured in a casting yard (**precast concrete**) or made on site (**in situ concrete**). Historically, precast elements were deployed mainly as non-structural elements such as balustrades, ventilation blocks, sills and sun-shading fins. On the other hand, historic RC structures tend to be cast in situ; therefore, their performance and appearance depend greatly on the quality and composition of raw materials as well as workmanship during construction.

From the 1950s, RC evolved to become the main mode of building, with its widespread use in the ramped-up postwar socialist government building programmes by the SIT and Public Words Department in standard-design public housing, schools, clinics, markets, community centres, hospitals and so on. Given that steel structures had to be erected from costly imported components, RC, which used much less steel, was likely the more economical choice for public construction. The much expanded market in reinforced concrete led to better availability of material, equipment and skilled builders.

In the independence period, local architects left their marks on the new nation's skyline with high-rise high-density RC structures such as People's Park Complex, Golden Mile Complex (both completed in 1973, by Design Partnership) and Pearl Bank Apartments (1976, Archurban Architects Planners).





Left: *The Chartered Bank (1916), designed by Swan & Maclaren, was one of the first buildings constructed entirely in RC, built by Brossard and Mopin.* ***Right:*** *View of Fullerton Building under construction c. 1927, showing the exposed reinforced concrete framework and casting in progress.*

HISTORIC RC STRUCTURES


Telok Ayer Chinese Methodist Church (1925)


Straits Settlements Volunteer Force Drill Hall (1933)


Circular Road shophouse (1938)


Chee Guan Chiang House (1938)


Civil service housing, Clemenceau Avenue (1950s)


Opal Crescent shophouses (1950s)


Yan Kit Swimming Complex (1952)


Golden Mile Complex (1973)

Jurong Town Hall (1974)


Pearl Bank Apartments (1976)

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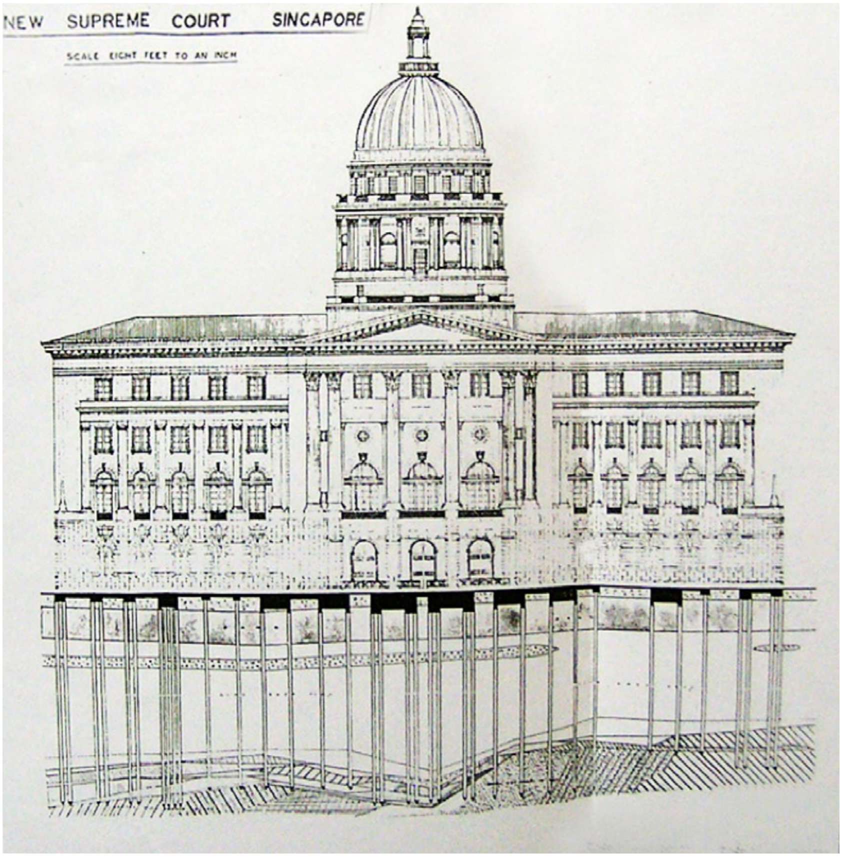
Structural Issues and Diagnostics

Refer to Chapter 1, General Notes on Investigation and Diagnostics for information on the prior investigation and documentation to establish a sound diagnostic basis.

Records of structural drawings and specifications are an important source of information in the appraisal and condition assessment of reinforced concrete structures, where steel members are embedded within and the concrete is usually plastered and painted over, leaving little visual cue of its construction. As with all past records, caution should be exercised as some records may be of an earlier design intent that differs from what was actually built. Non-destructive investigation techniques would aid in the detection and verification of embedded steel elements.



Archival drawing showing deep RC pile foundations provides vital structural information that may not be known without equipment-based or invasive investigations such as trial pits.

Concrete carbonation refers to the reaction of carbon dioxide from the air with the calcium hydroxide in concrete to form calcium carbonate, a slow continuous aging process that progresses from the concrete surface inward. In effect, it lowers the alkalinity of concrete cover resulting in the breakdown of a protective oxide layer surrounding the steel reinforcement, leaving it vulnerable to corrosion.

VISUAL AND TACTILE SURVEY

A commonly encountered structural distress is the **corrosion of steel reinforcement** resulting from **concrete carbonation**, water ingress and chloride salt attack. **Loss of concrete strength** can arise from severe leaching, cracks due to overloading or pressure from expansion of rusted steel, and chemical attack from acid and sulphates, etc. The following visual signs should be documented as an initial survey, with the pattern and extent of cracks along with spalling concrete mapped:

- **Efflorescence**
- **Rust stains and seepage stains**
- **Peeling paint and hollow plaster**
- **Cracks**
- **Spalling concrete**
- **Rusted exposed reinforcement**

From left: *Bubbling paint, seepage stains and efflorescence at soffit of concrete slab; spalling of concrete slab undercroft; corrosion of steel reinforcement and salt attack of concrete due to rising damp.*

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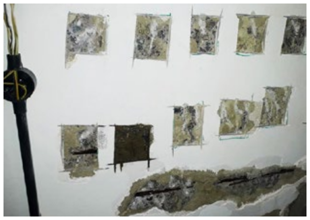
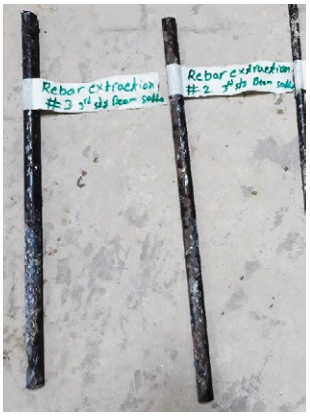


From top: *Surface hardness test on concrete using rebound hammer; measurement of half-cell potential to gauge degree of concrete deterioration.*

NON-DESTRUCTIVE AND SEMI-DESTRUCTIVE TECHNIQUES

For more in-depth condition assessment or verification, the following equipment-based in situ tests may be undertaken:

- **Surface-penetrating radar, pulse echo tomography** or **electromagnetic covermeter** may be used to detect the presence and orientation of embedded steel, other hidden construction details, and cavities.
- **Ultrasonic pulse velocity** measurement, **surface hardness test** by rebound hammer, or **penetration resistance test** by Windsor probe may be used to assess the strength or quality of the concrete.
- **Surface hardness test** by Equotip may be used as a qualitative check on the strength of the steel provided there is intact exposed steel, and a correlation between the hardness and the strength of the steel has been established.
- **Measurement tests of half-cell potential, resistivity** or **linear polarization** may be deployed to assess the degree of concrete deterioration



From top: *Depth of carbonation test and measurement carried out on a core sample; rebar sample extractions for testing.*

SAMPLING AND LABORATORY ANALYSIS

Breakouts and sample extraction for laboratory analyses should only be undertaken when necessary, and if structural integrity would not be affected. The location for such destructive procedures should be carefully chosen – it should be away from highly visible areas, and sensitive parts such as delicately ornamented segments should be avoided.

- **Localized breakout inspection** may be carried out in areas with spalled concrete for inspection of the steel underneath.
- **Depth of carbonation test** can be carried out by spraying a concrete core sample with a phenolphthalein solution.
- **Compressive strength test** of the concrete can be carried out in the laboratory on an extracted concrete core sample.
- **Tensile strength test** of the steel can be conducted if a sample is cut out from the exposed reinforcement.
- **Mix composition analysis** can be carried out on collected concrete dust samples to determine the chloride and sulphate contents.
- **Petrography** study of extracted samples under a microscope will yield critical information such as the composition of the historic concrete mix, including type of cement, aggregates, presence of other binders, secondary reactions and their compositions. This will inform the selection of compatible materials for repair and intervention works.

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Structural Repair and Rehabilitation

Refer to *Chapter 1, Principles and General Notes On Conservation and Intervention* for important concepts and issues to be aware of at the outset of planning for structural rehabilitation, including protection and temporary bracing.

Refer also to *Volume 2 Roofs, Chapter 5 RC Roof Cover* for more information on the rehabilitation of RC roofs.

Refer also to *Volume 3 Facades, Chapter 8 Precast Concrete* for similar conservation treatment for concrete surface defects and coatings that may be carried out as minor repairs or finishing works following structural repair and rehabilitation.

Through experimentation and adaptation to local environs, the use of reinforced concrete has changed considerably in practice methods, design and material selection since its early days. In fact, many issues concerning the conservation of historic RC are related to these early trials that may not yield the best results. Nevertheless, the material evidence of such **transitional technology** embodies valuable scientific knowledge and testifies to critical phases in the history of building technology. These should be properly documented prior to intervention and design enhancement works.

RC durability is highly dependent on the composition mix, individual material component, design, workmanship, environmental conditions and changes, and maintenance. Some basic repair and rehabilitation approaches are introduced in this section. When selecting the repair technique, the significance of the building and of the specific elements, condition, technical properties, required performance and environmental conditions should be considered together for a **sensitive, balanced approach**. Patching trials may be conducted for reinstatement of surface finish in terms of colours, aggregate and textures, especially for exposed concrete. It is important to ensure compatibility of any new material used, such as patching mix, in the intervention works.

Existing RC beam strengthened through increase in sectional depth by casting of new high-strength concrete beam below (note darker material along the bottom of the beam).

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***From top:** Concrete patch repair – removal of affected concrete cover to expose rebar for cleaning and treatment, before patching with compatible mix.*

Patch repair to RC beam spalling at midsection, prior to plaster and paint finishing.

LOCALIZED REPAIR AND PREVENTIVE MEASURES

Infill of non-structural cracks that show no sign of worsening may be done to avoid water ingress. The mix should be carefully designed according to the size of the crack and ensuring compatibility with the historic concrete properties.

Patch repair may be carried out to address minor to moderate defects on the concrete cover. Affected concrete surface is removed to expose the steel reinforcement, to be cleaned and treated with a primer to protect from further corrosion, or replaced if steel sectional loss is excessive. The concrete surface is then reinstated using a compatible concrete mix. A moderately invasive technique, this method should be constrained to localize repair only where needed.

Electrochemical techniques to protect RC have been developed in recent years, such as **cathodic protection** to reduce and prevent the corrosion of embedded reinforcements, **concrete re-alkalization** to address the issue of carbonation, and **electrochemical chloride extraction** to remove harmful salts such as chlorides from the concrete. These techniques are still evolving and should be designed or evaluated by specialists for specific projects in terms of their effectiveness, long-term performance and potential side effects.

Surface coatings for concrete include water repellent, surface sealers and paints to protect the concrete surface from direct exposure to the atmosphere and elements, and prevent moisture ingress. The application of coatings should be carefully considered, as they may change the appearance, especially of exposed concrete, and require periodic maintenance.

Corrosion inhibitors can be applied to the surface of the concrete (migratory inhibitors), incorporated in a repair mix, or applied directly to the steel during repair or introduced in pellet form in holes in the concrete (vapour phase inhibitors).

Ornamental facade RC feature corbels that may be adversely affected if strengthening is applied.

Addition of RC column to support existing beam and stiffen the masonry wall.

STRENGTHENING AND ADDITION

More interventionist strengthening, addition or even replacement methods tend to have higher heritage impact and should be minimized and applied judiciously, only where there is a need to restore or increase the loading capacity of historic structures. Strengthening serves to increase the capacities of the target RC members or joints in terms of strength, stiffness, stability and integrity. Addition of members to the existing structural scheme as reinforcement may be done to carry new loads, reduce spans, or transfer load to the new foundation piles. Any strengthening or addition works should take care to avoid or minimize affecting spatial character, including headroom or floor level, facade and other design features.

Underpinning and micropiling – Underpinning refers to the strengthening of foundations. The objective is to spread the load or transfer it to deeper soil or bedrock with higher bearing capacity. In particular, the micropiling method, which uses small-diameter piles (usually reinforced concrete) driven by compact-size piling rigs, is wellsuited for historic buildings where access and headroom may be restricted. To minimise impact on existing historic floor slab and floor finish, micropiles could be installed on the exterior and the load transfered via cantilevered needle beams. If this is not feasible, the impact should be mitigated by careful dismantling and reinstallation of the affected historic elements. Underpinning works are irreversible and subtractive, so the historic foundation should be well-documented, or even selectively protected and retained as a showcase, prior to underpinning works.

Addition of structural members – Shear walls, bracings and columns in RC or steel may be added to reduce spans, or new independent structural frames may be introduced to offload the stress on existing structures. New members should be sensitively designed and inserted to minimize visual, spatial and physical impact, while ensuring that the historic structural scheme remains coherent in its heritage presentation. Addition could potentially be designed as a reversible intervention.

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***Left:** Steel jacketing by installing steel plates on the columns and a new I-beam attached to the existing RC beam. **Middle:** Design enhancement of RC floor beams for added loading requirement, by sensitive introduction of haunched details at the joints. **Right:** External post-tensioning of historic RC beam by installing new high-tensile steel bars anchored at the beam ends.*

Strengthening by enhancement/jacketing (passive system) enlarges the existing structures by bonding new structural materials, usually reinforced concrete, steel sleeves or plates, or FRP wrap. This is, however an irreversible intervention that impacts on historic finishes and design proportions and should not be carried out on members that are also key design features or come with significant ornamentation or finishes of high artistic value.

Strengthening by external post-tensioning (active system), a relatively new technique, is carried out by installing high-tensile steel bars along target RC beams or slabs, typically anchored at the ends. The active introduction of external forces helps to offset part or all of the external loading on the target member. Unlike jacketing, surface preparation and removal of finishes to the concrete substrate is not needed and may offer a less invasive alternative for strengthening.

Like-for-like replacement of specific structural members may be undertaken as a last resort only if they are beyond repair and strengthening. The historic design and material should be thoroughly documented prior to dismantling. Replacements can be cast in place with compatible materials and designed to match the historic elements. If the surface of concrete is exposed, special care is required to reinstate the existing appearance in terms of colours, aggregate and textures.

6 COMPOSITE STRUCTURES

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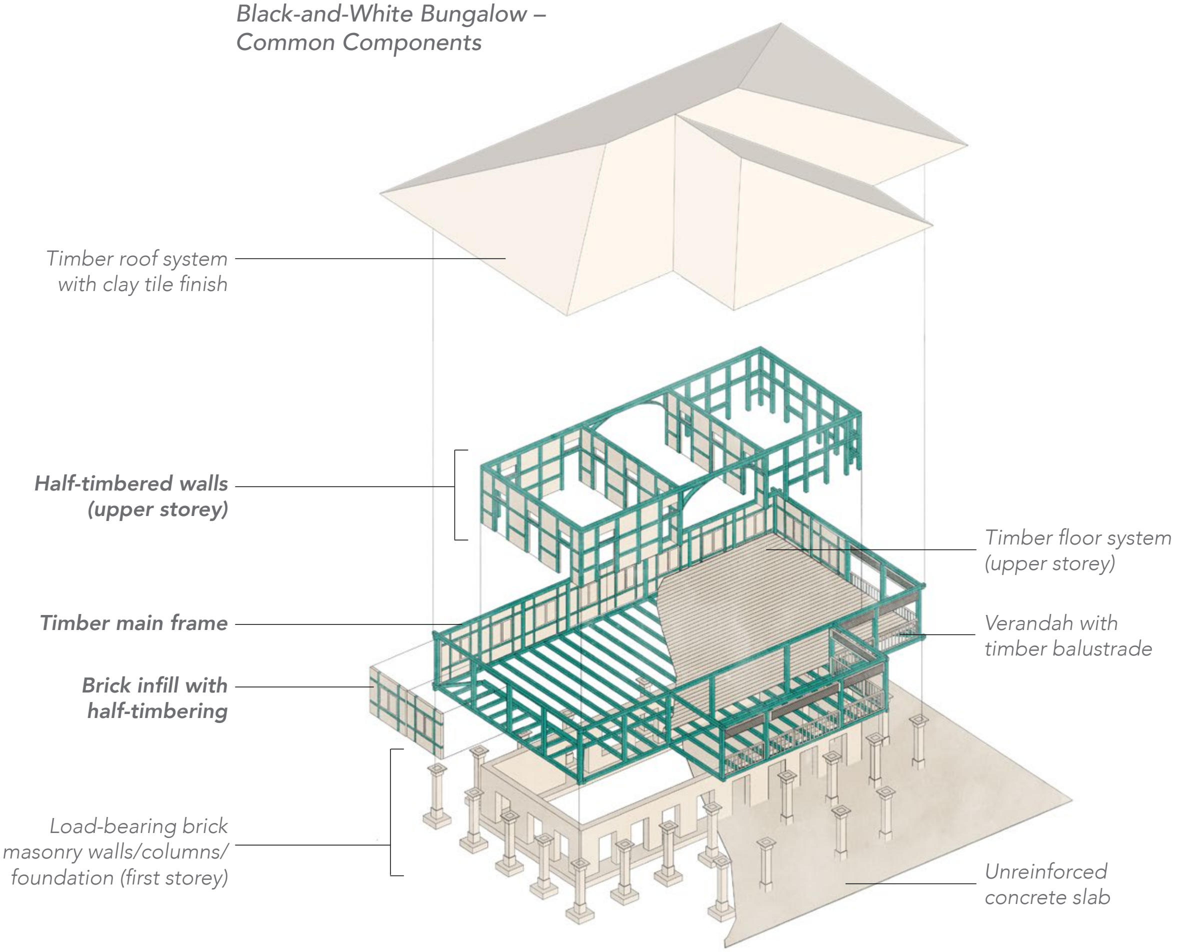
Overview: Composite Structures

Refer to Chapter 5 Reinforced Concrete Structures, for more information on this material.

Hybrid or composite structures here refer to those where different materials are bonded to perform structurally as a single unit, in what is termed **composite action**. Such structural designs are usually intended to compensate for the load resistance limits of one material by leveraging on the structural property of the other. The most common example today is **reinforced concrete**, where the high tensile strength of steel reinforcements is partnered with compression-resistant concrete. This chapter takes a brief look at other types of composite structures that can be found in Singapore's historic buildings.

Black-and-White Bungalow – Common Components



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*Types of concrete mixes used in ferro-concrete encasement – **Top:** Lightweight concrete with coke breeze aggregates. **Above:** Brick concrete with crushed red clay aggregates.*

Composite structures are not uncommon in traditional building practices – examples include stone buildings with timber ties for seismic resistance found in certain European locales that are earthquake prone, **composite timber trusses** with iron tensile ties, and **half-timbered construction** (timber frame with brick masonry infill) found in many cultures, including colonial black-and-white houses in Singapore.

Some, however, are more recent products of the Industrial Age arising from experimentation with then-newfound structural materials. Early combinations of steel and concrete are also known as **ferro-concrete**, mainly a transitional building technology prior to the proliferation of reinforced concrete from the 1920s onwards. Locally, prefabricated steel members may be found used in combination with concrete or masonry, especially in historic structures dating to the 1900s. I-beams, also known as rolled steel joists or RSJ may be encased in concrete or brick masonry for weatherproofing, and deployed where there is exposure to the elements or moisture, such as facade beams, or verandah and bathroom floor slabs.

Various types of **concrete mix** have been observed, including lightweight porous coke breeze concrete, and brick concrete with crushed clay aggregates.

***Left:** Composite timber roof trusses with iron tensile ties, St George's Church (1911). **Right:** Stamford House, a steel-frame building with masonry envelope built in 1904, has historic 'ferro-concrete' where steel I-beams are found encased in brick concrete on its facades.*

Corrugated steel deck may also double up as **permanent formwork** and external reinforcement for cast concrete slabs. 'Hy-Rib' was developed in the 1900s as a self-supporting metal lath or mesh reinforcement that served also as a substrate/formwork that the concrete mix could be directly cast in/applied on.

Another type of permanent formwork comprised hollow blocks (or 'pots') in clay or concrete packed closely to form the soffit voids of cast in situ ribbed concrete floors. Known as **hollow pot slab**, this was devised to reduce the dead load and material (as compared to solid slab construction) while maintaining its fireproof property. Precast concrete blocks were also used in combination with clay bricks in the construction of **composite load-bearing masonry walls or columns**.



Left: *Concrete slab soffit with curved corrugated steel permanent form, at Convent of the Holy Infant Jesus (1900s, current-day CHIJMES).* ***Middle:*** *Heavy gauge iron jackets as permanent form at a 1900s road bridge over a former railway line (current-day Neil Road).* ***Right:*** *Hollow pot slab construction with ribbed cast concrete and clay 'pots' formwork infill.*


Left: *1910s advertisement showing the use of curved 'Hy-Rib' mesh reinforcement in concrete vaults spanning between I-beams.* ***Middle:*** *Spalled concrete cover reveals mesh-formed concrete construction.* ***Right:*** *Composite masonry wall with clay bricks and concrete block, Stamford House (1904).*

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General Notes on Structural Issues and Diagnostics

Refer to *Chapter 1, General Notes on Investigation and Diagnostics* for information on the prior investigation and documentation to establish a sound diagnostic basis.

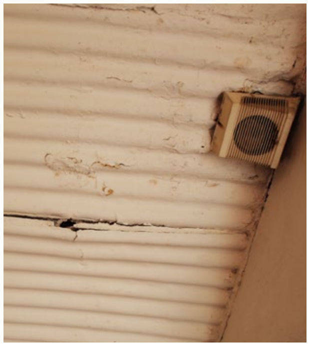
Also refer to *Chapters 2–5* for the relevant structural material for more details on deterioration and diagnostics.

Given the general lack of records, studies and understanding of local historic composite structures, it is especially important to carry out **thorough research and field investigation** to establish the material composition, details and construction to inform any conservation intervention works. Conservation professionals, material specialists and structural investigators with experience and knowledge of historic composite structures should be engaged to undertake appraisal and give recommendations if major works are planned.

Deterioration tendencies of composite structures, and specific diagnostic methods, vary from case to case depending on the type of material used and the construction method.

Poorly maintained **timber composite construction** may suffer from wet or dry rot, and termite infestation of the timber elements. A common cause of problems encountered in local half-timbered construction is moisture trapped by inappropriate unbreathable paintwork, which may also lead to deterioration of the plaster and brick masonry infill. In rare cases where timber beams are found encased within brick masonry, moisture ingress may also result in wet rot, or termite infestation may occur at the beam ends or where there are cracks. Insect infestation in timber that are embedded or thickly painted may remain undetected until structural failure occurs, or when a breakout inspection is done. Timber members may also undergo structural deformation from weathering, loading stresses or settlement, in turn affecting the infill or encasing brick masonry.

Right: *Double I-beam encased in brick concrete, already flaking with corrosion.* ***Far right:*** *Timber beam encased in masonry already severely compromised by wet rot went undetected until mid-construction.*

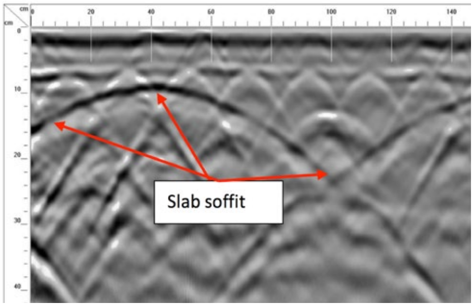


Corrugated steel form and concrete composite slab with water seepage, paint failure, and steel corrosion occurring at the slab-to-wall junction.

Similar to reinforced concrete, **embedded steel** may undergo corrosion due to ingress and retention of moisture due to rising damp, inappropriate paintwork, and cracks in the encasing brick masonry or concrete. In the case of **external steel reinforcement**, corrosion may arise from direct exposure to the atmosphere or moisture due to paint peeling or drainage issues.

A careful **visual and tactile survey**, especially in deteriorated areas where substrates or embedded elements may be revealed, or an observation of surface or formal manifestations such as corrugated or vaulted soffits, usually provides the first clues of a composite structure. In parallel, **desktop study** of archival records, old construction photographs, and material history research on the possible type of composite structure may verify initial site findings and shed light on its structural behaviour, material characteristics, and deterioration or failure tendencies.

Non-destructive techniques such as surface-penetrating radar and pulse echo will be useful to establish the specific construction details of such composite construction. Due to the lack of existing studies and to enable effective conservation intervention works, **limited breakout inspection and sampling** for laboratory analysis are usually unavoidable to verify the condition, construction details, and material composition – for example, the historic concrete mix and type used in a composite structure.



Surface-penetrating radar scan reveals a composite slab system with reinforced concrete vaults spanning between steel joists.

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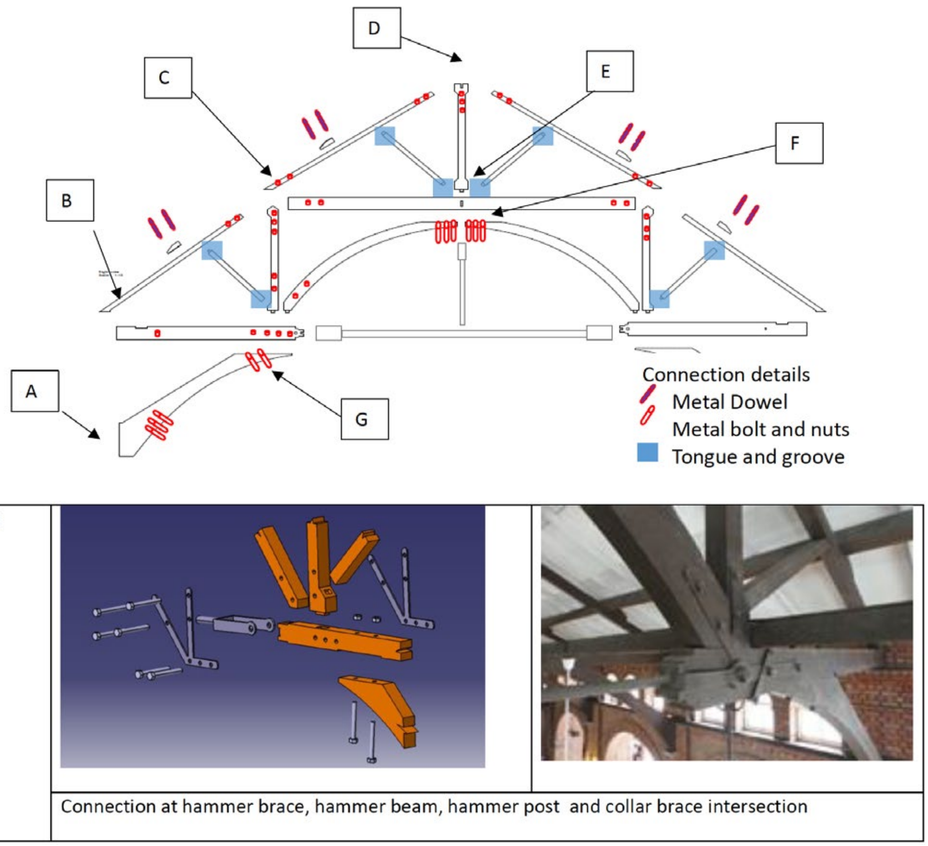
Conservation Considerations

Refer to Chapter 1, Principles and General Notes on Conservation and Intervention for important concepts and issues to be aware of at the outset of planning for structural rehabilitation, including protection and temporary bracing.

Also refer to Chapters 2–5 for the relevant structural material for the respective structural repair and rehabilitation approaches.

Historic composite structures, especially the products of transitional technology, present several challenges in their conservation. There is a relative lack of local empirical studies and documentation of their construction, composition, structural and material properties, long-term behaviour, and performance. Some of the building materials derived from transitional technology may no longer be readily available. Nonetheless, as far as possible, any conservation intervention design and method should take into account the heritage significance and material authenticity of the historic structure, beyond simply achieving the intended structural capacity.



Documentation of composite roof truss with iron tie with sketch diagram and photographs showing the truss design and details of timber joinery with metal connectors.

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A variation of hollow pot slab construction with steel joist reinforcements flanking the concrete ribs – without documentation, such historic building practices, techniques and the embodied knowledge would be lost through unthinking interventions.

- **Documentation** – Given the relative rarity of intact heritage composite structures in Singapore, a detailed heritage survey, documentation and material studies should be carried out prior to any intervention works that may result in the loss or alteration of the historic fabric. The findings may then be shared, contributing to a better understanding of these structure types.
- **Engaging relevant conservation expertise** – This is especially important for any major works planned on historic composite structures, given the complex material behaviour and structural performance. Depending on the scale of the project, a multidisciplinary team of experts with relevant conservation experience and knowledge of the structure type should work in collaboration to devise a sensitive yet effective conservation and rehabilitation scheme. The team may include a professional engineer, conservation professional, material specialist, structural investigator and specialist contractor, each with relevant skills and qualifications.
- **Offsetting load-bearing role** – Historic composite structures that may be unfeasible to rehabilitate to the needed structural capacity may instead be conserved with a reduced or even non-structural role. This may be achieved by the addition of new structures to offset existing and new live loads from the historic structure. Especially for exposed historic composite structures of high heritage and artistic value, the new additions should be sensitively designed to minimize visual obstruction or clutter.
- **Design enhancement and material replacement** – Historic composite structures with experimental, imported or adaptive construction techniques that were untested in the local climate may prove to have underperformed due to inherent material or design flaws. In some cases, instead of like-for-like repair, it may be necessary to carry out appropriate enhancement and even material replacement. Such alterations should as far as possible align with the historic materiality and construction logic. For example, badly deteriorated ferro-concrete elements could be considered for recasting in the more durable successor material of reinforced concrete.

Rehabilitation in process – deteriorated brick concrete encased beam is strengthened by re-encasing in rebar reinforced concrete. This allows the historic steel element to be retained in situ.

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ICOMOS 1964 Venice Charter
ICOMOS 1994 Nara Document
ICOMOS 1999 Burra Charter
ICOMOS 2005 Hoi An Protocol

Standards and Codes of Practice
BS EN (British Standard European Norm)
ASTM (ASTM International, founded as American Society for Testing and Materials)
SS (Singapore Standards)

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Journals:	*Journal of Institute of Architects of Malaya, The Malayan Architect*
Government records:	Building plans, Annual Reports of Public Works Department/Municipality/Singapore Improvement Trust

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