THE GLOBAL STABILITY OF LOAD BEARING STRUCTURES

By Nicolai Green Hansen/Hans Emborg/Adrian McCreadie August 2007 - August 2009
(ver. 2.2).

Structural Failure

Picture gallery

As can be seen from the pictures, many buildings have been built where safety has not been fully considered which can, in severe cases, result in partial or complete collapse.

There are many possible reasons as to why failure has occurred. For instance:

1. Faulty workmanship. Poor execution of works by contractors/tradesmen.

2. Errors in structural calculations. Calculations not checked.

3. Failure at the design stage. No project review or quality assurance of the project.

4. Failure to check the load path/transfer of forces through the building. Lack of appropriate design checks on load-transferring joints.

5. Poor communication between the project supervisors (consultants) and the participants in the construction phase.

During recent years significant efforts have been made to prevent such incidents occurring. All parties in the building industry are of course interested in avoiding such occurrences, but there are still too many failures in the building sector.

Which actions can reduce the potential for structural failures?

Ad 1:

Improved on-site inspections. Better communication between the project supervisors and the contractors/tradesmen.

Ad 2:

Quality assurance of the project. Calculations should always be checked by an independent (third) person.

Ad 3:

Improved communication between the consultants.- architects, engineers, construction architects, technicians etc.

Ad 4:

Additional focus on the transfer of forces and design of force-transferring joints. Determine and document the transfer of forces in all projects, even in minor structures. It is surprising just how many residential houses exhibit signs of structural problems, albeit not quite as extreme as those shown in the pictures.

Minor structural problems such as cracks and deformations that do not result in collapse, can cause other problems (for example water ingress through cracks or poorly constructed joints leading to dampness or water damage, degradation of lintels, etc) . These kinds of defects are frequently the cause of complaint from clients.

It is therefore very important to have an overview and check of the critical deflections in the structure before the construction phase.

There are many tradesmen and contractors that want to “save” on the cost of having an engineer involved or do not feel the need to consult an engineer when engaging in minor structural projects. Unfortunately this comes with a greater risk of the kinds of structural failures mentioned above.

Ad 5:

Improvement in the communication -both written and oral- between the client, the consultants and the contractors.

Follow-up of points 3 4 and 5.

- To avoid design failures, consideration must be given to the interdependence between the static analysis and the subsequent design of the load-bearing elements and structures.
- Verify that the general stability of the main structure is adequate, and clearly identify and document the transfer of forces down through the building.
- Identify the force-transferring joints.
- Design the joints/nodes so that they can transfer the necessary forces.
- Ensure the stability of each load bearing element in the structure.
- Ensure that all the necessary information is exchanged between the parties concerned.
- Because of the high number of structural problems in buildings, the Danish Housing and Building Agency has written new demands in Appendix 6 of the Danish Building Regulations - BR95.

  Here they state the requirements for the static calculations - "Statical documentation statement" . The "static design report" is the document that helps you to prevent the problems mentioned above, and is especially useful in the early stages of the design. This document can be found in the Fronter archive for the course GSA BS1.

In the first 5 double lessons of GSA-BS1 we will try to give you the students some tools that can be used in connection with the above mentioned 'follow-up' points.

We will examine how the forces are transferred through a structure, examine the global stability of the main structures and examine the force-transferring joints.

Stability

If a building is stable it means that it is in **equilibrium with all external forces**, related to forces such as self-weight, snow load, wind load etc. We call it **the global stability of the structure** - in some literature it is referred to as **main or overall stability**. As well as global stability, you also need to look at the stability of individual building components where you should examine whether it is stable for the imposed load.
In the beginning of this course we will look at the global stability. Later we return to the stability of the individual elements.

When we look at the structural failures we can see that the global stability seems to be okay in many cases, but there is a substantial risk of failures in the joints between the individual building components.

In the pictures an extreme **uncontrolled deformation** has occurred which has resulted in the collapse of a significant part of the structure.

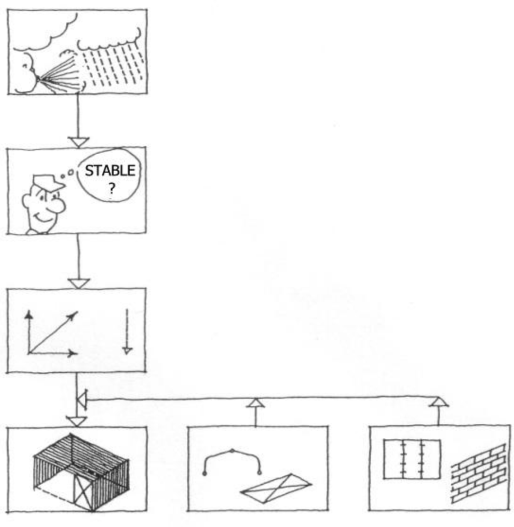
Even if the deformations are not of a magnitude that results in the damage shown,they can result in more localized failures. For example, crack formation, local rupture, damage to brittle building elements (glass, plasterwork, etc.)

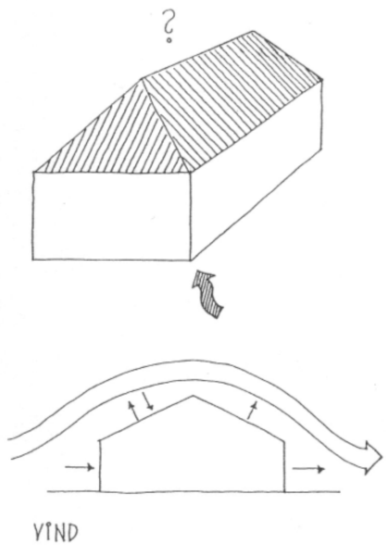
When we design structures consideration must be given to:

1. **Stability by achieving equilibrium with all external forces.**

2. **Prevention of uncontrolled deformations.**

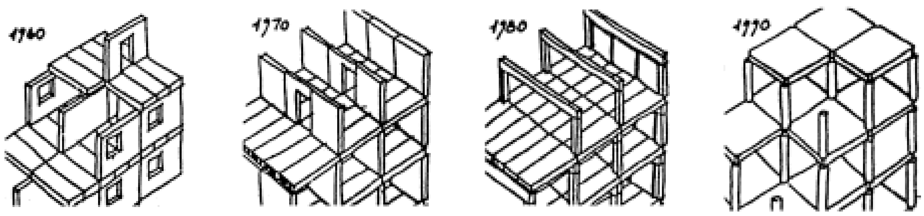
The structural engineer should be involved as early as possible in the design phase, particularly when considering point 2. Already in the outline proposal phase (draft design) the architect and the engineer can work together to design a building that satisfies both the demands of the client and the architect. Simultaneously the structure can be designed in a way so that the deformations will be within the acceptable limits for the building in question.





Statical analysis

History



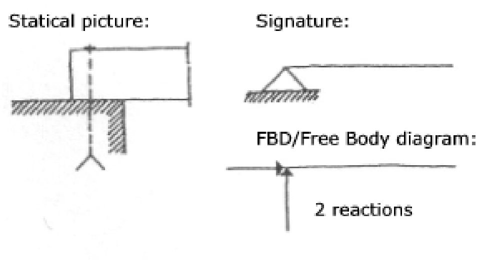
In relation to the design of the building and the load bearing structure, a statical analysis should be performed. This analysis provides a statical model of the entire building.

In the early phases this is often done in the form of sketches.

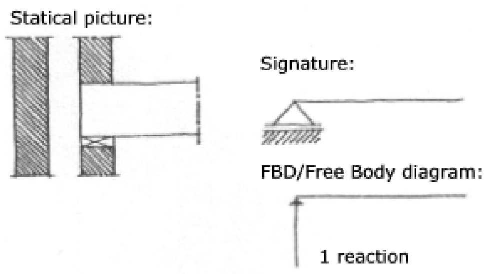
A statical analysis could for example take the form of a 3D sketch/drawing of the structural elements of the building supplemented with a description of the elements. This gives a good overview of how the structural elements work together. The sketch can also be annotated with a description of the course the forces follow (commonly referred to as the load path) through the building.

Support types

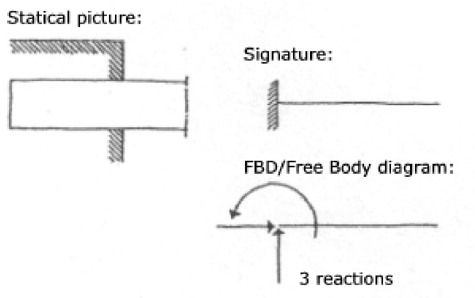
Pinned support.



Roller support.

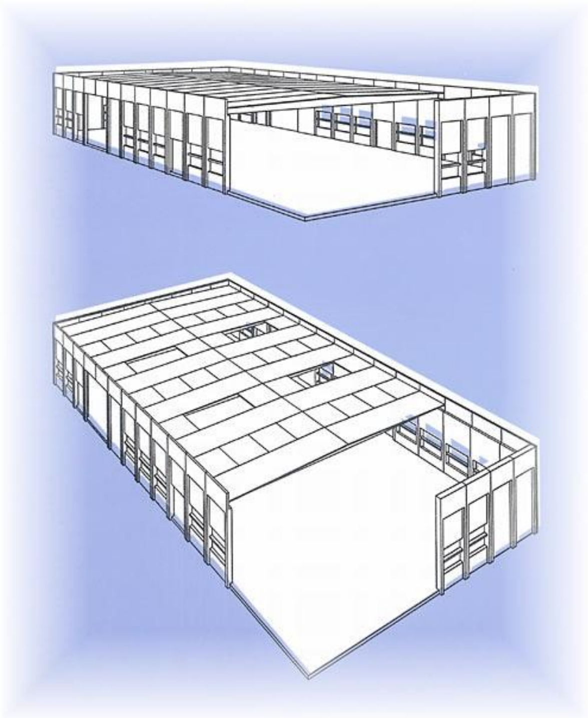


Fixed support.



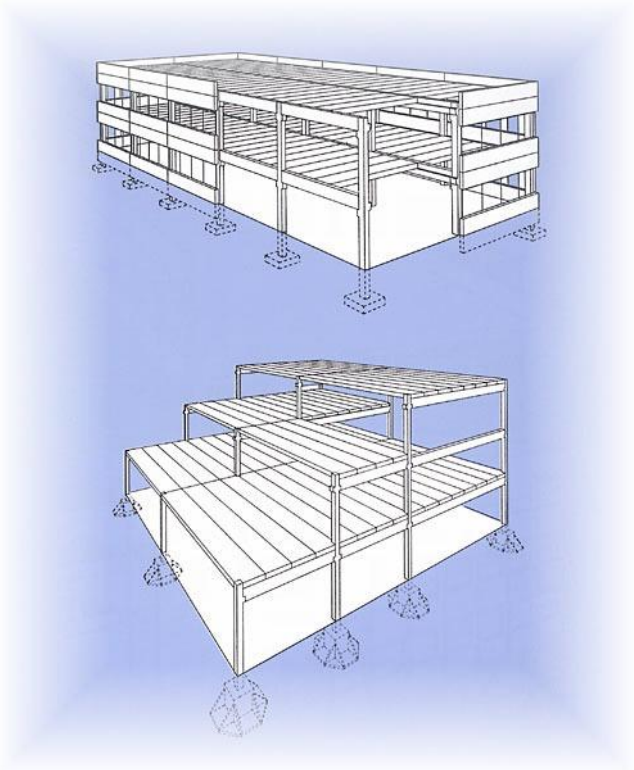
Examples of buildings

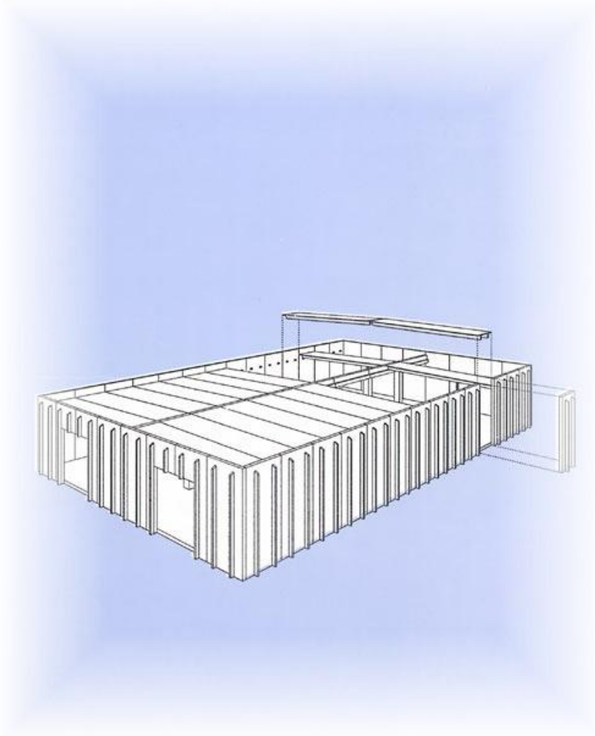
Industrial buildings (shear wall halls, column /beam halls, combination halls):



Type 1

Type 2





Type 2

Type 1

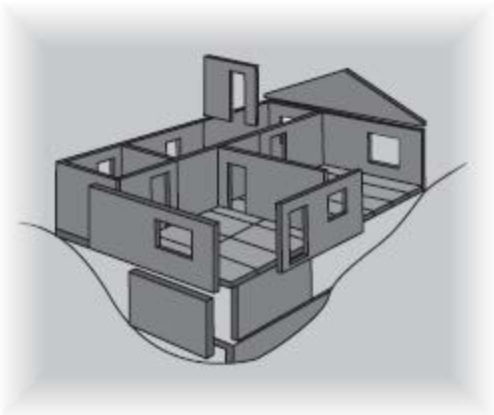

HOLMBOESALLE
SEJRØGADE







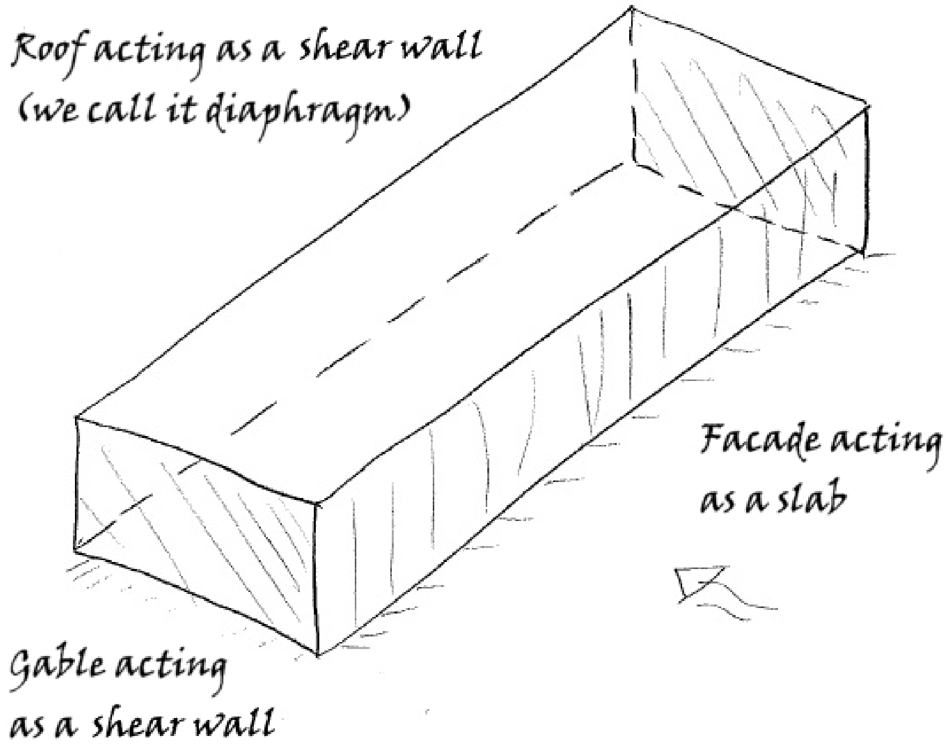

Residential building:

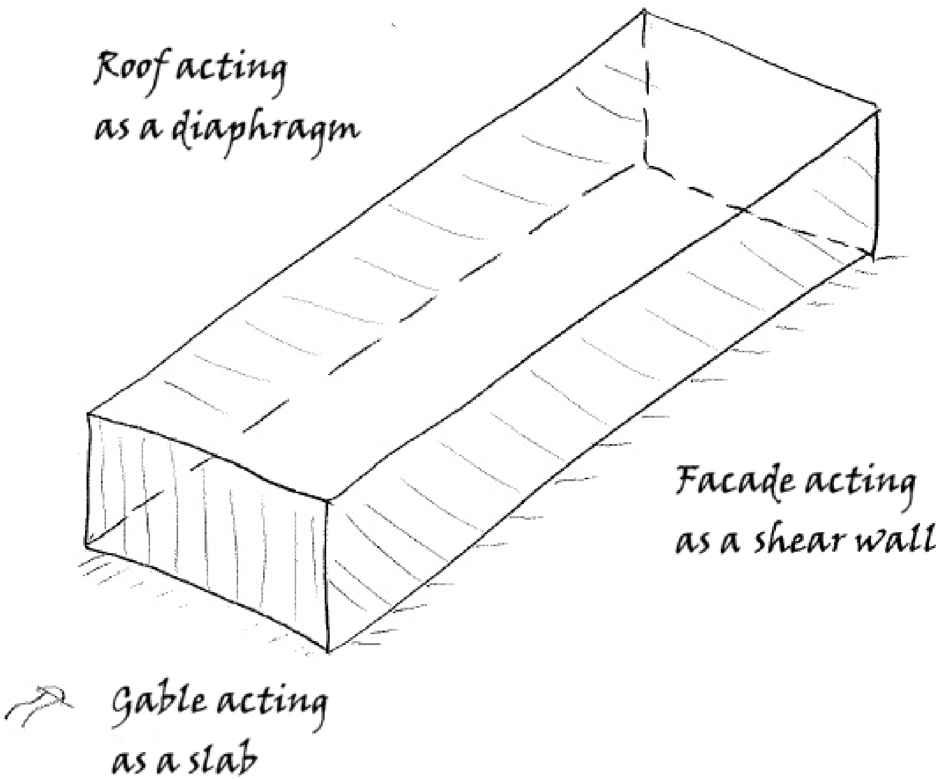


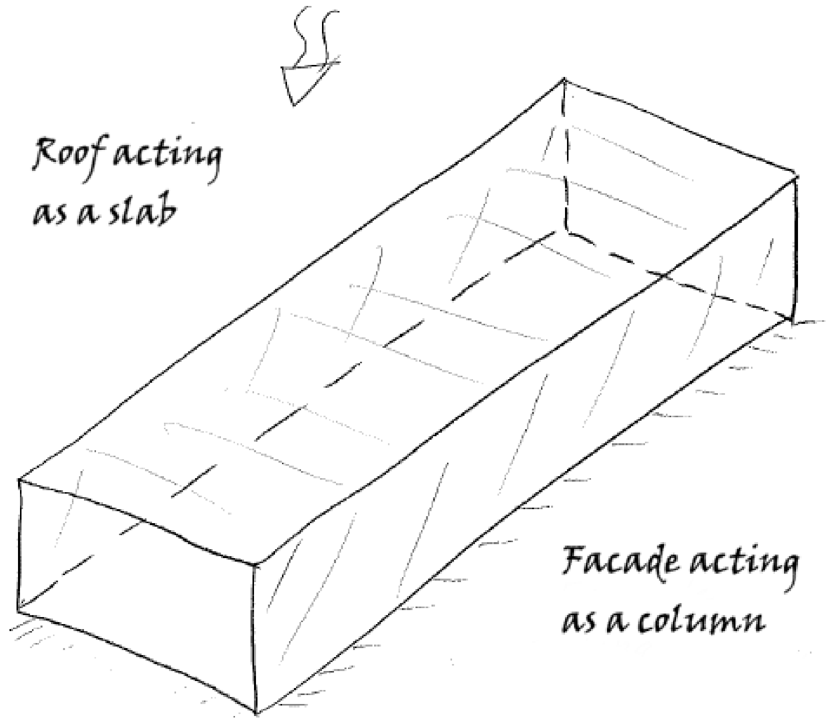
Type 3

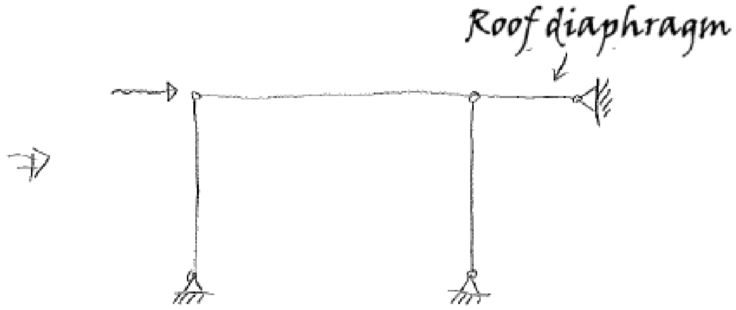
Examples of statical models:

Building 1:

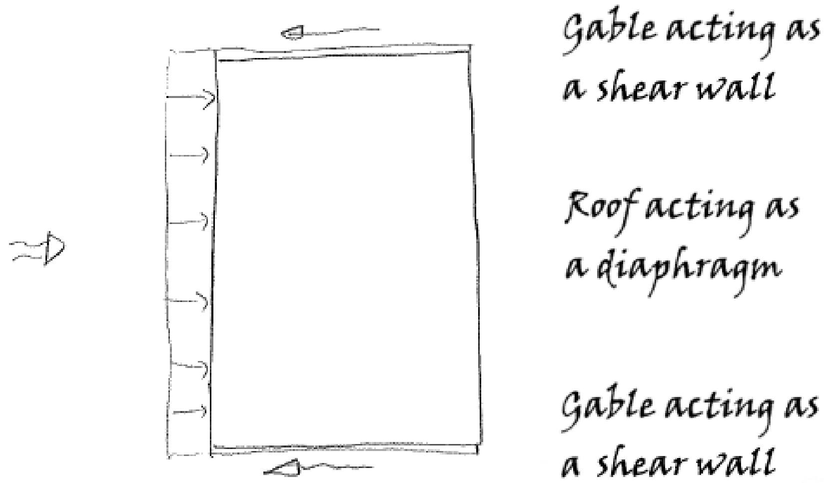






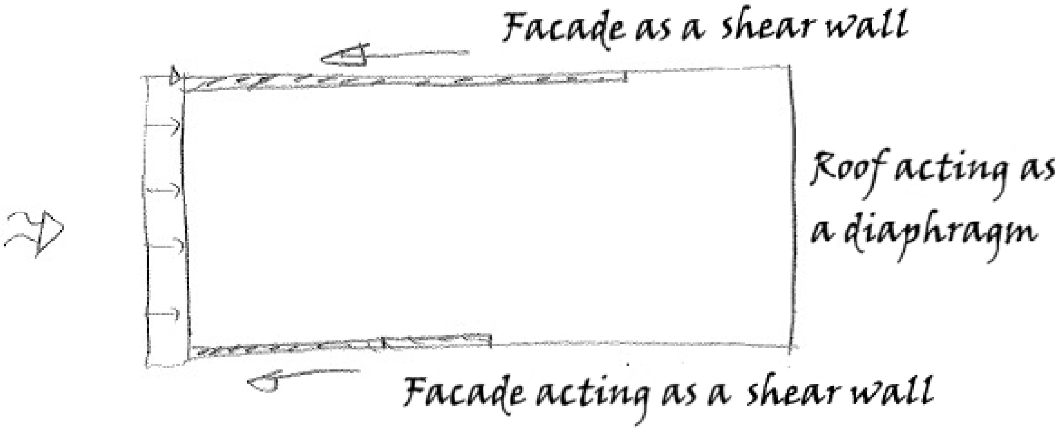


Cross section:



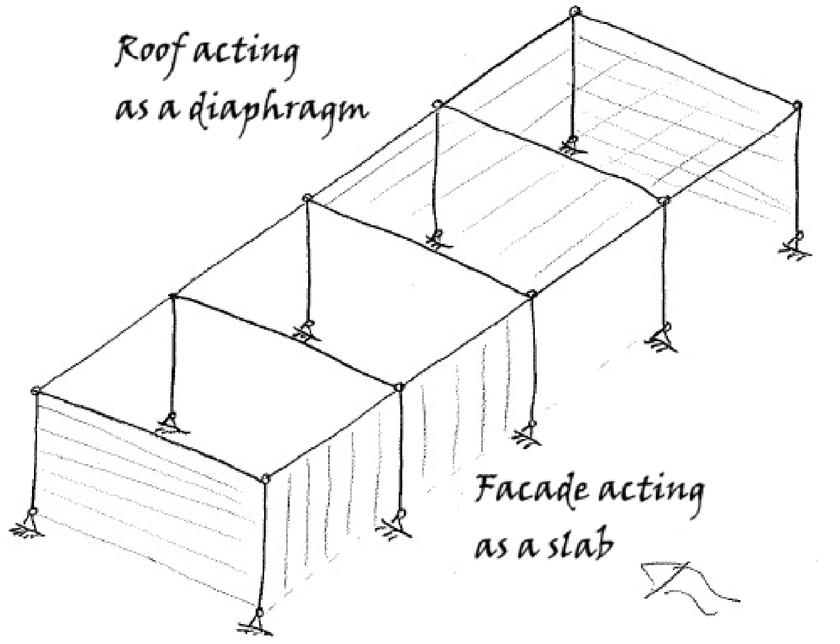
The roof diaphragm:

Longitudinal section:

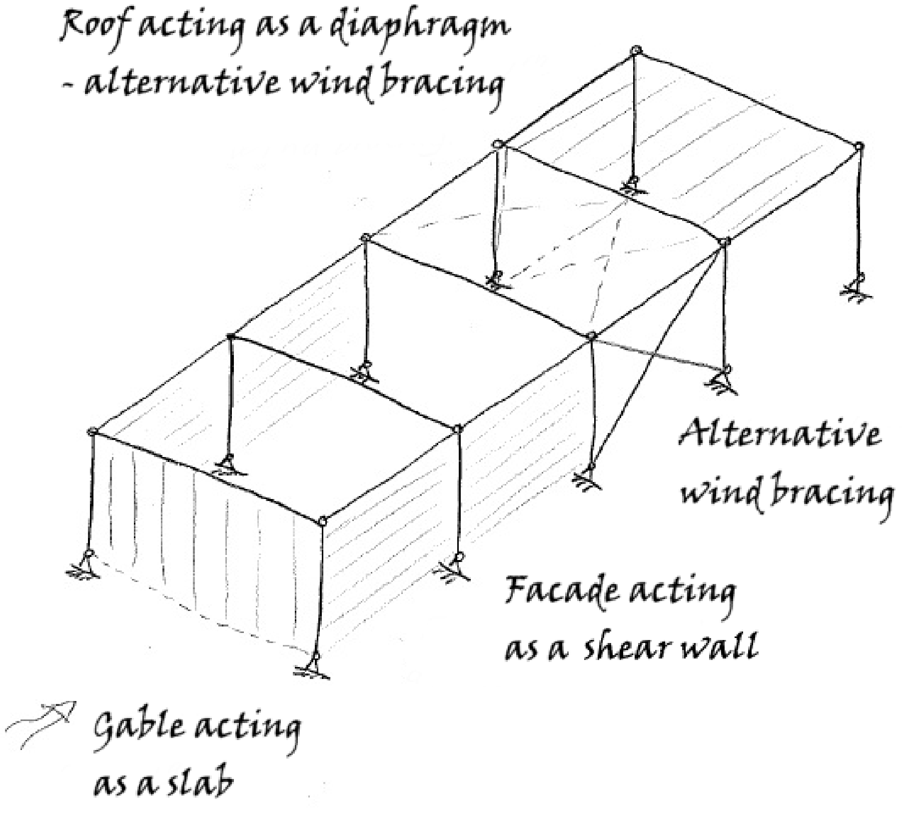


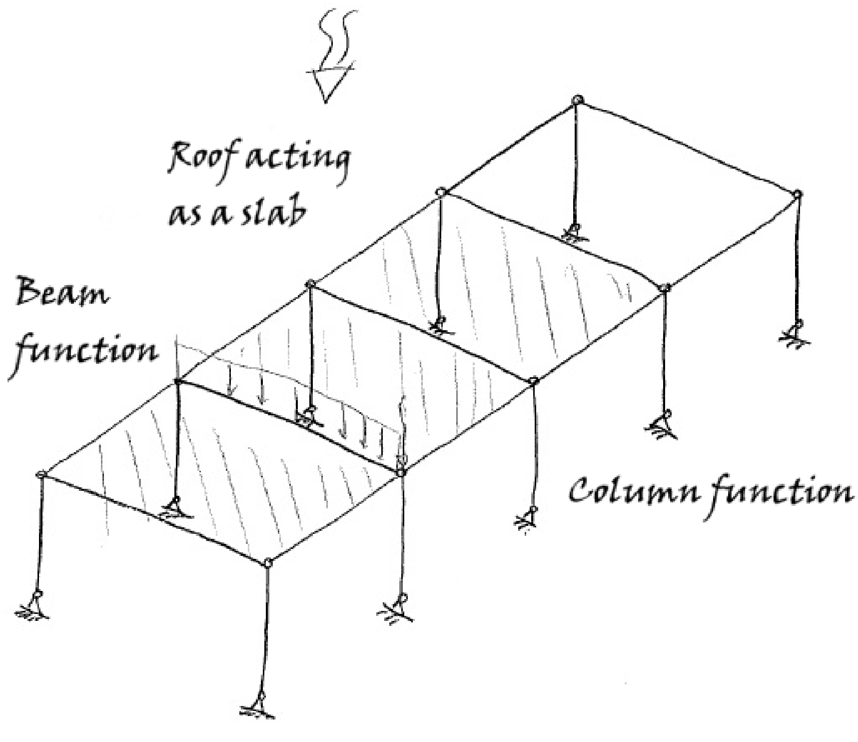
The roof diaphragm:

Building 2:



Gable acting as a shear wall
- alternative in gable and wind bracing

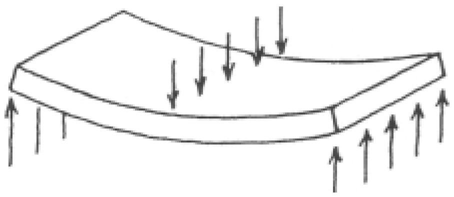

Roof acting as a diaphragm
- alternative wind bracing
Alternative
wind bracing
Facade acting
as a shear wall
Gable acting
as a slab


Roof acting
as a slab
Beam
function
Column function

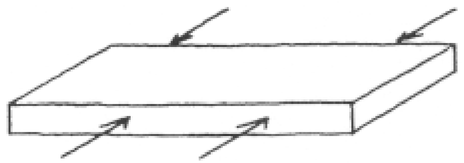
Transfer of forces through the structure

We make some demands for the 'statical' behaviour of the components.

Slab function - the ability to transfer loads perpendicular to the plan of the component.



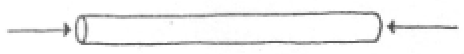
Wall function – the ability to transfer loads parallel with or just inside the plan of the element.



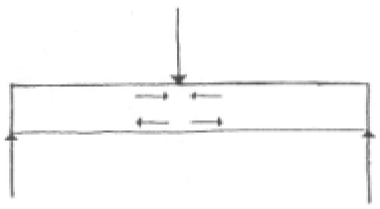
Vertical element: Shear wall function

Horizontal element: Diaphragm

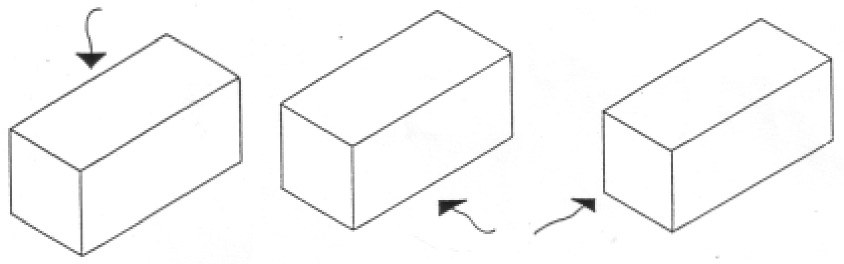
Column function – the ability to transfer loads parallel with the longitudinal axis.

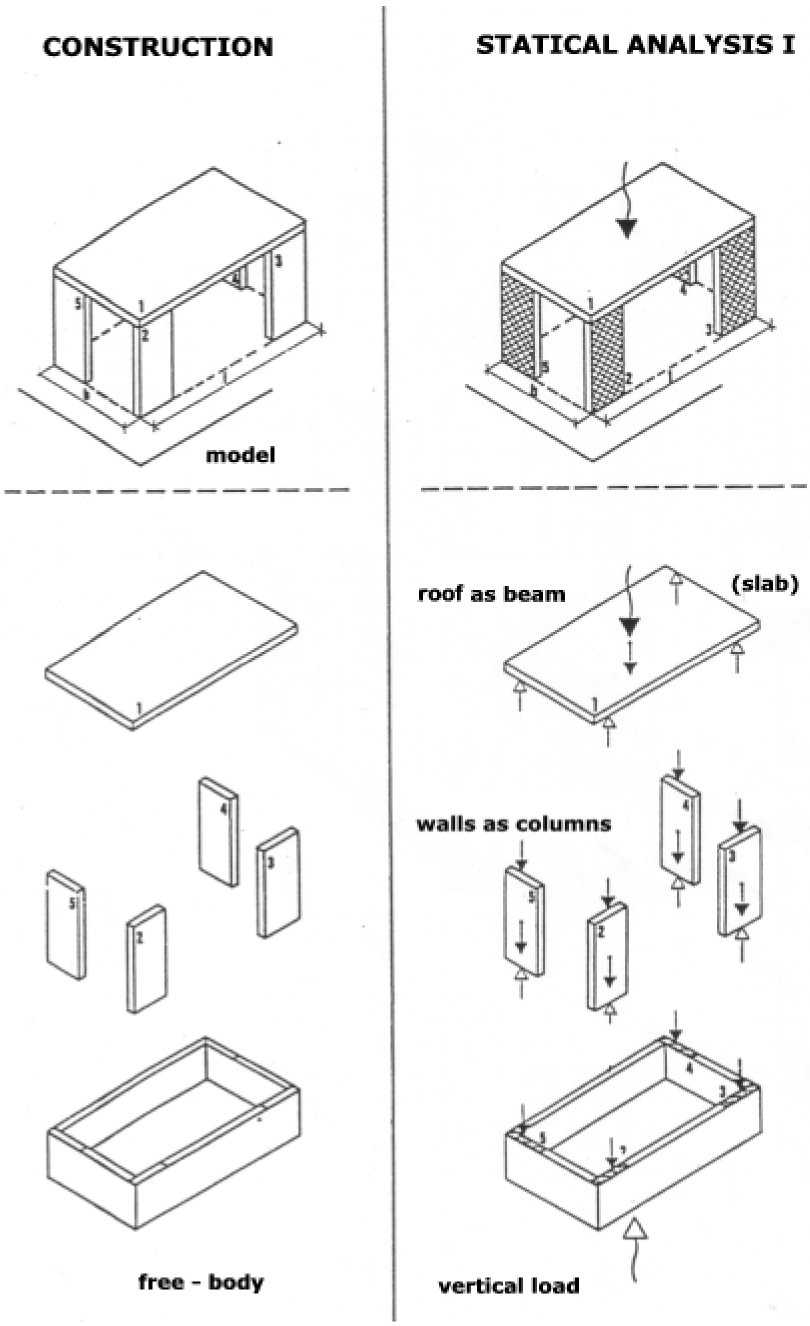


Beam function – the ability to transfer loads perpendicular to the longitudinal axis.

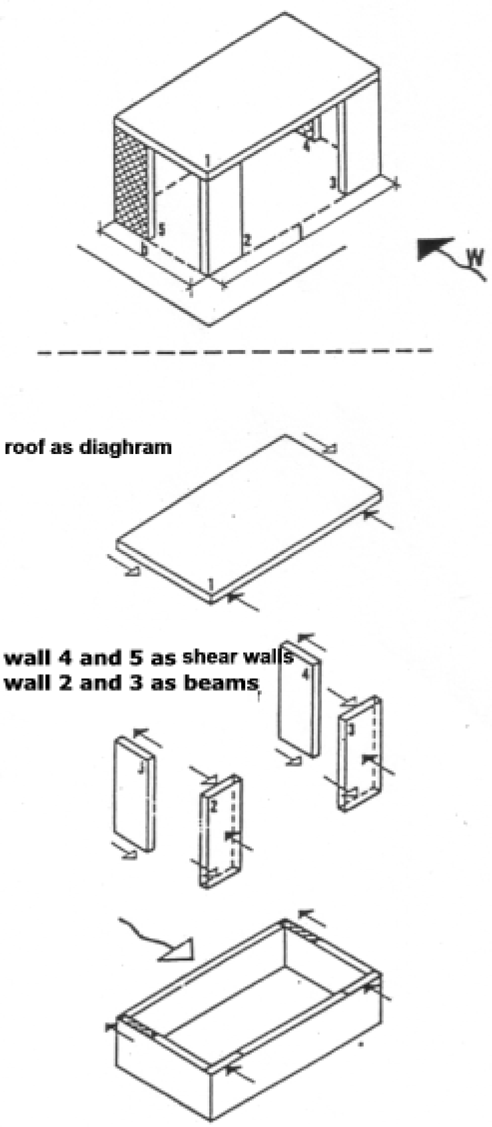


The methods of the analysis



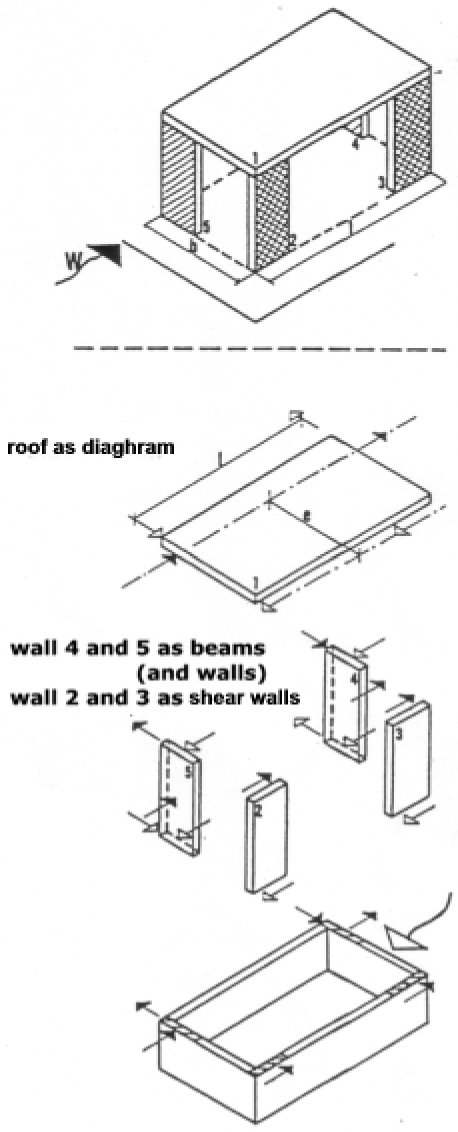


STATICAL ANALYSIS II

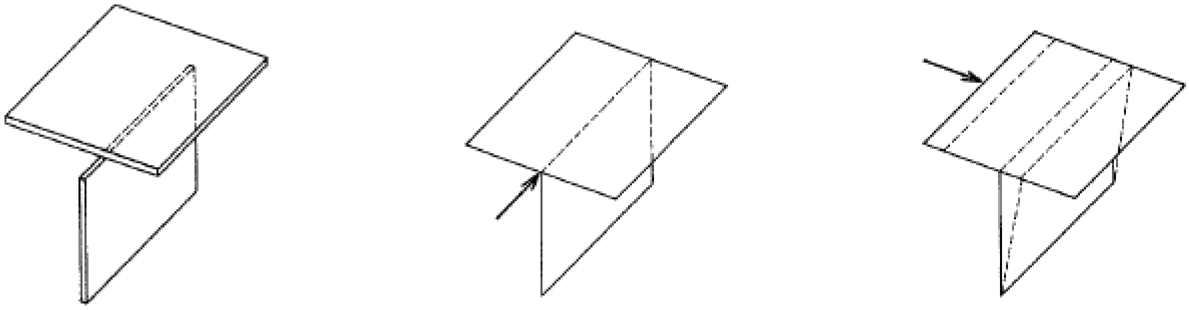


horizontal load ⊥ on facade

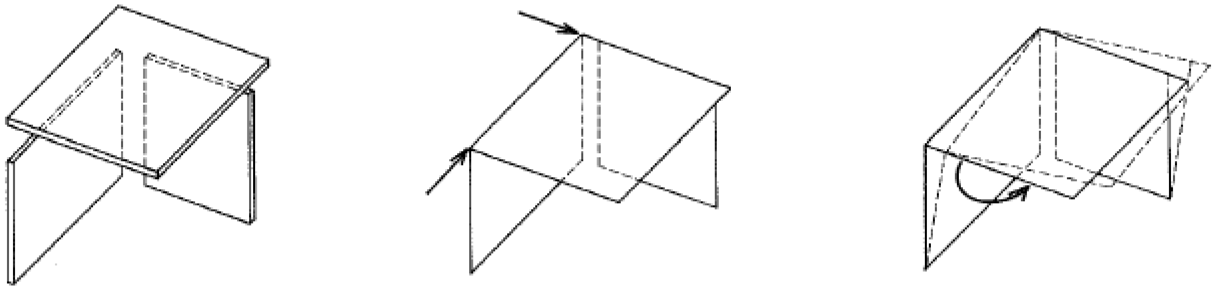
STATICAL ANALYSIS III



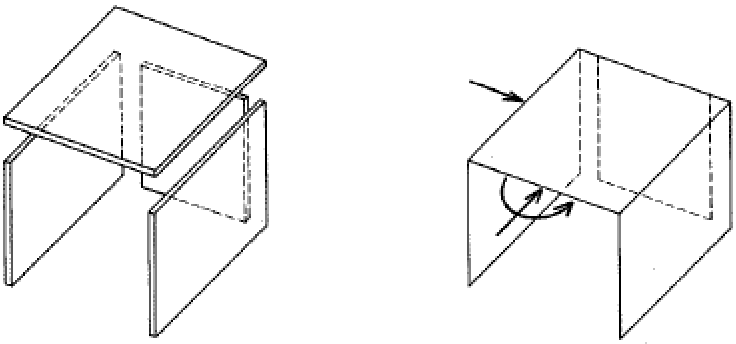
horizontal load ⊥ on gable



If the wall has 1 fixed support line it is unstable (moveable).



If the wall has 2 fixed support lines it is unstable (moveable).



If the wall has 3 fixed support lines it is stable.

We introduce some demands for 'statical' behaviour of the structure when determining how the forces are transferred.

Early in the outline proposal phase of a project, the transfer of forces should be determined in the overall statical system of the structure.

At this early stage of the project you are often not restricted by a certain choice of materials and therefore the determination of the transfer of forces can be done entirely by statical principles.
Thereafter, you can combine the building components to form a structure that is globally stable.

Principles

Global stability can be achieved by applying one or more of the following principles:

a) By setting up statical demands for the behaviour of the individual building components.

b) By using "self-bracing" building components in the structure

c) By using triangular bracing structures (additional structures).

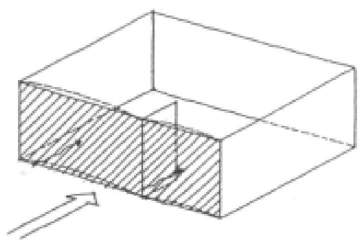
d) By identifying the transfer of forces from one building component to another.

ad. a)

Determining statical demands for the behaviour of individual building components.

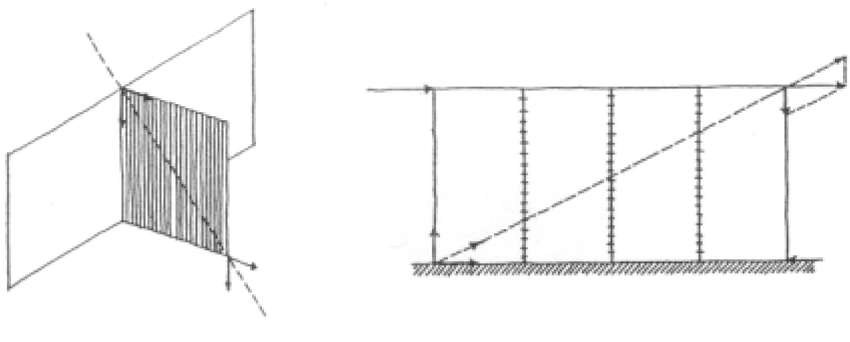
Slab function

The ability to resist loads perpendicular to the planar face.



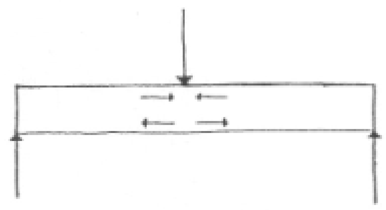
Wall function (shear wall, diaphragm)

The ability to resist loads in plane with the component.



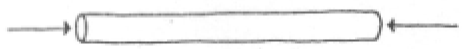
Beam function

The ability to carry loads perpendicular to the longitudinal axis.



Column function

The ability to carry loads within the plane of the element.

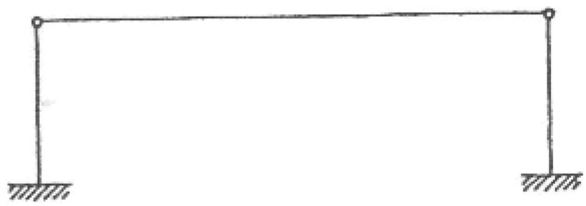


ad. b)

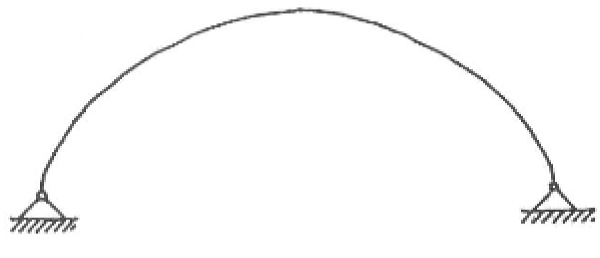
Self-bracing building components.

Some commonly used examples are:

Column-girder system with
cantilevered fixed columns.

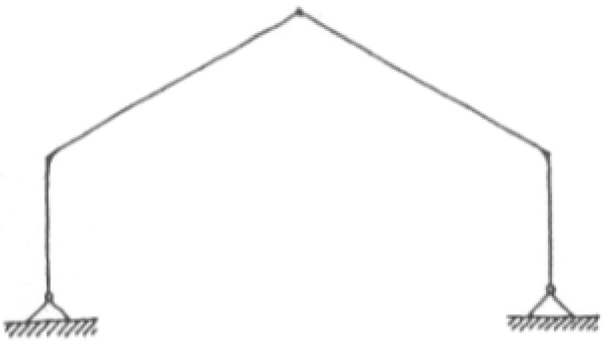


2 pin-jointed arch.



Flat-roofed portal frame with
rigid jointed corners.
(2 pin-jointed frame)

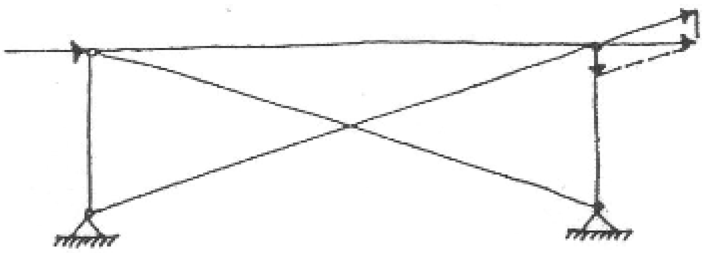
Pitched-roofed portal frame with
rigid jointed corners and pin-
jointed in the top.
(3 pin-jointed frame)



ad. c)

Triangular bracing structures

Diagonals work as tension
and/or compression bars. In the
structure they act as stable
simple triangles or trusses.

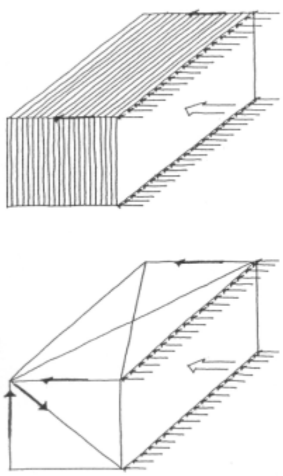


ad. d)

**Identifying the transfer of forces
from one element to another.**

This is essential for the design of the
load-transferring joints.

For instance:
- How are horizontal forces transferred from a diaphragm to the ends of the building (gables)?
- How is a force transferred from wind bracing to the structure below?



The individual building components

There are of course also demands for the stability of the individual building components.
The components will be additionally loaded by, for example, forces caused by temperature fluctuation, eccentrically acting forces due to deviation in execution etc.

These forces also need to be considered and this can be done later in the engineering design phase.

The examples below show how the transfer of forces can be identified and how they can be illustrated at the planning stage.

This can be performed in many different ways. Here two essentially different methods are shown.

Method A: A mixture of text and sketches.

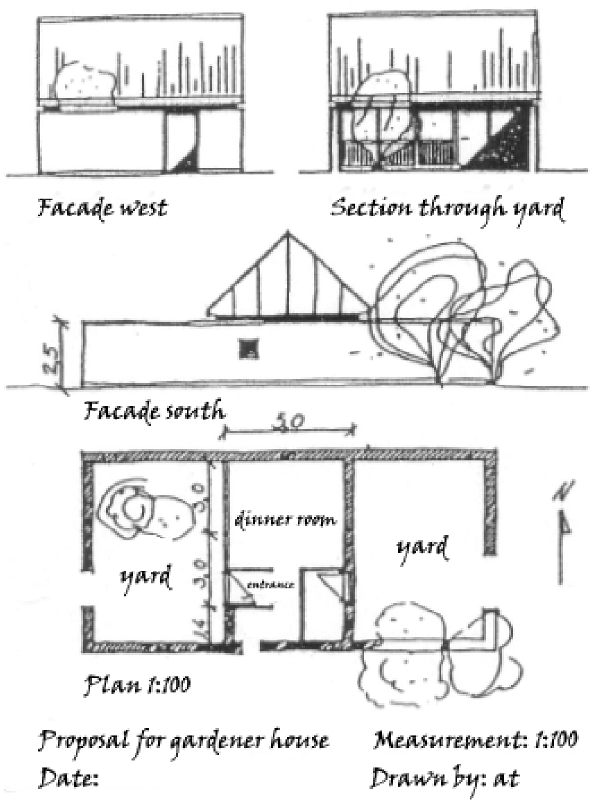
Method B: A strictly schematic form.

Example 1

Determination of the transfer of forces in a small single-storey building.

Outline - example

Extract of construction description



Roof construction:
Roofing tiles on battens/purlins with an underlay of plastic foil.
Wooden trusses - 45º roof inclination.
Ceiling- 19 mm tongue and groove boards.
200 mm insulation mats.

Masonry:
Outside: 350 mm thick cavity wall with insulation and steel wall ties.
Inside.: 11 cm thick wall.

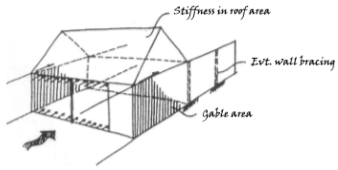
Light weight facades:
Timber frame.
200 mm insulation.
High impact external and internal cladding.

Method A

Proposal for the transfer of forces.

Wind load on facades

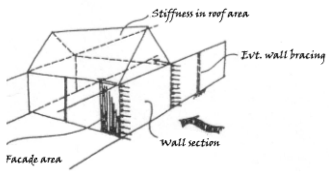
The load is transferred by slab function in the facade to the ceiling area (diaphragm) or the roof and the foundation of the facade.



Through the diaphragm action or stiffness of the roof area (shear function or wind bracing) the load is transferred to the gable areas which in turn transfer the load to the foundations of the gables by shear function.

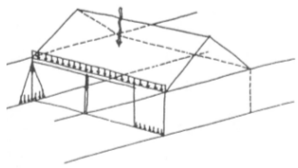
Wind load on gables

The load is transferred by the gable area to the facades and the roof and ceiling area by slab function. By shear wall/diaphragm action, the load is transferred to the facades which in turn transfer the load by wall function down to the facade foundations.



Vertical load

The load from the roof area is transferred through the trusses (beam function) to the facades and then through beams, columns and masonry to the foundations (column function).



Method B

Proposal for the transfer of forces.

Key:

BF = beam function

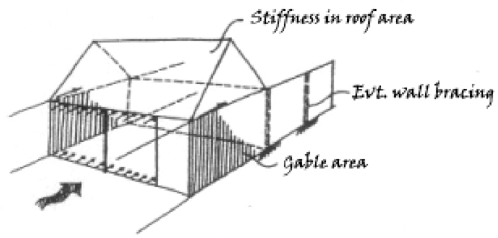
SF = slab function

CF = column function

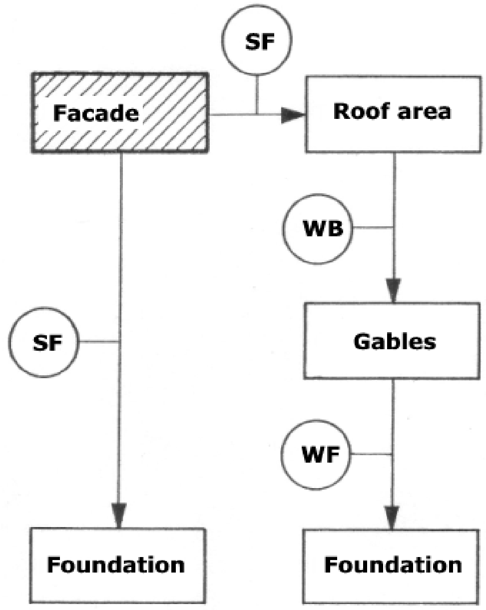
WF = wall function

WB = wind bracing

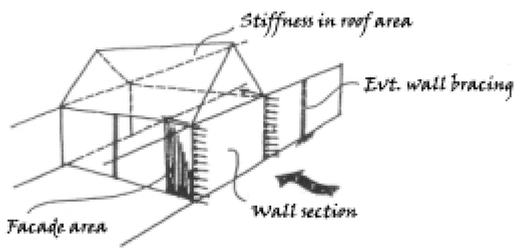
Wind load on facades

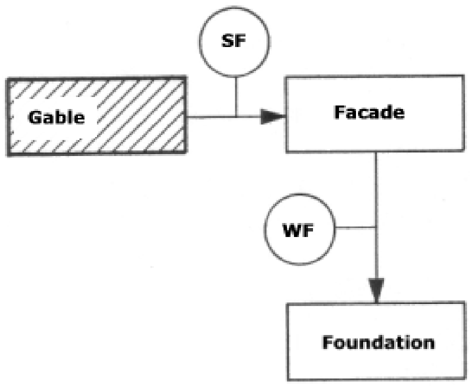


No diaphragm function in the ceiling area here!

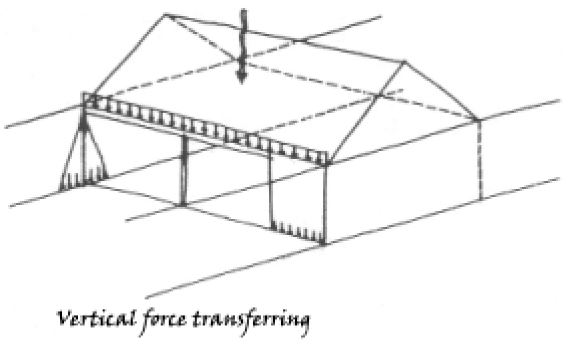


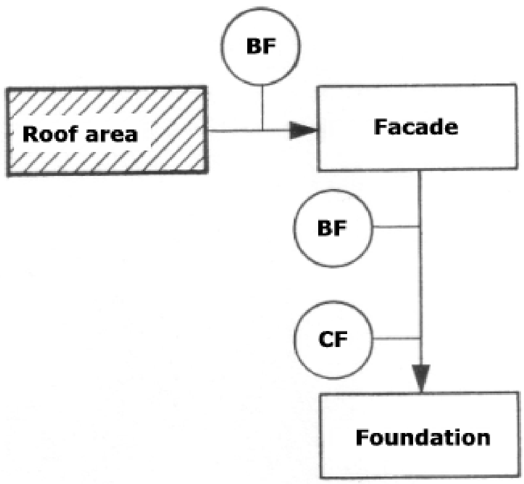
Wind load on gables





Vertical load





Example 2

Determination of the transfer of forces in a small single-storey hall building.

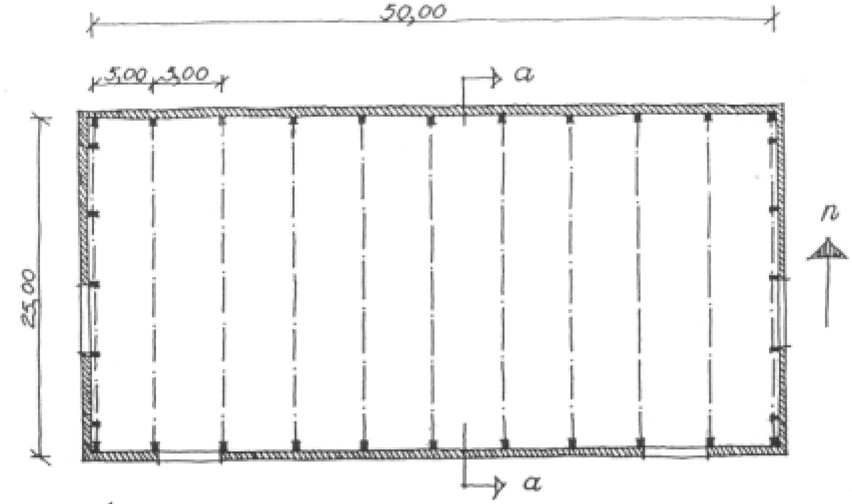
Outline - example

Extract of construction description

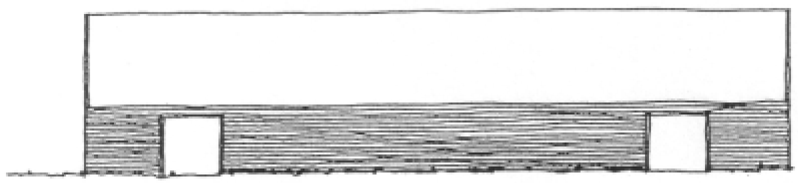
Load bearing structure:
3 pinned arch on pad foundations. Columns are provided along the gables

Roof construction:
Roofing felt on plywood on an underlay of 250 mm insulated roofing components with an exposed underside.

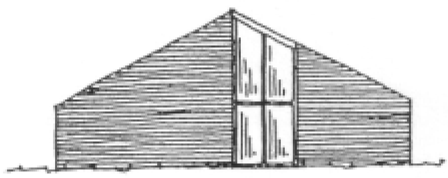
Masonry:
Outside: 400 mm cavity wall with insulation and steel wall ties.



plan

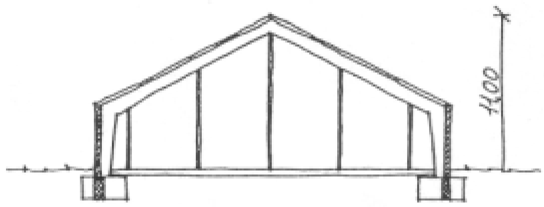


facade south



gable west

3 pin-jointed frame



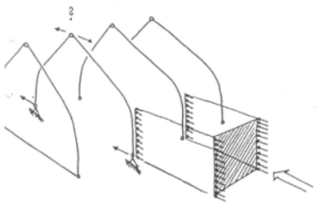
section a-a

proposal

Method A

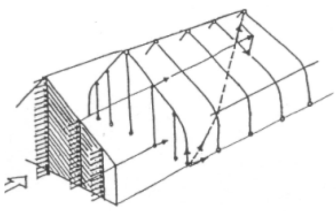
Proposal for the transfer of forces.

Wind load on facades



The load is transferred from the wall area by slab function to the 3 pin-jointed frames/arches and by their self stiffening function they transfer the load directly to the pad foundations in the facade.

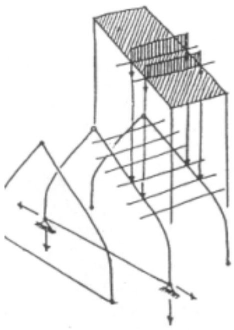
Wind load on gables



The load is transferred from the wall area by slab/beam function to the gable columns which act as windposts spanning vertically from the gable foundation to the roof area.

The load is transferred through the purlins in the roof area acting in compression (column function) and on to wind bracing (triangular bracing structures) and then by tension to the foundation of the facade.

Vertical load



The load from the roof area is transferred through the purlins (beam function) to the 3 pin-jointed frames/arches in the structure.

By beam-column function the arches transfer the load to the pad foundations of the facade.

Method B

Proposal for the transfer of forces.

Key:

BF = beam function

SF = slab function

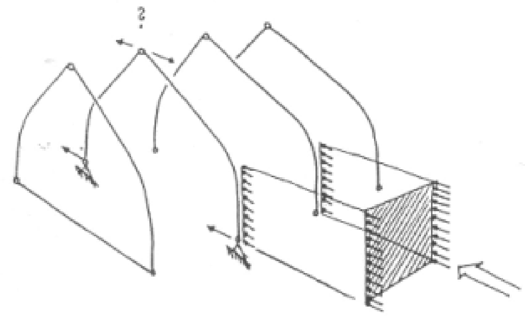
CF = column function

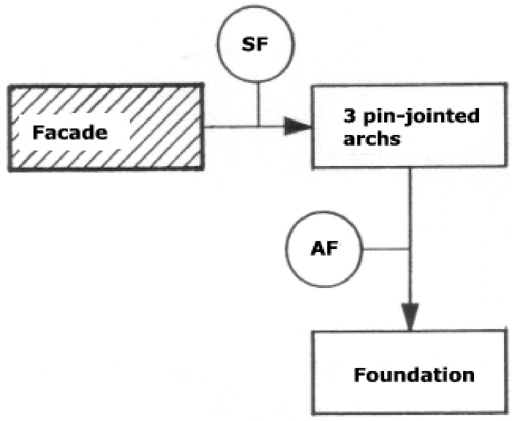
WF = wall function

WB = wind bracing

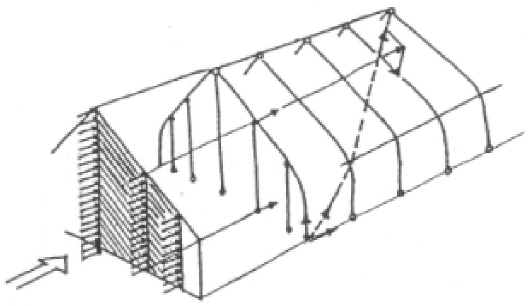
AF = self stiffening function

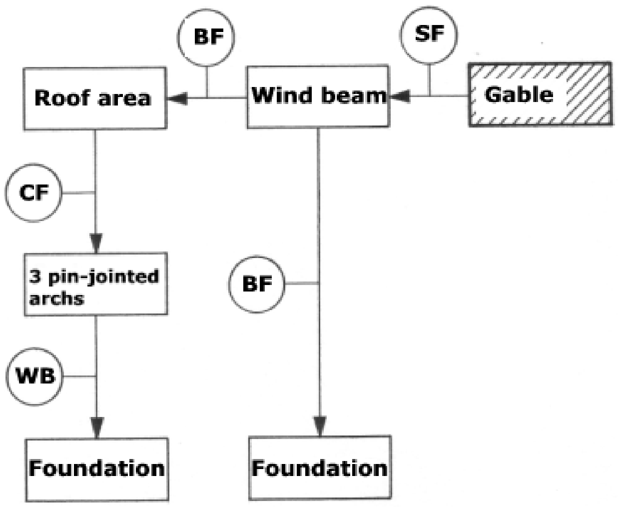
Wind load on facades



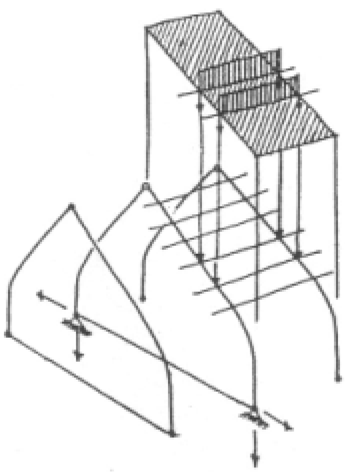


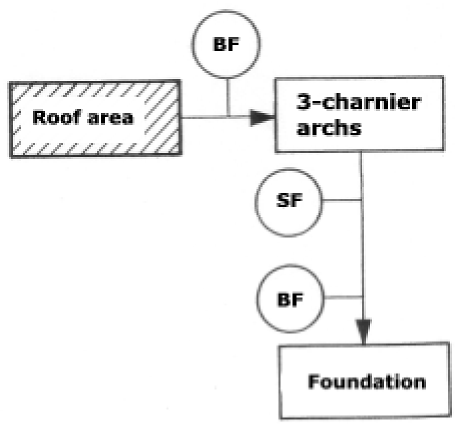
Wind load on gables





Vertical load





Example 3

Determination of the transfer of forces in a small two-storey building.

Introduction to example 3

Extract of construction description

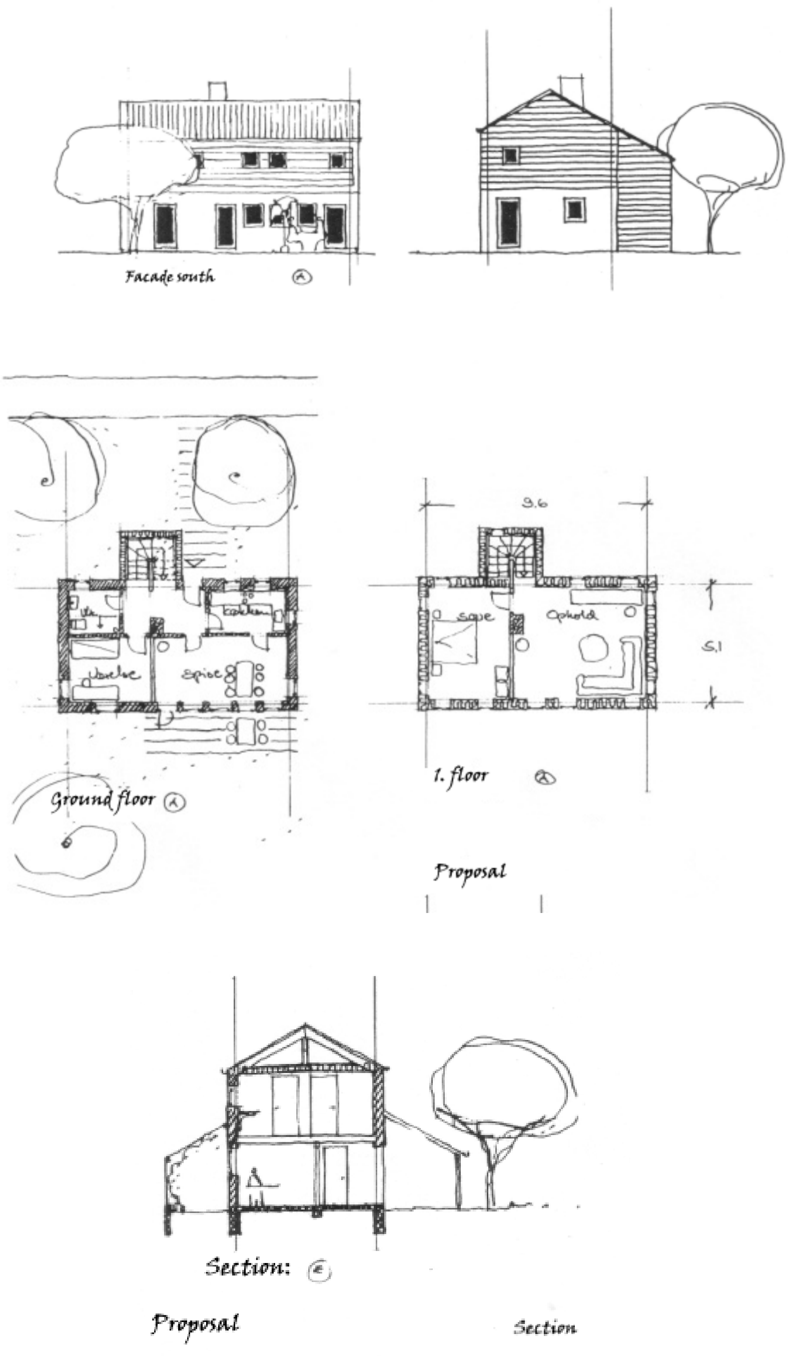
Roof construction:
Plywood on trusses.

Ceiling construction:
Class 1 facing with insulation.

Suspended floor:
Precast hollow core floor units.

Walls:
Ground floor:
External: Precast concrete sandwich elements
Internal: precast concrete elements

First floor:
Lightweight timber walls with external facing board and internal class 1 facing.

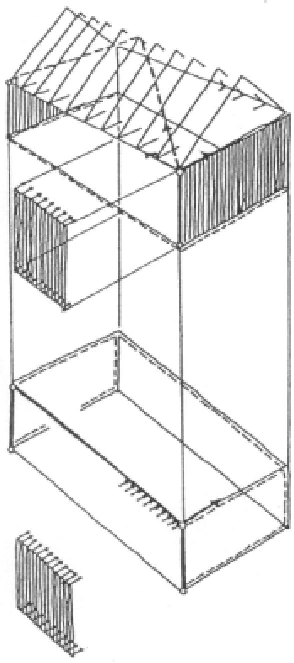


Design phase/feasibility-study.

Method A

Proposal for the transfer of forces.

Wind load on facades



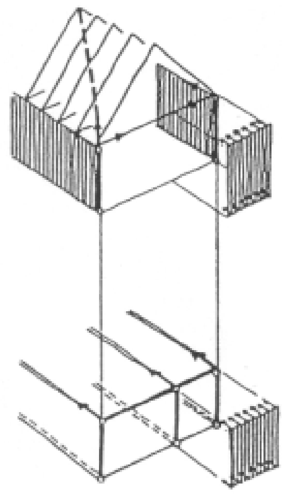
First floor:
The load is transferred from the wall area by beam function to suspended floor and roof area/ceiling area.

Through the wind bracing of the roof area or the diaphragm function in the ceiling area the load is transferred to the gable areas that by wall function transfer the load to the foundations of the gables.

Ground floor:
The load is transferred from the wall area by slab function to the foundation of the facade and the suspended floor.

Through the diaphragm function of the suspended floor the load is transferred to the gable areas that by wall function deliver the load to the foundations of the gables.

Wind load on gables



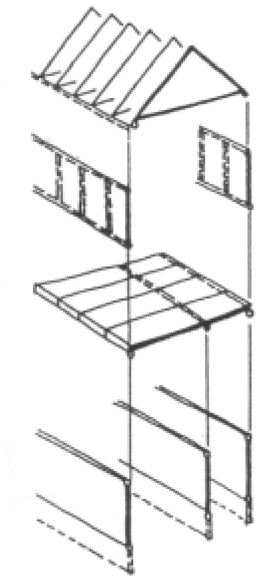
First floor:
The load is transferred from the wall area by beam function to the suspended floor and roof area/ceiling area.

Through the wind bracing of the roof area or the diaphragm function in the ceiling area the load is transferred to the facades that transfer the load to the foundations of the facades by shear (wall) function.

Ground floor:
The load is transferred from the wall area by slab function to the foundation of the gable and the suspended floor.

Through the diaphragm function of the suspended floor the load is transferred to the partition wall and facades. These walls then transfer the load to the foundations by shear (wall) function.

Vertical load



The load from the roof area is transferred by the trusses by beam/column function to the timber-framed facade that by beam- and column function transfer the load further down the structure

The load on the suspended floor is transferred by slab function to the facades and the partition wall and from here down to the foundation by column function.

Method B

Proposal for the transfer of forces to ground.

Key:

BF = beam function

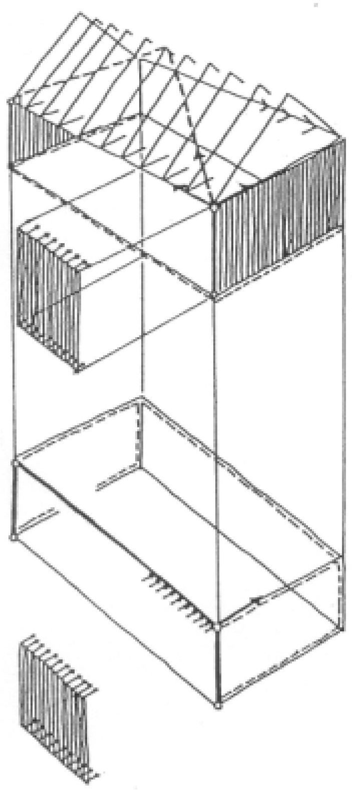
SF = slab function

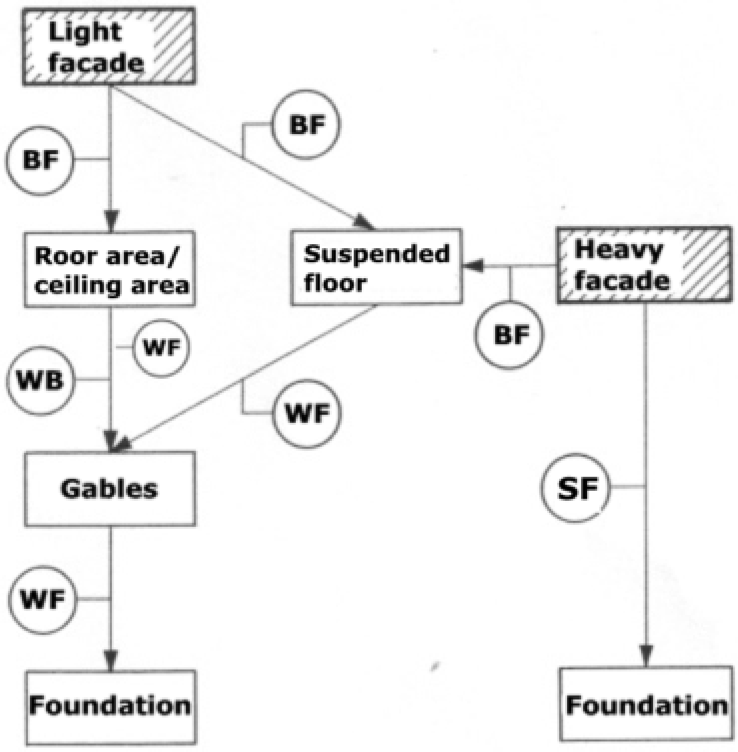
CF = column function

WF = wall function (shear wall or diaphragm function)

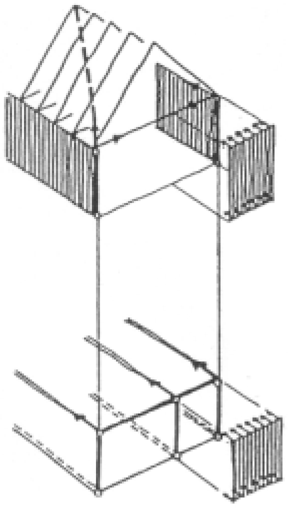
WB = wind bracing

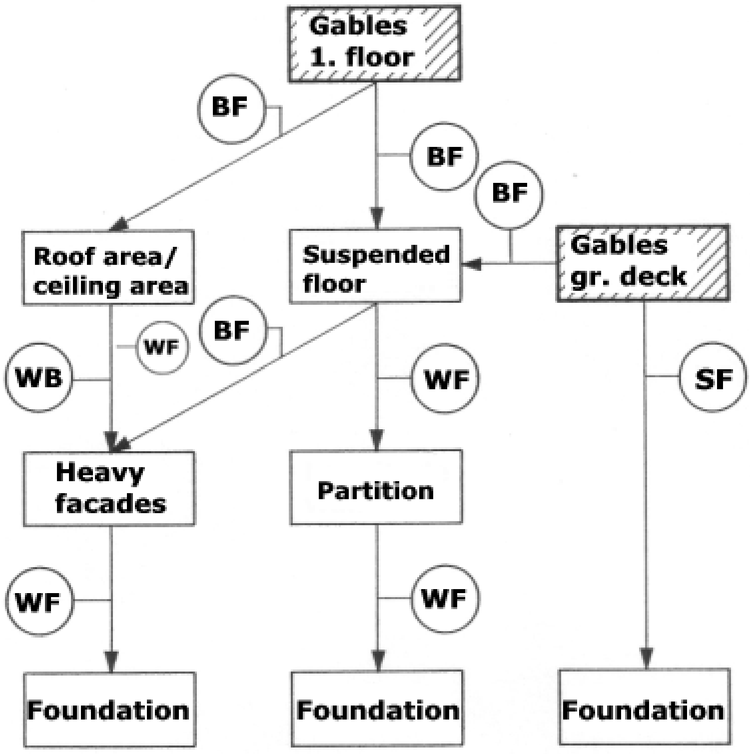
Wind load on facades



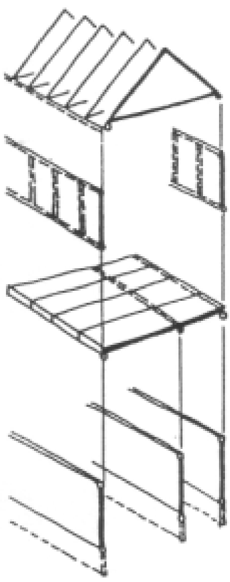


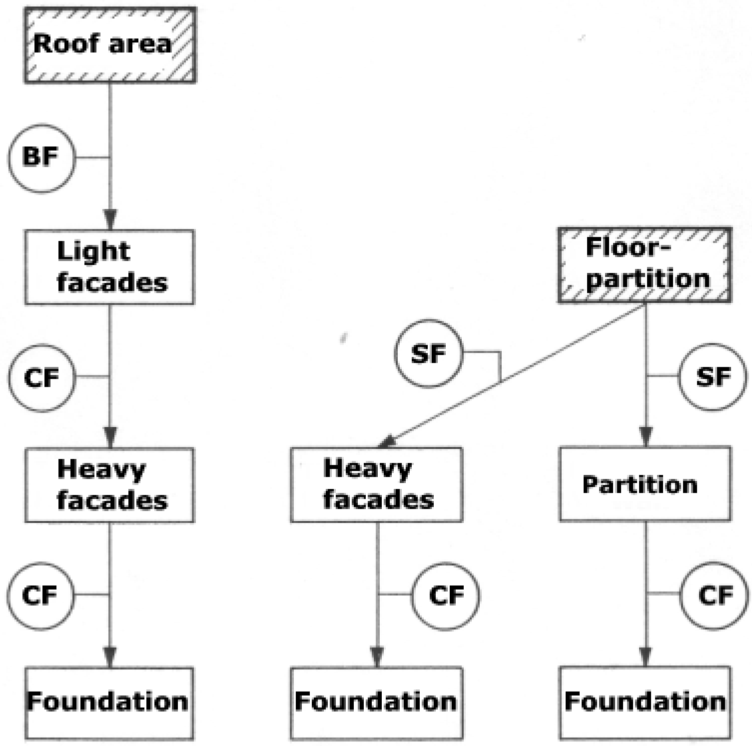
Wind load on gables





Vertical load

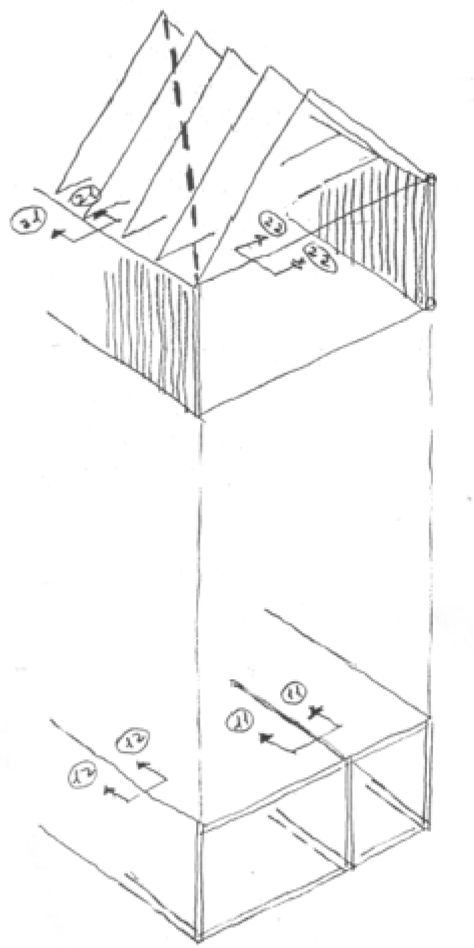


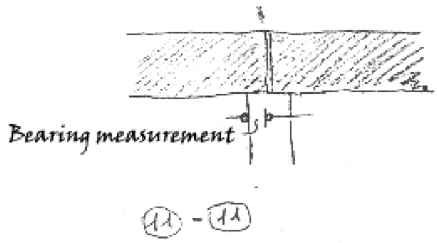


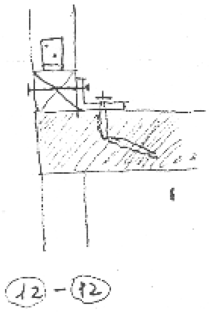
Force-transferring joints

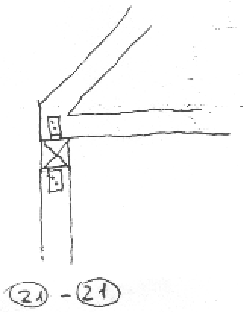
Due to our knowledge about the transfer of forces through the structure, we can now evaluate the force-transfer joints.

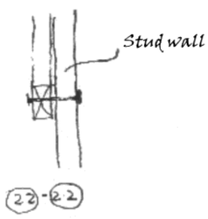
In the early phases hand sketches of the essential force-transfer joints are made. In this way the geometrical conditions (and restrictions) can be identified.
Thought must be given to the types of joints most suitable for your structure. Will you for example use mechanical connectors (for example bolted joints) Is there sufficient space for the connectors?
An approximation of the forces acting on the building components can be used to estimate the dimension of the individual elements and estimate the forces in the force-transferring joints.



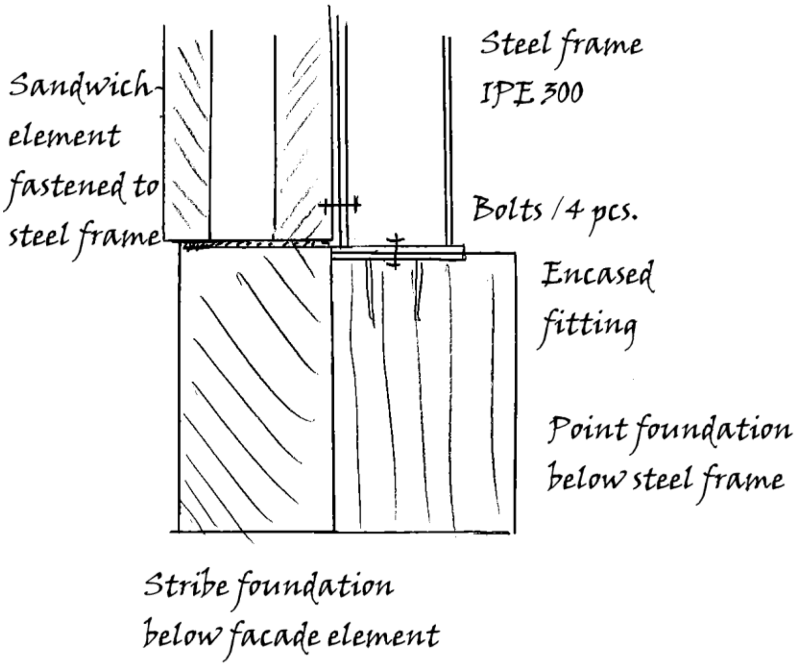




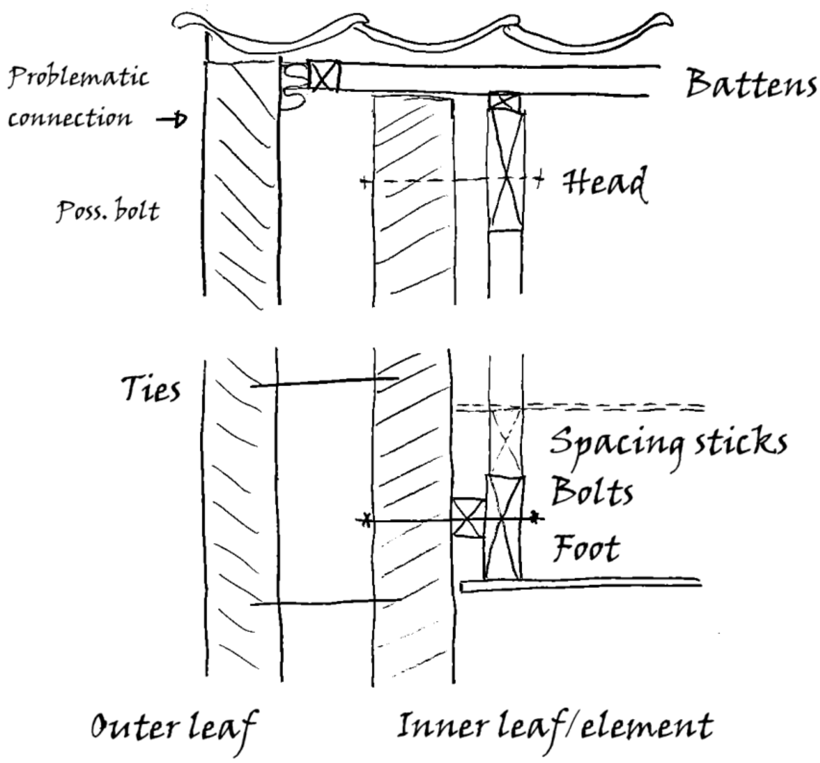




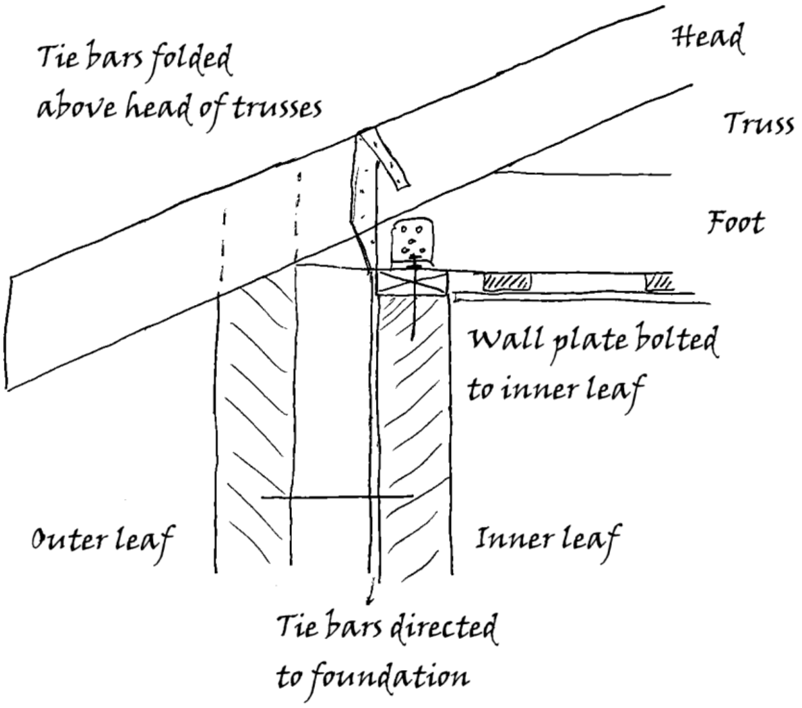
Connection between steel frame sandwich element and foundation



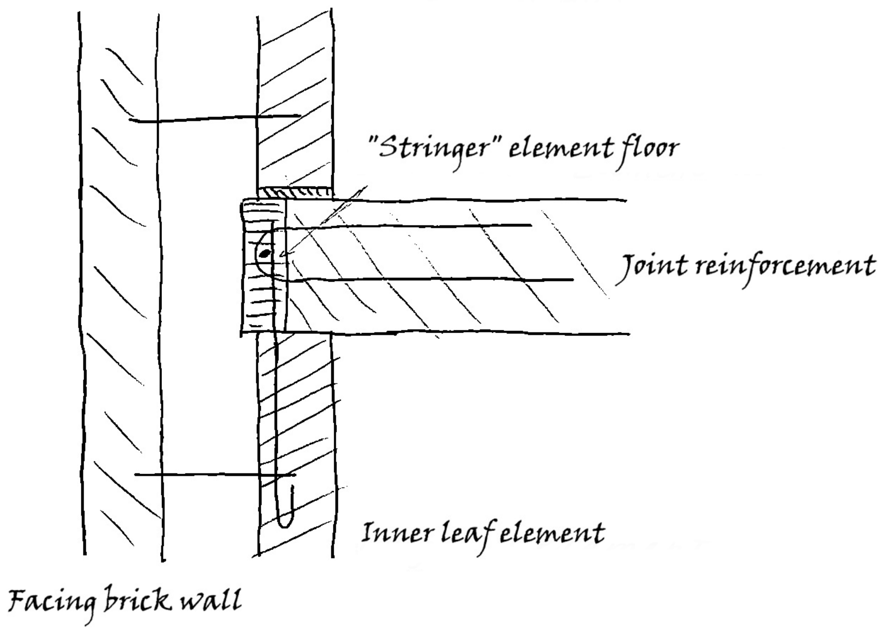
Connection between gable and roof construction - roof area



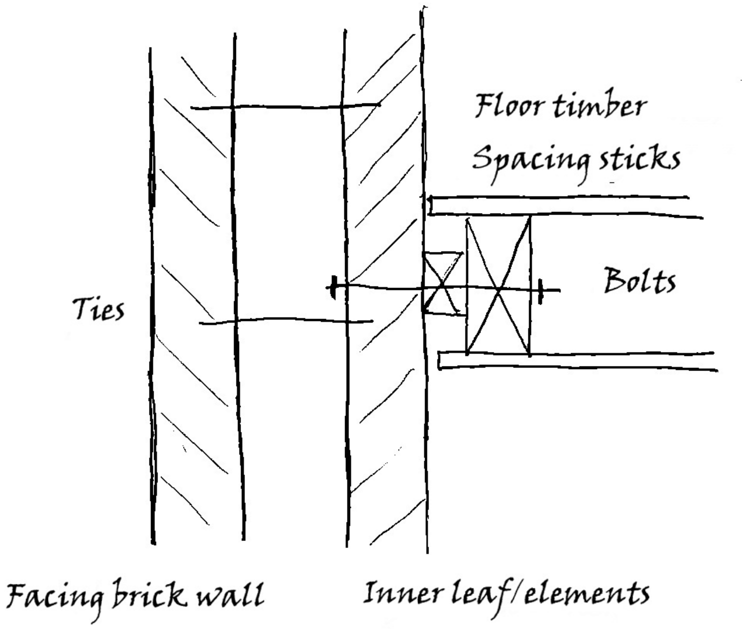
Connection between facade and roof



Connection between wall and floor partition



Connection between gable and floor partition



Structural components suitable for "wall" or diaphragm function.

Reinforced concrete:

In-situ Concrete.

Precast Concrete elements: Be aware of construction joints and the requirement for joint reinforcement.

Porous concrete:

Leca (trade name) , Siporex , Aerated concrete, etc.

Follow the manufacturers guidelines and specifications for general arrangements and joint requirements

Masonry:

Load-bearing masonry.

Non load-bearing masonry: Very problematic in particular in relation to the joints.

Timber:

plywood, particle boards, chipboard etc. Format at least 1,2 m x 2,4 m.

Plasterboard (Gypsum).

Timber-framed houses with steel tension rods.
Follow the manufacturer's instructions for general arrangements and joints. Often calculations are necessary to determine the numbers of nails and screws, etc. See also brochures and TOP-booklets.

Steel:

Thin trapezoidal metal sheeting.
Follow the manufacturers instructions.