



# STRUCTURAL DESIGN OF BUILDINGS

PAUL SMITH



WILEY Blackwell

# Structural Design of Buildings

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**WILEY** Blackwell

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York Press for the use of Figure 12.1, photograph of a sinkhole in Magdalen's Close, Ripon.

# About the Author

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Paul has worked for over 20 years in the public and private sectors, mainly on infrastructure projects. He now runs his own company, Geomex – Structural Engineers & Architectural Design Consultants, which specialises in architectural design, surveying, project management and structural design.

# Introduction

The intention of this publication is to embark on a journey taking the reader through a brief history of buildings, how the construction of buildings has evolved over the years and then examining in more detail the structure of buildings and their principal elements. We also examine other factors which affect the stability and structure of buildings, including ground investigations and environmental factors, and detail the materials used in their construction. Finally, we examine structural failures of buildings, their likely causes and common remedies.

This book explains some of the structural engineering principles in the design of residential dwellings and their various structural elements. Some structural theory has been included to demonstrate and reinforce understanding of the comments made. In addition, structural calculations have been included to demonstrate the key points. Diagrams and photographs add clarity.

The theoretical concepts contained in this book are equally applicable to all building structures, whether commercial, traditional or modern. To emphasise some of the issues raised, large examples such as castles and churches are used, which clearly demonstrate the building science and technology.

It must be understood from the onset that specialist structural advice should be sought before undertaking any alterations, or in the identification of structural failures and defects. This book attempts to provide some guidance on understanding the behaviour and construction of buildings, but should not be taken as an exhaustive text.

## Health and Safety

It must be recognised that the building and construction industry can be a hazardous environment in which to work, and each individual has responsibility to minimise the risks to both themselves and others.

There is legislative framework which ensures that everyone involved in the commissioning of works, the design, construction and maintenance of building structures has clearly defined responsibilities for health and safety. It is essential that you are aware of your responsibilities under the legislation to reduce risks and prevent accidents. The Health and Safety at Work Act 1974 places responsibilities on contractors, members of the public, clients and construction workers, and is enforced by the Health and Safety Executive.

The Construction Design and Management Regulations 2015 (CDM) place further responsibilities on clients, contractors and designers. Under Regulation 9, a designer must not commence works in relation to a project unless the client is aware of his/her responsibilities. The responsibilities are different for commercial and domestic clients. For domestic clients, unless the designer has a written agreement, the responsibilities must be carried out by the contractor and if more than one contractor is engaged on a project then the client must appoint a principal contractor. This does not mean that the regulations do not have to be carried out, but merely places the responsibilities on

another duty holder. The client always has the responsibility for ensuring all pre-construction information is available.

Commercial clients have responsibility for ensuring a construction phase plan is drawn up by the contractor, and that the principal designer prepares a health and safety file for the project. This is undertaken by another duty holder if the client is domestic.

Commercial clients also ensure that management arrangements are in place for health, safety and welfare. The regulations make it clear that clients are accountable for their decisions and the approach they have in regard to the health, safety and welfare of the project.

The client is responsible for the submission of a notice to the Health and Safety Executive subject to the responsibility being undertaken by another duty holder, and with the criteria set out below.

*Projects are notifiable to the Health and Safety Executive if the construction work on a construction site is scheduled to:*

- *Last longer than 30 working days and have more than 20 workers working simultaneously at any point in the project. Or*
- *Exceed 500 person-days.*

*Works may include alterations, maintenance, construction and demolition.*

The activities that are defined as domestic works require consideration as the client dictates the classification, for example works can be undertaken on a residential dwelling but if these are undertaken by a private landlord or someone engaged in property development, they would be defined as commercial activity and not domestic works because they relate to a trade or business.

Although in the case of a domestic client regulations 4(1) to (7) and 6 must be carried out by another duty holder, the client still has responsibilities under the regulations. If the domestic client fails to make the necessary appointments under regulation 5, the client's responsibilities are then passed on to other duty holders.

Ignorance of the legislation is no protection against prosecution, and professionals have been prosecuted for not informing clients of their responsibilities under this legislation. Further information is available from the Health and Safety Executive website. Clients, contractors and designers who are in any doubt about their responsibilities are strongly advised to check with the appropriate body or seek professional advice.

## **Building Regulations, Listed Buildings and Planning Consent**

It is also important to recognise that works undertaken on buildings may be subject to other conditions and restraints.

All works must be compliant with the Building Act 1984 and Building Regulations 2010, Local Authority Planning Conditions, Listed Building Consents and Building Regulation Approvals. These should be checked via your Local Authority before embarking on any works. Other legislation may also apply to the proposed works, such as the Wildlife and Country Act 1981 and the Conservation of Habitats and Species Regulations 2010. This legislation makes it an offence to disturb certain species such as bats, and licensed ecologists are required to provide advice.

There are many factors and considerations that may affect the proposed works, and for this reason it is always wise to seek competent professional advice.

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# Chapter 1 The History of Buildings

## The development of building knowledge

In order to understand the construction of buildings it is necessary to determine the age of the building and the technologies likely to be included in the construction and design of that period. For this reason, this first chapter briefly explains the construction and features of buildings over the years and this is further developed in chapter three where the construction is discussed in more detail.

Since the beginning of time man has been engaged in building structures and it is remarkable that many of the early structures still exist. The Neolithic period as early as 6500–10 200 BC saw the first structures being made which may have been simple huts and bridges but nevertheless commenced mankind's quest to construct buildings. Buildings continued to develop through the Mesopotamian, Ancient Greek and Ancient Egyptian periods, which ranged from 6000 BC until 146 BC, and some of these structures – such as the pyramids – are a lasting legacy to the ingenuity and understanding of building construction principles. Following this, the period of the Ancient Romans from around 753 BC until 476 AD saw large-scale buildings become more commonplace. As techniques and materials became better understood, more adventurous structures were constructed.

The Medieval period of the 12th century until the 18th century saw timber frame houses being constructed and some of the early timber frame houses of this era still exist, such as the Medieval Merchants House in Southampton, Hampshire. The development of these structures is intrinsically linked to the understanding of materials and the behaviour of structures which carpenters gained over these centuries.

Masons involved in the construction of churches would travel across the east and west, refining techniques and applying them to new and larger structures. One such example is the development of the arch from a circular arch to a gothic pointed arch, which improved its ability to carry loads, thus resulting in larger-scale and more impressive structures. This is evident in the late 16th century when large glass windows became fashionable in churches to provide light, which also had a significant theological meaning.

The understanding of flying buttresses to resist large lateral and horizontal loads meant that vaulted ceilings could be constructed which accommodated large spans. The first example in England was in Durham Cathedral, which was commenced in 1093. Other early examples include the apse of the Basilica of Saint-Remi in Reims dating from 1170.

Although some of the structural principals were understood, many were based on trial and error and then carried through as tried and tested means of developing structures.

Such scholars as Marcus Vitruvius Pollio wrote some of the earliest books on architecture, and his work *De architectura* (known as *Ten Books of Architecture*) is the only surviving book from the classical period. This provided dimensions for columns based on the number and type of column used and the style of temple required. The height of the column was expressed as a multiple of the diameter. This work was not discovered until 1414 in a library in Switzerland, and interestingly there had been no other printed works prior to this time.

During the Renaissance period, in 1450, Leon Battista Alberti published *De re aedificatoria*, which translates as *The Art of Building*. This was one of the first printed books on architecture. Later, Sebastiano Serlio (1475–1554) published *Regole generali d'architettura*, which translates as *General Rules of Architecture*. Then, in 1570, Andrea Palladio published *I quattro libri dell'architettura*, which translates as *Four Books of Architecture*. This final publication carried many of the Renaissance ideas into Europe.

Prior to these publications there were very few books for architects and masons to reference how structures were constructed. Following the Renaissance period (15th–17th centuries), more information became available.

During the years 1100–1200, fire was the major concern and a hazard in built-up cities. The construction of houses during this time was predominantly in timber, and densely populated areas resulted in accommodation being provided by extending existing properties and adding additional storeys.

In 1666 the Great Fire of London transformed building control and regulation in the UK. The following year the London Building Act banned the use of timber and insisted on the use of brick and stone in the construction of houses. In 1694, following another major fire in Warwick, more major cities were prompted to introduce Building Acts based upon that introduced in London. By the 18th century, most cities had a Building Control Authority and had adopted a Building Act.

The Building Act of 1858 meant that plans had to be deposited with the authorities for new buildings and alterations. This makes it easier – after this period – to ascertain the history and construction of properties throughout the UK.

## Styles of architecture and building construction

It is remarkable that today we still dwell in houses constructed as far back as Medieval times, and it is at this point that we begin our analysis of the structures of buildings based on the techniques used in the past.

### Medieval

The majority of the remaining residential dwellings of this period are of timber frame. Predominantly these were of cruck construction or box frame, where the roof is a separate structure to the walls. Medieval buildings tended to have thick timber members which were irregular in shape, and the timber posts were placed directly onto or inserted into the ground. The floor joists were generally large and laid flat rather than upright, typically these would be 200 mm × 150 mm timbers. Figure 1.1 shows a photograph of a typical cruck frame construction used in a house in Herefordshire.

In their simplest form, Medieval buildings were four-bay cruck frame structures with a large hall occupying at least two of the bays. The open-plan design centred around a large



**Figure 1.1:** Photograph of typical cruck construction in Herefordshire.

fire, which was the only means of heating. Access was gained through two large doors normally located on opposite sides, which formed cross passages. Of the remaining bays, one would form a parlour which would create some privacy for its occupants and the other would be split as a pantry and buttery for storing food and drink. Over 4000 cruck frame buildings remain in the UK today.

Other forms of construction existed at this time, and stone cottages have been constructed from materials close to hand from a very early period in history. Cob construction is another form of construction with the main component being mud, earth or clay. This form of construction can be traced back to the 14th century and was particularly evident in the south-west and central-southern England.

### Tudor (1485–1560)

With the exception of churches, most buildings in the Tudor period were also of timber frame construction with box frame construction being dominant. Houses tended to be one-room deep with a limited span, as the walls did not have sufficient load-bearing capacity to support the heavy roof structure. Some masonry brick construction was used to fill the timber panels and some stone construction for windows and quoins.

Bricks were a luxury product and found only in the homes of the wealthy, and generally in the east and south parts of the country. This was predominantly because the people who knew how to make and use bricks were Flemish immigrants who settled on the east coast.

Most large houses were constructed around a central hall, with wings containing private chambers at one end and kitchens and service rooms at the other. As today, space within the towns and cities was valuable and the timber frame houses were generally





**Figure 1.2:** Photograph showing the close proximity of timber frame housing in Leominster, increasing the risk of fire.

owned by rich merchants. Plots in the cities tended to be long and narrow, and houses often had a rectangular form with the gable end facing onto the street. The ground floor was used for commercial enterprise, with the living accommodation being above. To gain additional space, jetties were introduced to extend over ground floors and create additional storeys.

The jetties extended the higher storeys forward of the building line into the street, reducing the distance between the facing properties. Consequently, this resulted in an increased fire risk, as fire could travel easily from one building to another. Figure 1.2 is a photograph showing the close proximity of timber frame properties in Leominster, increasing the risk of fire. This was a prominent reason for the spread of the Great Fire of London in 1666.

Initially little consideration was given to external appearance, but towards the end of the Tudor period the finest timber frame houses featured close timber studding, decorative panels and brick panels with diagonal patterns.

Glazing was not generally used in properties at this time, and only the finest properties enjoyed this privilege. Timber frame houses at this time had shutters and mullions rather than glass.

Floorboards above the floor joists were usually left exposed and the joists were chamfered and did not have plastered ceilings. Joists were laid flat and were usually 125 mm × 100 mm in size.

During the Medieval and Tudor periods thatch was the most likely roof covering, and the pitch of the roof had to be steep (generally 45°–60°) to dispel water from the roof. The overhang was deep so that the water was thrown clear of the walls.