Diaphragms and shear walls

STEP lecture B13
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Objectives
To explain in principle, the behaviour of structural diaphragms, such as floors and walls, in timber framed buildings and to present appropriate design methods.

Summary
Walls, floors and roofs in timber framed buildings are often sheathed using different types of sheathing materials and may be used as structural diaphragms in order to transfer lateral forces to the foundation. This lecture describes the structural behaviour of horizontal floor diaphragms as well as the behaviour of shear walls. Simplified design methods to be used in ultimate limit state are suggested.

Introduction
A building is subjected not only to vertical loadings, such as self weights and imposed loads, but also to horizontal loadings caused by wind or earthquakes. This lecture relates to structural behaviour under wind action. Wind has a number of effects on a building. Its direct action is to cause pressure on one or more of the faces and suction on the others. Figure 1 shows the principal distribution of wind loads on a building for wind direction perpendicular to the long side wall, see STEP lecture A3.

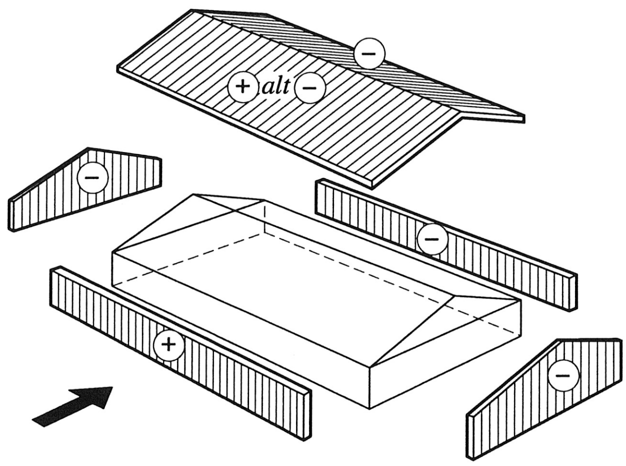

Figure 1 *External wind loads for wind direction perpendicular to the long side wall. The arrow shows the wind direction.*

The wind direction shown in Figure 1 results in pressure on the windward wall and the windward side of the roof and suction on the corresponding faces of the leeward side. A low pitch may result in suction on the windward side of the roof as well. Note, that the side walls are subjected to suction perpendicular to the wind direction. In addition to these principal wind loads, the wind may also cause suction or pressure on the inner faces of the building.

In order to transfer wind loads to the foundation, some form of wind resistant system is needed. Quite often the use of diaphragms and shear walls can provide an effective and economic design. The principal structural behaviour is illustrated in Figure 2 for a simple single storey box like building, exposed to wind perpendicular to the long side wall. The walls are assumed to be simply supported between the roof and the foundation. Hence, half of the total wind load acting on the long side walls is distributed into the horizontal roof diaphragm, which is assumed to act as a deep beam. The roof diaphragm is supported by the end walls, which transfer the forces to the foundation by their in plane shear action.

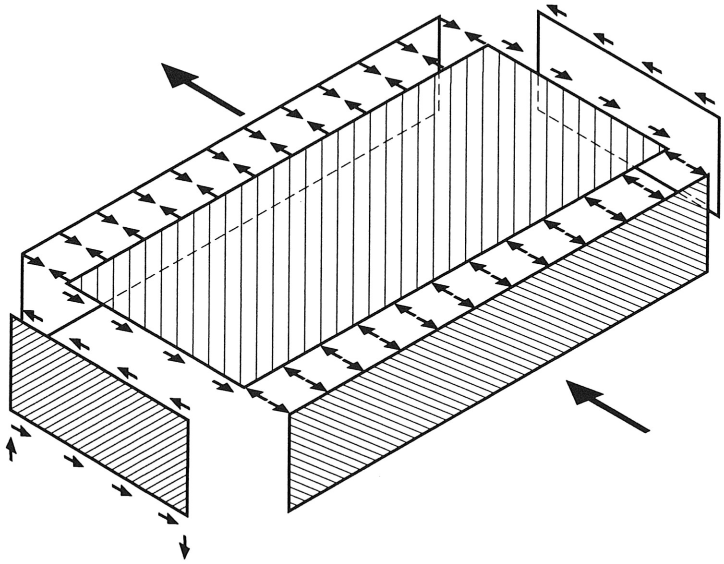

Figure 2 *Principal force distribution in a simple single storey box like building, where the roof acts as a horizontal diaphragm and the end walls as shear walls.*

The stabilising system in timber framed buildings consists of several components which must be properly fastened together to ensure that there is a complete load path for the shear transfer.

Horizontal diaphragms

Floors, ceilings and roofs may be used to transfer horizontal forces to the supporting walls. In timber framed buildings these structures are basically built up from timber joists sheathed with different types of wood based sheathing materials for floors and most commonly fastened to the joists by screws. The ceilings typically consist of one or two layers of gypsum plasterboard, either nailed directly to the roof trusses or joists or screwed to secondary spaced timbers, which in turn are nailed to the joists. These types of ceiling may also be used as structural diaphragms, see Alsmarker (1992). However, in this lecture only floor diaphragms will be discussed, see Figure 3.

This type of floor diaphragm may be assumed to behave in a similar way to a deep I-beam, supported through the struts by the walls running parallel to the wind direction. According to EC5 this may be assumed so long as the span is less than six times the width of the diaphragm. The sheathing acts as the web, resisting shear forces, while the chord members act as the flanges, resisting the applied bending moment. Figure 4 illustrates the principal behaviour.

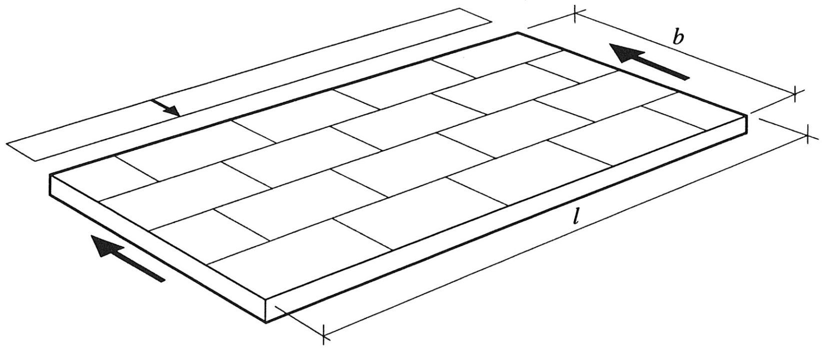

Figure 3 Horizontal diaphragm.

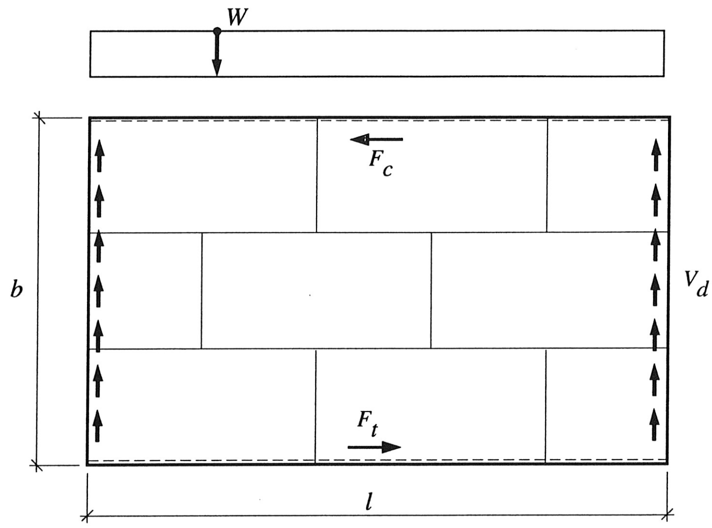

Figure 4 Principal behaviour of floor diaphragms.

For timber framed buildings, the double top plate of the walls is used as the chord member of the diaphragm. The plate members are lapped with staggered end joints and connected together by nailing or bolting. Alternatively, a continuous header or trimmer joist may be used as the chord. It is assumed that all of the bending moment is resisted through the chords. Hence, the chord members must be designed for tension or compression forces of

$$F_{t,d} = F_{c,d} = M_{max,d}/b \tag{1}$$

where M_{max} is the maximum moment and b is the width of the diaphragm.

The shear flow $q_{f,d}$ between the sheathing and the chord may be calculated as

$$q_{f,d} = F_{v,d}/b_c \tag{2}$$

where $F_{v,d}$ is the total shear force and b_c is the centre-to-centre distance between chords.

The sheathing must be designed to resist a shear flow of

$$v_d = F_{v,d}/b \tag{3}$$

where $F_{v,d}$ is the total shear force and b is the width of the diaphragm.

Finally the spacing of the fasteners connecting the sheathing to the joists is calculated as

$$s = R_d / v_d \tag{4}$$

where R_d is the design capacity of an individual fastener, and v_d the calculated shear flow.

For simply supported diaphragms, as shown in Figure 4, the shear force is transmitted from the diaphragm to the shear walls by the perimeter members, known as struts, at the end of the diaphragm. The shear force is assumed to be uniformly distributed along the diaphragm edge. The struts as well as the chords must be properly fastened to the top plate in order to transfer actual shear forces to the shear wall below. Where the sheathing is not directly fastened to these members, it is necessary to ensure that another load path exists.

For a wind direction perpendicular to the end wall the struts become chords and vice versa. Therefore, these members must be designed, including the nailed or bolted lap splices, to carry the strut forces as well as the chord forces. Where the chord and the strut also function as a header, they must be designed for a combination of vertical and axial loadings.

When using the suggested model it is assumed that the sheathing boards essentially act as one and hence the individual sheets should be blocked. The stiffness of the diaphragm will depend on the orientation of the sheets relative to the joists or blockings. Hence, the best performance is obtained from a floor with the sheets staggered rather than in a stacked configuration. However, the diaphragm is often used for wind bracing in two opposite directions. Staggering should therefore be oriented for the worst loading direction. The sheets are well restrained from buckling by the joists and their thickness is normally determined by gravity loads.

In the case of large holes in floor diaphragms, it is vital to ensure a path for the transfer of forces around the hole. Compression and tension forces can be transmitted by using blockings and steel straps respectively. To ensure the shear transfer it is essential that the sheets are properly nailed or screwed to the blockings and joists around the hole. The detailing of the different connections details is critical.

Shear walls

In general the walls in a timber framed building consist of vertical studs, spaced at a regular interval, forming a ladder type frame together with the top and bottom plates. The framework is usually sheathed on one or both sides with different types of sheathing material, nailed or screwed to the frame. Structurally the wall can be regarded as a cantilevered diaphragm loaded by a concentrated force applied at the top plate. Using the sheathing as a bracing this force may be transferred to the foundation in a very effective manner. Figure 5 illustrates the structural behaviour.

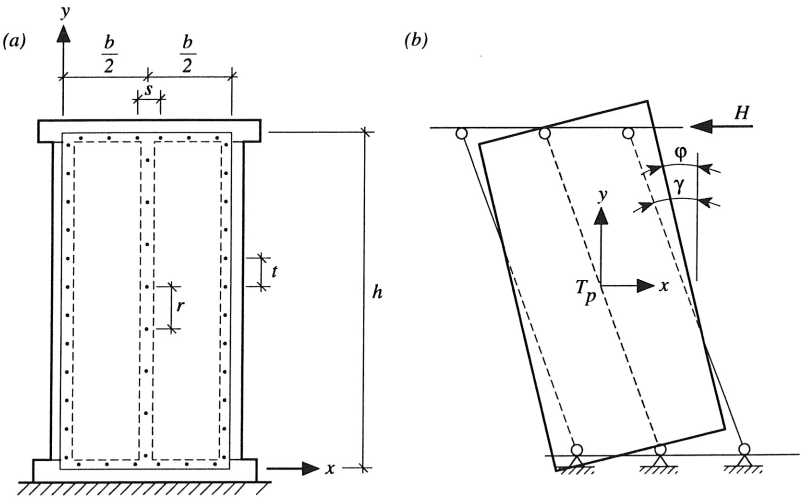

Figure 5 Typical wall unit. Principal structural behaviour.

The studs are fastened to the bottom and top plate by nails or other types of metal fasteners. From a structural point of view the frame joints can be regarded as being pinned. Hence, the displacement of the timber frame must be resisted by the sheathing and the fasteners connecting it to the frame. The most heavily loaded fasteners are located where the largest displacements occur between the frame and the sheathing, that is in the corners. In the upper corner to the left and the lower corner to the right fasteners will have force directions towards the free edge. The other two corners will have opposite force directions. In Figure 5 the studs are assumed to be fixed to the foundation. Whether the studs can be prevented from lifting from the foundation or not is often the most important factor influencing the shear capacity of wall diaphragms in timber framed buildings. In addition to appropriate fastening, vertical loads can be used to resist uplift and stiffen the panel. Apart from uplift, the studs must be designed for a concentrated compression force. The strength of the fasteners as well as the shear strength of the sheathing are other important factors that influence the load-bearing capacity of wall diaphragms. These factors would have further significance if it is necessary to consider the stiffness of the diaphragm and its horizontal in-plane deflection under load.

The total maximum load for a wall that is built up of several wall units, can be calculated in a simplified manner as the sum of the maximum loads for each unit, even where the wall units are built up from different combinations of sheathing materials and fasteners. However, where there are different combinations of sheathing materials and fasteners on the two sides of the framework, according to EC5, only half the load carrying capacity of the weaker side should be used. When there are window or door sections in a wall, these sections should be disregarded in calculating the load-bearing capacity of the entire wall.

A rather simple model may be used to calculate the internal force distribution between fasteners connecting the sheathing to the framework. This model assumes linear elastic behaviour of the fasteners, hinged connections between individual beam elements and that uplift is prevented. Furthermore, the beam elements as well as the sheathing are considered to be completely stiff against bending and elongation in the loading plane. Taking these assumptions into consideration, the internal force distribution may be calculated as

$$F_{xi} = \frac{H h y_i}{\sum y_i^2} \quad \text{and} \quad F_{yi} = \frac{H h x_i}{\sum x_i^2} \tag{5}$$

where F_{xi} and F_{yi} are the force components in x- and y-directions respectively for a fastener in position (x_i, y_i).

The total force is simply given by

$$F_i = \sqrt{F_{xi}^2 + F_{yi}^2} \tag{6}$$

where

x_i, y_i	are the co-ordinates for the actual fastener.
H	is the total shear force on the wall unit.
h	is the height of wall unit.
Σx^2_i, Σy^2_i	are the sum of the squared distances for all fasteners.

The ultimate design condition is failure in the most heavily loaded fastener, which is located at the corners of the panel.

EC5: Part 1-1: 5.4.3a

According to EC5 the racking load carrying capacity of the panel is calculated as

$$F_{v,d} = F_{f,d} \; b/s \tag{7}$$

where $F_{f,d}$ is the design capacity per fastener and s is the spacing of the fasteners. In this model the applied force is uniformly distributed over the fasteners connecting the sheathing to the top plate and does not account for concentrated forces at the corners of the panel.

EC5: Part 1-1: 5.4.3d

The tensile studs and the anchorage should be designed for a force $F_{t,d}$, where

$$F_{t,d} = F_{v,d} \; h/b \tag{8}$$

and the compression studs should be designed for a force:

EC5: Part 1-1: 5.4.3b

$$F_{c,d} = 0{,}67 \; F_{t,d} \qquad \text{for sheathing on both sides, or} \tag{9}$$

EC5: Part 1-1: 5.4.3c

$$F_{c,d} = 0{,}75 \; F_{t,d} \qquad \text{for sheathing on one side} \tag{10}$$

The end studs of the shear wall as well as the bottom plate must be adequately anchored to the foundation in order to resist uplift forces and shear forces respectively. In multi-storey buildings the shear walls must be connected to each other in a manner that allows these forces to be transmitted through the different levels of the building.

Design example

Calculate the horizontal design capacity H_d for the wall unit in Figure 5, where b = 1200 *mm* and h = 2400 *mm*. The spacing of the fasteners are as follows: s = 150 *mm*, t = 150 *mm* and r = 150 *mm*. The design capacity, $F_{f,d}$, for a single fastener is 0,2 *kN*.

$$\Sigma x^2_i = 30 \cdot 600^2 + 4 \cdot 150^2 + 4 \cdot 300^2 + 4 \cdot 450^2 + 4 \cdot 600^2$$
$$= 13{,}5 \cdot 10^6 \, mm^2$$

$$\Sigma y^2_i = 6 \cdot 150^2 \cdot (1 + 2^2 + 3^2 + 4^2 + 5^2 + 6^2 + 7^2) + 18 \cdot 1200^2$$
$$= 44{,}82 \cdot 10^6 \, mm^2$$

The force in x- and y-direction for fasteners located in the corners are

$F_{x,d} = 0,5 \cdot H_d \cdot 2400^2/44,82 \cdot 10^6 = 0,0643 \cdot H_d$

$F_{y,d} = 0,5 \cdot H_d \cdot 1200 \cdot 2400/13,5 \cdot 10^6 = 0,107 \cdot H_d$

which gives the total force as

$F_i = 0,125 \cdot H_d$

and

$H_d = 1,6\ kN$

For the actual wall unit, the same result is obtained if using the EC5 method.

Internal walls

The distribution of horizontal loading to the internal walls is governed by the stiffness of the diaphragm relative to the stiffness of the walls. Assuming a rigid diaphragm supported by flexible walls is one extreme of the solution, and a flexible diaphragm supported by stiff walls another.

In the first case the horizontal loading is distributed to the shear walls according to the relative stiffness of the walls. For a diaphragm supported by three walls of equal stiffness, each wall will resist one third of the total load. Note, that if the internal wall is not placed in the centre of the diaphragm, the torsional component must be accounted for as well.

Assuming a flexible diaphragm supported by stiff walls the question is whether the diaphragm may be regarded as a horizontal beam spanning continuously over intermediate supports or as separate beams being simply supported. The conservative approach is to design the end walls assuming the simply supported condition and the interior wall based on continuity.

The case of timber diaphragms on timber shear walls is in between the two extremes and the assumption of a rigid floor diaphragm should be used with caution. The assumption of a rigid diaphragm should only be used for a plan aspect ratio near unity, related to the diaphragm depth, b, divided by the span between internal walls, l.

Concluding summary

- All of the components of the shear wall and diaphragm system must be adequately fastened together so that the structure acts as an effective unit.

- Floor diaphragms may be assumed to behave similarly to a deep I-beam.

- The assumption of rigid floor diaphragms should be used with caution.

- Wood shear walls can be regarded as cantilevered diaphragms loaded by a concentrated force applied at the top plate.

- Shear walls must be prevented from lifting from the foundation by adequate anchorage at the end studs to comply with EC5 design rules.

Reference

Alsmarker, T. (1992). Gypsum Plasterboards as Wind Bracing Elements in Timber Framed Buildings. Lund Institute of Technology, Dept. of Structural Engineering.