Bracing of structural systems

STEP lecture E14
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Objectives

To develop an understanding of the minimum requirements for bracing of structural systems and to give some examples of bracing elemenets in practical use.

Summary

The lecture begins with the minimum requirements for bracing structural systems. It presents the calculation of the load distribution in unsymmetrical statically indeterminate systems and shows the different elements used for bracing. The bracing of a roof structure is detailed as an example.

Introduction

Structural systems must be designed to carry lateral loads caused by wind and/or earthquakes. Together with lateral bracing forces the load-carrying capacity of structures to resist wind-loads is discussed in detail and the problems of resistance against earthquake loads are shown in a qualitative manner.

Bracing criteria

Lateral load resisting systems consist of vertical elements or a combination of vertical and horizontal elements. The minimum criteria are shown in Figure 1:

- Together with a horizontal diaphragm three vertical elements are required. The elements, or their line of action, must not intersect at one point. Nor must they all be parallel to one another.
- Without a horizontal diaphragm four vertical elements are required, which only two of these elements are allowed to cross at one point.

More parts of the structural system could be added to this "basic box", which when braced as described allows the lateral loads to be transferred partly or completely to the foundations through the elements.

The bracing shown in the Figure 1 gives balanced situations (e.g. wind loads along the narrow side of the building). If the horizontal loads are not centred, torsional situations occur which lead to additional forces and deformations.

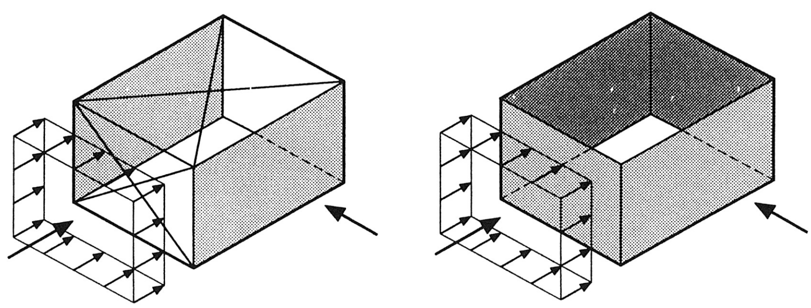
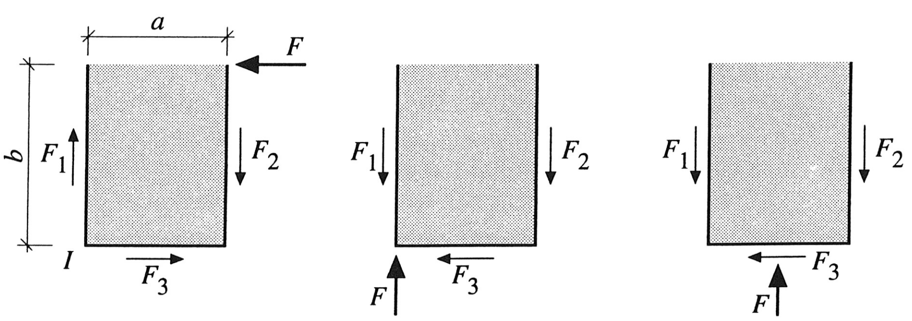


Figure 1 Bracing of a structural system - minimum requirements.

Bracing - geometrical location

Bracing elements of a structural system should be located in such a way, that symmetrical systems are created. Otherwise the centre of resistance will not coincide with the centre of pressure of the loads and additional torsional loads have to be taken into account. This may be ignored for buildings up to two storeys in timber frame construction, if vertical shear wall units are located in a minimum of four circulating walls (Brüninghoff et. al., 1989). Support loads to continuous horizontal diaphragms may be calculated assuming a number of non-continous two-hinged beams. The bracing elements should be of the same stiffness for each direction of lateral loads, otherwise an additional excentricity has to be taken into account. The calculation method given in Figure 2b is only valid for an equal stiffness per unit length of all wall diaphragms. For a more detailed calculation with regard to displacements due to bending, shear and slip in joints, see Steinmetz (1992).



$\Sigma M_I = 0$
$F\ b - F_2\ a = 0$
$F_2 = F\ b/a = F_1$
$F_3 = F$

$F_1 = F$
$F_2 = F_3 = 0$

$F_1 = F_2 = F/2$
$F_3 = 0$

Figure 2a Calculation of forces in vertical elements, statically determinate system.

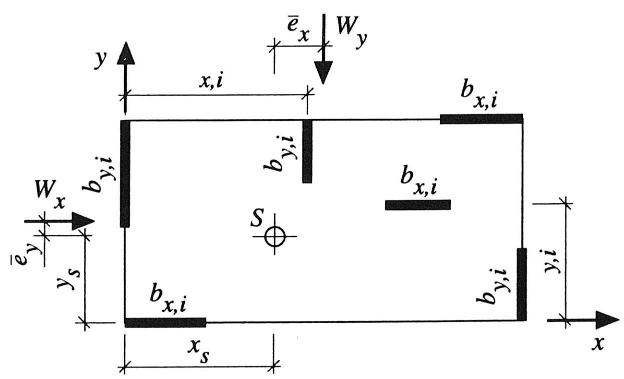


Figure 2b Vertical elements in a statically indeterminate system.

The forces in the system shown in Figure 2b may be calculated according to Equations (1) to (8).

$$x_s = \frac{\Sigma b_{yi}\, x_i}{\Sigma b_{yi}} \tag{1}$$

$$y_s = \frac{\Sigma b_{xi}\, x_i}{\Sigma b_{xi}} \tag{2}$$

$$s_{xi} = (x_i - x_s) \tag{3}$$

$$s_{yi} = (y_i - y_s) \tag{4}$$

Wind direction W_x

$$H_{xi} = \frac{b_{xi}}{\Sigma b_{xi}} W_x + \frac{W_x\, e_y\, s_{yi}\, b_{xi}}{\Sigma b_{xi}\, s_{yi}^2 + \Sigma b_{yi}\, s_{xi}^2} \tag{5}$$

$$H_{yi} = \frac{W_x\, e_y\, s_{xi}\, b_{yi}}{\Sigma b_{xi}\, s_{yi}^2 + \Sigma b_{yi}\, s_{xi}^2} \tag{6}$$

Wind direction W_y

$$H_{xi} = \frac{W_y\, e_x\, s_{yi}\, b_{xi}}{\Sigma b_{xi}\, s_{yi}^2 + \Sigma b_{yi}\, s_{xi}^2} \tag{7}$$

$$H_{yi} = \frac{b_{yi}}{\Sigma b_{yi}} W_y + \frac{W_y\, e_x\, s_{xi}\, b_{yi}}{\Sigma b_{xi}\, s_{yi}^2 + \Sigma b_{yi}\, s_{xi}^2} \tag{8}$$

Vertical elements

Frames

Frames have rigid moment-resisting connections which resist vertical and lateral loads. They are commonly used in single-storey industrial buildings. To produce moment-resisting connections fasteners (e.g. dowels) or finger jointed corners are used. For horizontal loading timber frames are normally used only to resist wind loads. For higher loads, e.g. horizontal braking-forces from cranes, the cross-section requirements would rapidly increase mainly due to the need to accommodate more fasteners. The restricted clear width of the building due to the large corner cross-sections is another disadvantage. All these reasons lead to uneconomic solutions when higher loads are present.

Cantilevers

In industrial buildings with cranes, steel or concrete cantilevers are used. If lower load-values are expected, roundwood (see STEP lecture E19) and glulam (Heimeshoff, 1983) cantilevers could be economic, e.g. for agricultural buildings or small sized halls. Deformations and stresses should be calculated according to EC5 except in the design of the base connection. Rigid base connections for clamped columns are given by Heimeshoff (1983) and to avoid fungal attack caused by high moisture content very careful detailing of the base connection is necessary.

Diagonal bracing

Diagonal members may be designed to act in tension and/or compression, e.g.

timber diagonals in frameworks. When acting only in tension, crossed steel rods with threaded ends are used. Diagonal bracings are often located within the wall, but sometimes they are located outside the cladding and are used for architectural reasons.

Vertical shear wall units

Vertical shear wall units consist of timber studs and plates and wood-based or gypsum-based panels. Shear forces are transferred through a large number of connections (nails or screws) around the panel edges (see B13). To prevent uplift vertical shear wall units must be fixed to the foundation. The compression-studs have to be designed for vertical loads and the additional vertical forces caused by horizontal loads. Because of their good strength and stiffness, fibreboards, Oriented Strand Board and plywood are the most common materials to produce shear wall units. In timber framing construction they act as multi-functional elements. They also fullfill functions such as fire-resistance, separation and noise insulation and, structurally, resist vertical and horizontal face loadings.

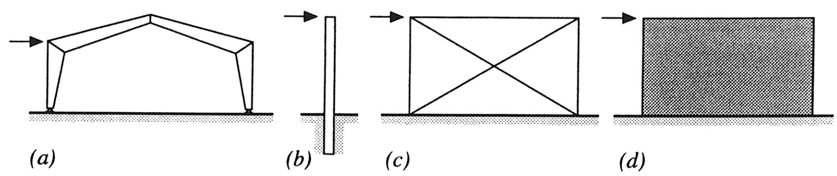


Figure 3 *Vertical bracing elements, (a) frame, (b) cantilever, (c) diagonal bracing, (d) shear wall unit*

Bracing elements for horizontal forces

All buildings require horizontal bracing at each floor and at roof level using horizontal diaphragms or horizontal diagonal bracing. At roof level the lateral load resisting system is normally located within the plane of the roof. In floors wood-based panels are carrying vertical loads and shear forces. In the perimeter edge beams and attached wall plates carry the flexural forces of the horizontal diaphragm. The floor acts as a horizontal beam carrying lateral loads to the vertical elements (see STEP lecture B13).

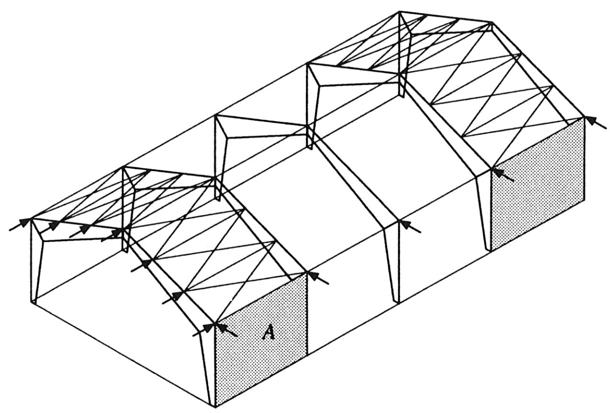


Figure 4 *Combination of different types of bracing to horizontal forces in a industrial building.*

Diagonals at floor or roof levels can form parts of trusses carrying the horizontal loads to the adjacent vertical elements. Therefore all connections and the tension and compression members have to be detailed very carefully.

At roof level steel rods or lightweight thin gauge steel diagonals acting together with purlins, or small horizontal trusses can be used. Trussed rafters always have to be laterally braced by additional trusses at roof level. Using trusses and glulam beams the bracing not only acts as a lateral load resisting system but is also used to avoid lateral buckling (see STEP lecture B15).

Design - Details

Design procedure

- Establish the building geometry and the lateral load resisting permanent walls and parts of the structure. In buildings in earthquake regions the system must be designed to resist seismic and wind loads. The ductility of the bracing system will influence the value of the equivalent static lateral force. Non-ductile structures or joints may be designed for higher lateral loads but give uneconomic solutions in earthquake design.
- Specify lateral loads according to EC1 and/or EC8 taking care to relate the load to the practical structural system, for example checking if studs are continuous over storey height when considering horizontal wind load distribution.
- Calculate the resulting forces in bracing elements. For symmetrical buildings simple rules could be used. For buildings with uneven distribution of bracing elements or differing stiffnesses of the bracing elements the additional torsion forces may be calculated as given in Figure 2b. The best torsional resistance is provided by widely spaced vertical elements.
- Calculate the load carrying capacities, $S_d \leq R_d$.
- Consider joint design for the bracing elements. The flow of load from application point to foundation should be traced. Design these joints:
  - Connections of load carrying members such as studs or rafters to horizontal elements, e.g. horizontal diaphragms, with special care taken in dealing with uplift forces caused by suction.
  - Joints within the horizontal bracings, e.g. connections of prefabricated floor or wall elements, joints within horizontal trusses, connections of purlins and frames etc.
  - Connections of horizontal elements to vertical elements e.g. horizontal diaphragms to shear walls or chords of horizontal trusses to shear walls.
  - Connections within vertical elements, e.g. connection of prefabriated shear walls or nailing of wood-based panels.
  - Connections of vertical elements to foundation, e.g. nail-on plate at the end of shear walls or anchoring systems of steel rods to the bottom of studs.

  When detailing joints it is important to avoid stressing timber perpendicular to grain, because timber is weak in this direction and sudden failure could occur.

- Calculation of displacements. The allowable displacements depend on the type of building. The calculation is more important for structures with high vertical loads. High values of deformation lead to high values of additional forces and will lead to cracks in claddings which should be avoided.

- Calculation of lateral load resisting systems in place during the erection of the building to secure stability of the structure in all stages of fabrication. During the erection of prefabricated timber framing buildings only a temporary bracing is necessary, e.g. by adjustable, oblique steel studs. In this case a special calculation is normally not necessary. For frames and spaced frames etc. special calculations may be required. Here it is normal practice to start erection with the vertical parts of the structure connected directly to bracing elements, e.g. Figure 4, section A.

Bracing elements

- Light steel diagonals are mostly used for roof constructions acting within the roof level. They are also used at walls and floors in small buildings. The end connection is provided by nails (EC5: Part 1-1: 6.2.2(1)). The design value of the lightweight thin gauge steel diagonal is normally governed by the design load-carrying capacity of the nails. The maximum design load-carrying capacity should be taken as

  $$max\ R_d = A_{net}\ f_{y,d} \tag{9}$$

  The number of nails can be increased by using additional pieces of timber beside the rafters at the end of the diagonals (see Figure 8). Lightweight thin gauge steel diagonals must be tensioned during erection but have the advantages of low cost and an easy and quick installation. However erection in practice is often incorrect and disadvantages are the low load carrying capacity and the thermal elongation. If a lightweight thin gauge steel diagonal is erected during a cold winter period, due to thermal elongation of steel great deformations along the diagonal could occur in the summer. Therefore the load carrying capacity of the diagonal could only be activated by large deflections of the entire structure.

- Steel rods with threaded ends are effective and aesthetic bracing elements. They are normally custom designed and can transfer large loads. Many alternative systems are possible, some details are shown in Figure 5. It is an advantage that the simple tensioning system of the steel rods can be used to adjust the structure during erection. To reach a good ductility of the bracing, all connections have to be overdesigned to ensure tension yielding of the rod is the failure mode. If steel rod bracing is designed carefully it can be used to enhance architectural appearance.

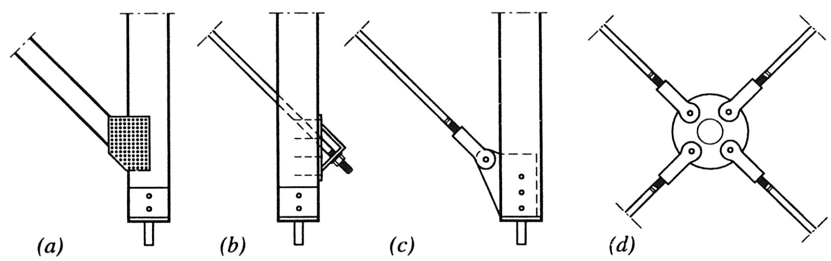


Figure 5 *Different details of diagonal bracing, (a) timber diagonal with nailed steel plate, (b) steel rod with simple end connection, (c), (d) steel rod with cast-iron connectors.*

- Timber or glulam diagonals are custom designed according to their loads and buckling lengths. They carry tension and compression forces. Connections take the form of nailed steel-plates, nailed wood-based panels, nails, bolts, connectors etc. (see Figure 5). Timber diagonals are often more economic than steel rods but since adjustment of the structure during erection is not possible, precise workmanship is necessary. Carrying tension and compression forces stiff constructions with small deflections are produced. To create good ductility well detailed nail plate connections or nails and bolts with small diameters should be used.

- Diaphragms made from wood-based panels and timber plates and studs are normally used in single- and multi-storey houses. Using the multi-functions of the panels this kind of bracing is often the most economic and also gives an excellent ductile behaviour, much better than any diagonal bracing system. Wall- and floor-elements could be prefabricated, connections of prefabricated elements have to be calculated, especially the connections of horizontal and vertical diaphragms. Board edges not fixed to a stud or a beam have to be secured with additional timber joists if no special calculation and detailing is used. The characteristic load-carrying capacity of the wood-based or gypsum-sheathed panels are given in European Standards, National Application Documents or European Technical Approvals. These are normally determined by test since calculation would involve embedment values which are only available for timber, plywood and hardboard in EC5. Tension and compression studs of shear walls have to be calculated considering also vertical loads. Holding-down details such as those given in Figure 6 must also be calculated.

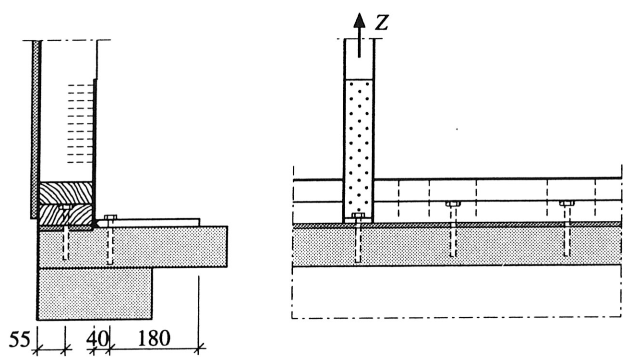


Figure 6 *Typical holding-down detail along shear wall edge.*

Example

Bracing of a roof construction with lightweight thin gauge steel diagonals.

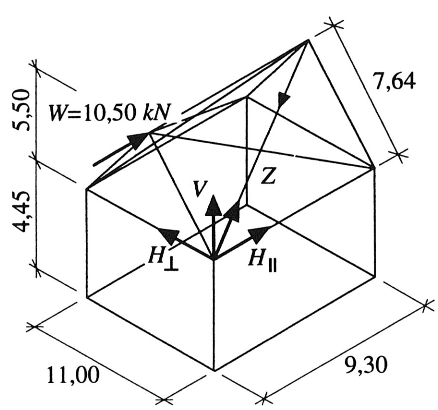


Figure 7 *Roof system.*

Material properties: softwood C24 according to EN 338
steel Fe 360

annular ringed shank nails 4,0 x 60 *mm*,
Service class 2

$k_{mod} = 0{,}9$

$$\alpha = 45° \qquad \beta = arctan\,\frac{7{,}64}{9{,}30} = 39{,}4°$$

$$H_{\parallel} = \frac{w}{2} = 5{,}25\ kN = F_w \qquad Z = \frac{F_w}{\cos\beta} = 6{,}79\ kN$$

$$H_{\perp} = F_w \tan\beta\ \cos\alpha = 3{,}05\ kN = V$$

Calculation of bracing member

Lightweight thin gauge metal steel diagonal 40 x 2,0

$$A_{net} = 40 \cdot 2 - (2 \cdot 5 \cdot 2) = 60\ mm^2$$

$$\sigma_{R,d} = \frac{f_{y,k}}{\gamma_M} = \frac{235}{1{,}1} = 214\ N/mm^2$$

$$\sigma_d = \frac{6790}{60} = 113\ N/mm^2 \qquad \frac{\sigma_d}{\sigma_{R,d}} = \frac{11{,}31}{21{,}40} = 0{,}53 < 1{,}0$$

Calculation of nails

Annular ringed shanked nails 4,0 x 60 mm

$t \leq 0{,}5\ d = 2{,}0\ mm$

$R_d = 0{,}4\ f_{h,1,d}\ t_1\ d$

where $t_1 = 58\ mm$ (penetration depth), $d = 4{,}0\ mm$ (nail diameter).

EC5: 1-1: 6.3.1.2a

$$R_d = 1{,}1\ \sqrt{2\ M_{y,d}\ f_{h,1,d}\ d}$$

$$f_{h,k} = 0{,}082\ \rho_k\ d^{-0,3} = 0{,}082 \cdot 350 \cdot 4{,}0^{-0,3} = 18{,}9\ N/mm^2$$

$$f_{h,1,d} = k_{mod}\ \frac{f_{h,k}}{\gamma_M} = \frac{0{,}9 \cdot 18{,}9}{1{,}3} = 13{,}1\ N/mm^2$$

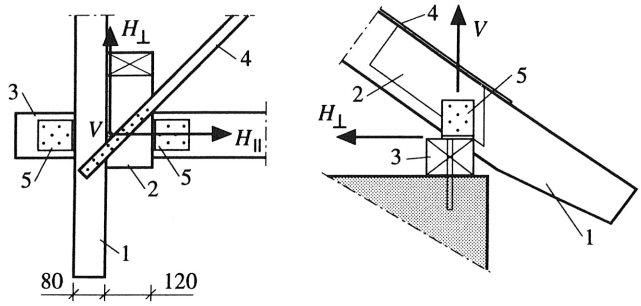
$$R_d = 0{,}4 \cdot 13{,}1 \cdot 58 \cdot 4{,}0 = 1220\ N$$

$$M_{y,d} = \frac{M_{y,k}}{\gamma_M} = \frac{180 \cdot 4{,}0^{2,6}}{1{,}1} = 6015\ N/mm$$

$$R_d = 1{,}1\ \sqrt{2 \cdot 6015 \cdot 13{,}1 \cdot 4{,}0} = 873\ N$$

$$n = \frac{6790}{873} = 7{,}77 \text{ say } n = 8 \text{ nails}$$

Angle bracket to transfer V and $H_{||}$



$V = 3{,}05\ kN$; $H_{||} = 5{,}25\ kN$

Figure 8 *Base connection of lightweight thin gauge diagonal: (1) rafter 100/180 mm, (2) additional timber 120/160 mm, (3) purlin 100/140 mm, (4) lightweight thin gauge steel diagonal 40 x 2,0 mm, (5) angle 105 x 105 x 90 mm .*

The additional timber (2) is necessary to keep nail distances when nailing lightweight metal gauge diagonal. The angles are each nailed with 8 nails on the side and with 10 nails on the bottom. According to technical reports from the producers of the angles the design load-carrying capacity may be taken as

$V_d = 9{,}94\ kN$ and $H_{||,d} = 7{,}89\ kN$

Combined load

$V / V_d + H_{||} / H_{||,d} \leq 1{,}0$

$3{,}05 / 9{,}94 + 5{,}25 / 7{,}89 = 0{,}98 < 1{,}0$

Concluding summary

- The flow of forces must be followed throughout the structure, in order that all connections be accurately calculated.
- Minimum bracing requirements must be taken inro account.
- Location of bracing elements with respect to the stiffness of the bracing should be symetric to load location to avoid additional torsion of the structure.
- In earthquake regions ductility of bracing has to be confirmed. Design of the bracing structure should be calculated according to wind and earthquake loads.
- Selection of bracing structures should consider load-carrying, ductility, economic and erection aspects (e.g. prefabrication).
- Lightweight thin gauge steel diagonals have to be tensioned to guarantee their immediate take up of bracing loads.

References

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