11. CONCRETE STRUCTURES LOADED IN TORSION

11.1. Introduction

In general, structural elements loaded in torsion can be divided into two categories. In this division boundary conditions play an important role.
The first category consists of structural elements where the presence of torsional resistance is required to provide equilibrium of forces in the structural system. In this case it is denoted as equilibrium torsion (or primary torsion). Equilibrium torsion is required to have basic static equilibrium.
The second category consists of structural elements where torsion occurs due to the fact that these elements follow the deformation of adjacent elements. If, in this case, there would be no torsional resistance, the structural element would still be in equilibrium. In this case, it is denoted as compatibility torsion (or secondary torsion). Statically indeterminate structures may have any of the two types of torsions.

A practical example of equilibrium torsion is a traffic viaduct supported by centrically placed columns (Fig. 11.1). Traffic loads can create significant torsional moments in this structure, which need to be transferred to the columns or the abutments. Calculation needs to demonstrate that the torsional resistance is sufficient to pick up these torsional moments. Besides strength, also stiffness has to be checked: is the torsional stiffness sufficient to enable that the traffic is not hindered by too large torsional deformations.

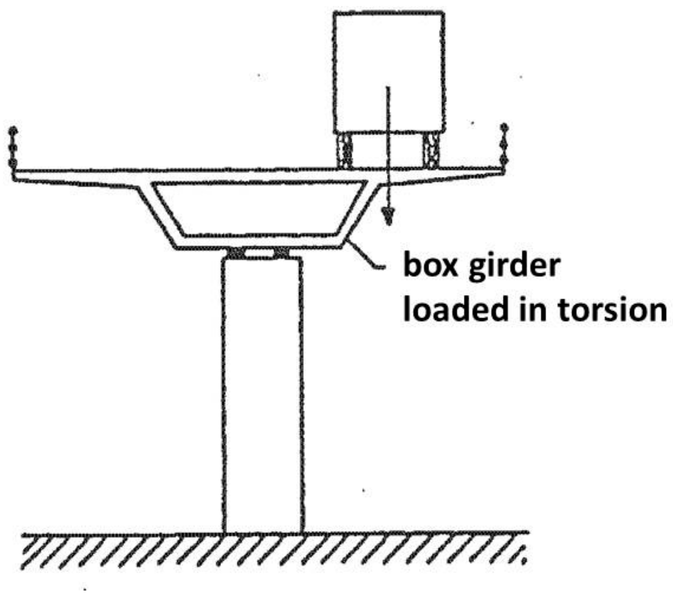


Fig. 11.1 Example of equilibrium torsion

A practical example of compatibility torsion is a floor system where floors and beams are connected monolithically (Fig 11.2, top and bottom, right). When the distribution of forces is calculated with the theory of elasticity, assuming that the structural elements are uncracked, the distribution of bending moments as drawn in figure 11.2 (top and bottom, right) will occur: in the floor a hogging moment will occur due to the torsional stiffness of the edge beam.

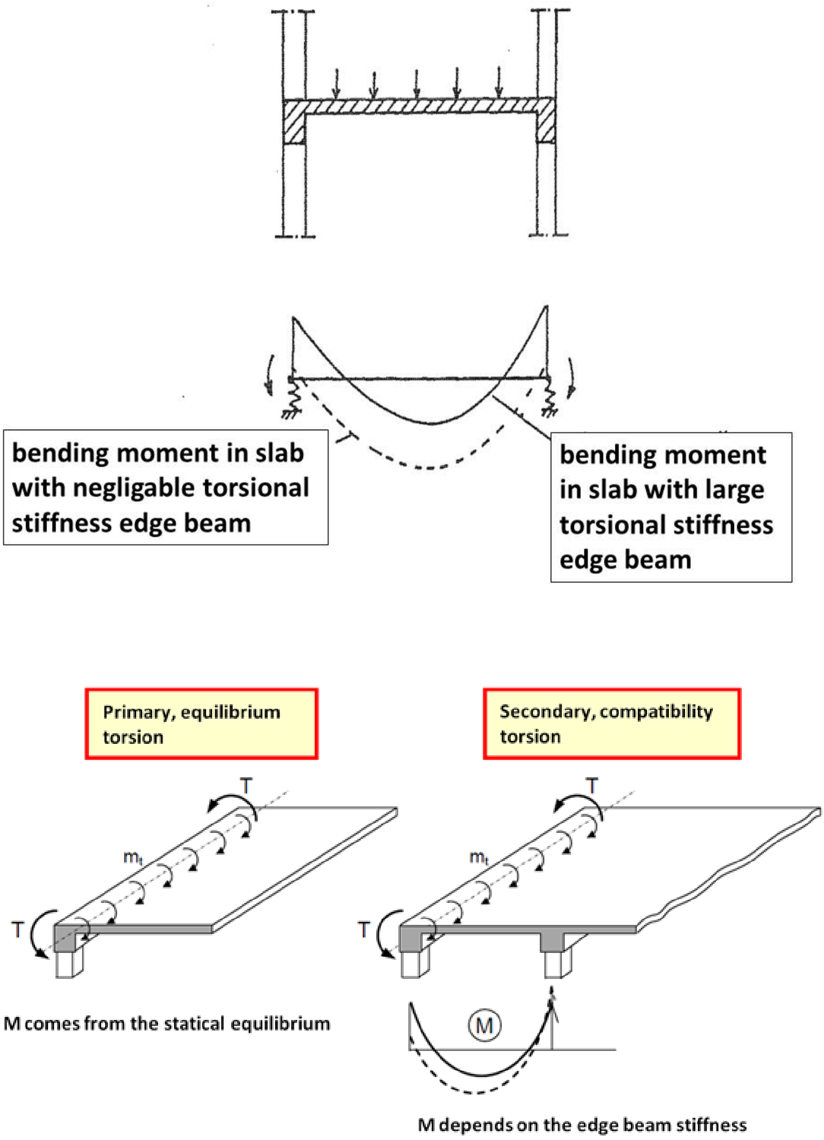


Fig. 11.2 Examples of equilibrium and compatibility torsion

As soon as the edge beams cracks, its torsional stiffness reduces dramatically. When performing calculations using the "cracked stiffness", the hogging moments in the slab will be reduced and the mid-span bending moment increases. Even when the torsional stiffness of the edge beam would be reduced to zero, there would still be a system providing equilibrium: the reinforcement of the slab has to be based on the mid-span bending moment, assuming a simply supported beam.

In a case like this, the procedure is as follows:

- When calculating the mid-span reinforcement one assumes that the torsional stiffness of the edge beams is equal to zero, i.e. the floor is modelled as being simply supported. As a consequence, the reinforcement of the edge beam does not need to be designed for torsion.
- Because the torsional stiffness of the edge beam is small but not completely equal to zero, some limited hogging moments will occur at the edge of the floor. These bending moments are clamping moments that don't result from the static scheme, but are the result of the "partial fixity". If one doesn't anticipate on these moments, severe cracking might occur in this area. To avoid this, additional reinforcement is applied to control cracking. For more information see the 'Slabs' chapter.
- For end supports of floor slabs the amount of top reinforcement needs to be at least 15% of the required bottom reinforcement in the adjacent span (EN 1992-1-1 cl. 9.3.1.2 (2)). This reinforcement has to be applied over at least 20% of the adjacent floor span, starting at the face of the support.
- When determining the loads on the columns these clamping moments must be taken into account. These moments increase the eccentricity of the normal force acting on the column and result in an increase of the amount of reinforcement required.

The difference in torsional stiffness in the uncracked and cracked phase is illustrated in Fig. 11.3. The stiffness in the cracked phase, $(GI)_{II}$, is approximately only 10% of the stiffness in the uncracked phase, $(GI)_I$.

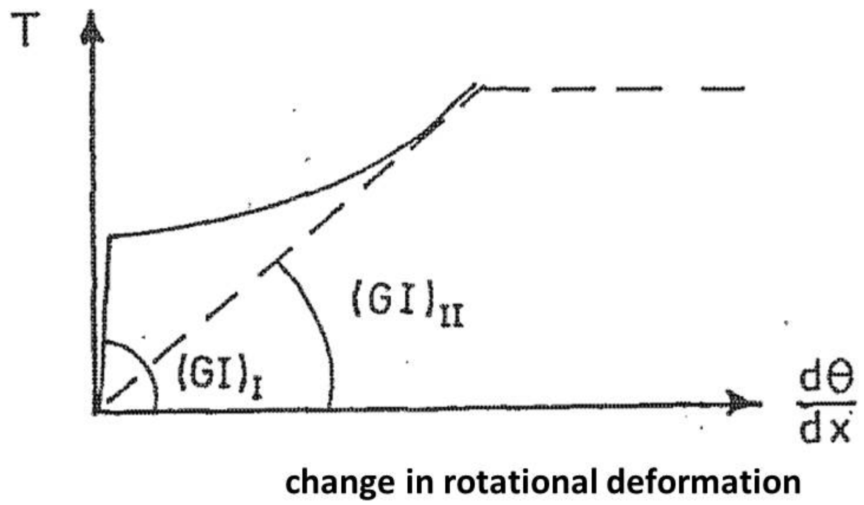


Fig. 11.3 Behaviour under pure torsion

In the case of equilibrium torsion, as opposed to compatibility torsion, one needs to consider the effect of torsional moments for both load bearing capacity (ultimate limit state) as well as deformations (serviceability limit state). The required load bearing capacity can be provided by a load transfer mechanism with stresses that do not exceed the available strength. Like for structural elements loaded in shear, one can apply strut-and-tie models to verify this. In this case these trusses are no longer two dimensional, but they become spatial, 3D trusses, like the ones shown in Figures 11.4 en 11.5.

The dimensional aspects of a spatial truss are discussed in chapter 11.3. Note that for torsion, in contrast to shear, no arching effects can be considered: the structural element loaded in torsion is cracked all around, resulting in a “pure” strut-and-tie model (Fig. 11.5). Measurements on the strain of stirrups show that the stresses in the stirrups (calculated as $\sigma_s = E_s \cdot \varepsilon_s$), after cracking, are close to the theoretical value based on the strut-and-tie model (Fig. 11.6). The deformation in the cracked phase is so large, that in case of equilibrium torsion, the torsional stiffness is in general governing for the design.

By applying prestressing, the structure will remain uncracked to a higher load level. Prestressing in the longitudinal direction of the structure improves the torsional behaviour of a structure or structural element.

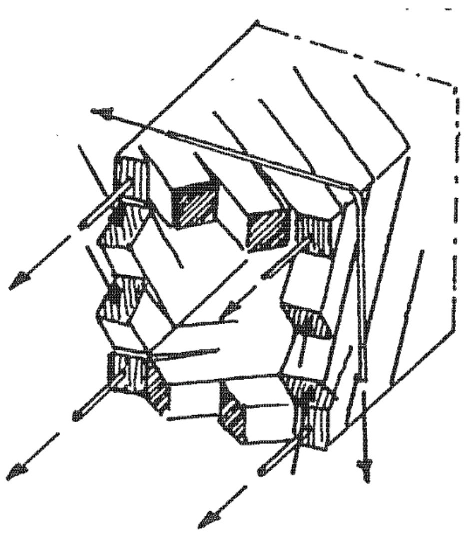


Fig. 11.4 Forces in a cracked cross-section loaded in pure torsion

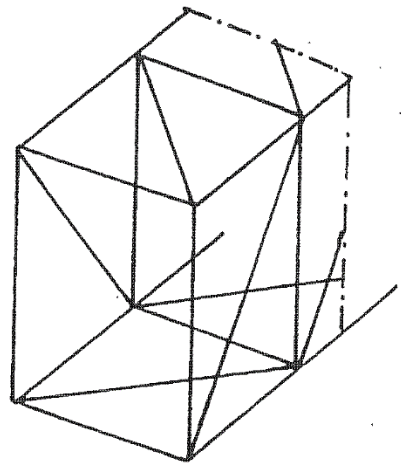


Fig. 11.5 Spatial strut-and-tie model

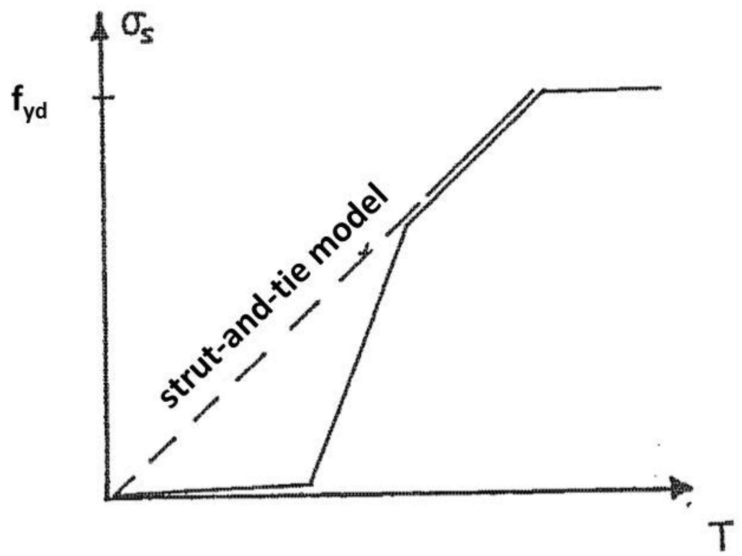


Fig. 11.6 Steel stress in a stirrup in an element loaded in torsion

To reduce torsional deformations, it is important to choose an adequate shape of the cross-section. Fig. 11.7 shows some cross-sections with increasing torsional stiffness.

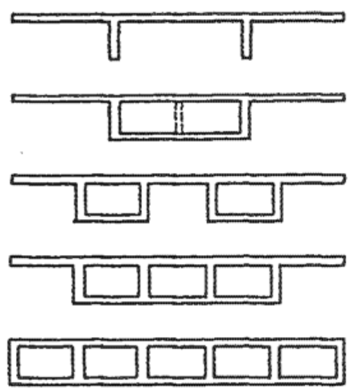


Fig. 11.7 Cross-sections with increasing torsional stiffness (from top to bottom)

It is noted that applying a solid cross-section instead of a box cross-section has no advantage with regard to torsional resistance: As soon as cracking occurs, tension will be present in the stirrups and the strain in outer layer increases to such a level, that it is detached from the core of the cross-section (Fig. 11.8).

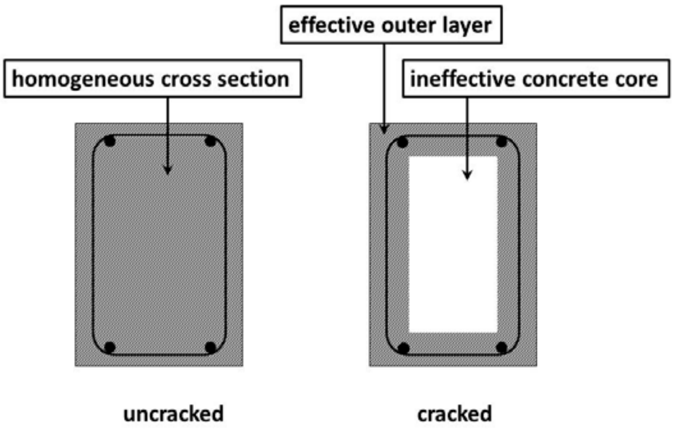


Fig. 11.8 Structurally active outer layer of a solid cross-section loaded in torsion, after cracking

The contribution of the core to the torsional stiffness is relatively small and often neglected. Although a solid cross-section has a greater cracking moment than a box cross-section, it has little practical value: Once cracking occurs, there is hardly no difference between a solid and a box cross-section. Figure 11.9 shows the behaviour of a solid cross-section and a box cross-section. The reinforcement is in both cases identical. It is clear that with increasing load, the difference in behaviour diminishes.

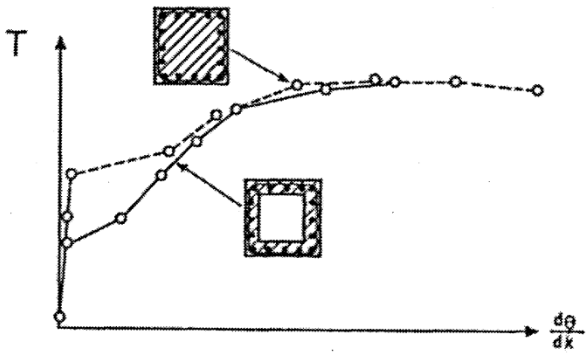


Fig. 11.9 Behaviour of a solid and a box cross-section loaded in torsion

The torsional stiffness of a structural element can be increased by applying prestressing. Figure 11.10 illustrates this. The behaviour of two box girders is compared. In one of them, a part of the reinforcement is replaced by prestressing steel, keeping the overall yielding force the same. The prestressing can increase the cracking moment of the cross-section to a such a level that the cross-section is uncracked in the serviceability limit state (SLS). The deformation in SLS then is significantly lower for the prestressed cross section. Since for structures or structural elements loaded in torsion, both the uncracked and the cracked phase are important, the behaviour in both phases will be discussed.

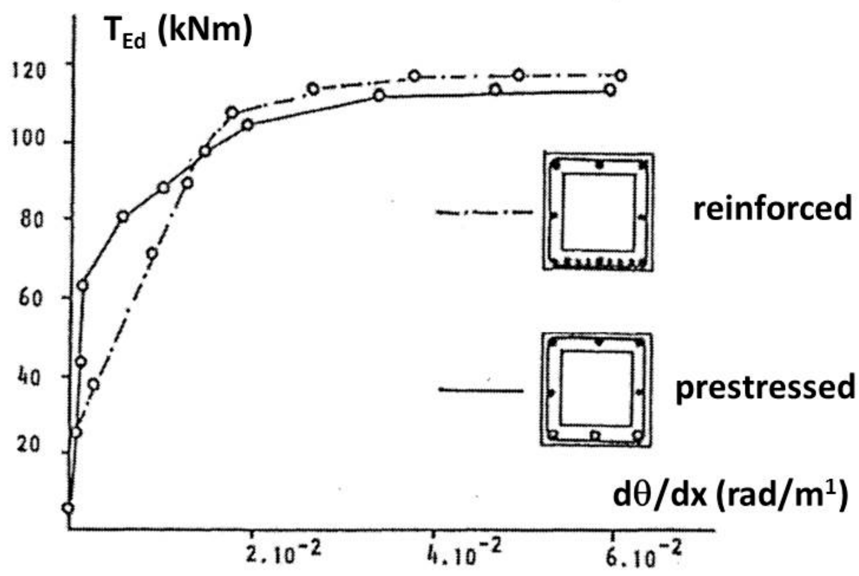


Fig. 11.10 The effect of prestressing on the behaviour of elements loaded in torsion

11.2. Torsion in the uncracked phase

Since in certain situations one might aim at having an uncracked cross-section (instance by applying prestressing), it is important to know the stress distribution and deformation in the uncracked phase. Figure 11.11 shows an example of a symmetrical element (radius r) subjected to a torsional moment T_{Ed}.

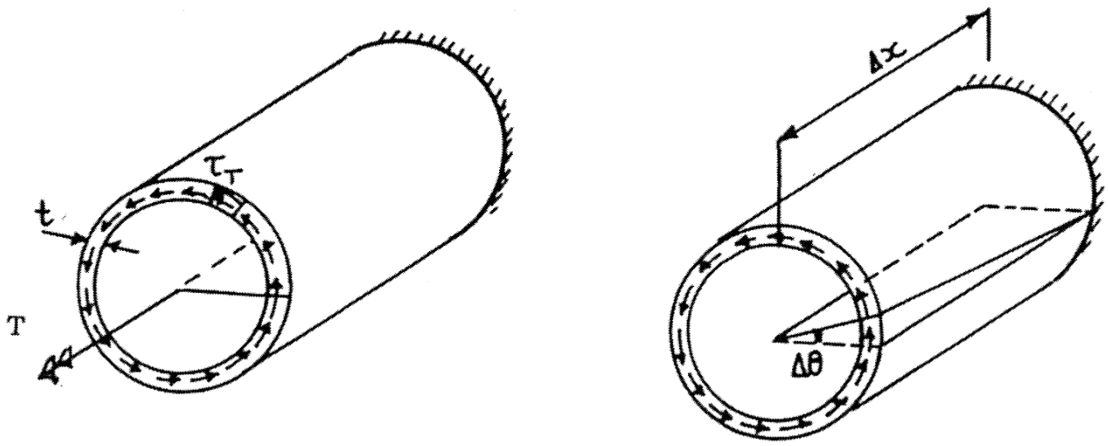


Fig. 11.11 Shear stress τ_T and rotational deformation $d\theta/dx$ in a symmetrical element

Because of symmetry, the shear stresses are uniform over the full cross-section. The following applies:

$$T_{Ed} = \tau_T \cdot 2 \cdot \pi \cdot r^2 \cdot t$$

where:

t is the thickness of the cross-sectional wall ($t << r$)

by defining
$$A_k = \pi \cdot r^2$$

One finds
$$\tau_T = \frac{T_{Ed}}{2 \cdot A_k \cdot t}$$

equation (11.1)

Later on it will become clear that this expression (the so-called Bredt formula) is typical for closed cross-sections.

The rotational deformation:

$$d\theta = \frac{T_{Ed} \cdot dx}{G_c \cdot I_t}$$

or
$$\frac{d\theta}{dx} = \theta' = \frac{T_{Ed}}{G_c \cdot I_t}$$

For the torsional stiffness in the uncracked phase it holds:

$$G_c \cdot I_t = \frac{E_c \cdot I_t}{2 \cdot (1 + \nu)} \approx 0{,}4 \cdot E_c \cdot I_t$$

where ν is cross contraction, Poisson's coefficient (for concrete equal to 0,2).

11.3. Torsion and warping

In the previous example it is assumed that "plain sections remain plain". Warping is free to occur as it is not restrained by supports. As a result, there are no stresses perpendicular to the surface of the cross-section. This case is therefore denoted as St. Venant torsion or pure or uniform torsion. In St. Venant torsion the torque is balanced by shear stresses only.

For cross-sections that are not thick-walled and closed, but thin-walled and open, another mode of torsion, the so-called warping occurs. A warping moment is the bending moment acting as a result of restrained warping. Equilibrium is then provided by bending stresses too, so the torque is balanced by axial stresses. In general, both torsional mechanisms occur simultaneously. The division between St. Venant torsion and warping depends on the properties of the specific cross-section. Figure 11.12 shows a situation where warping dominates.

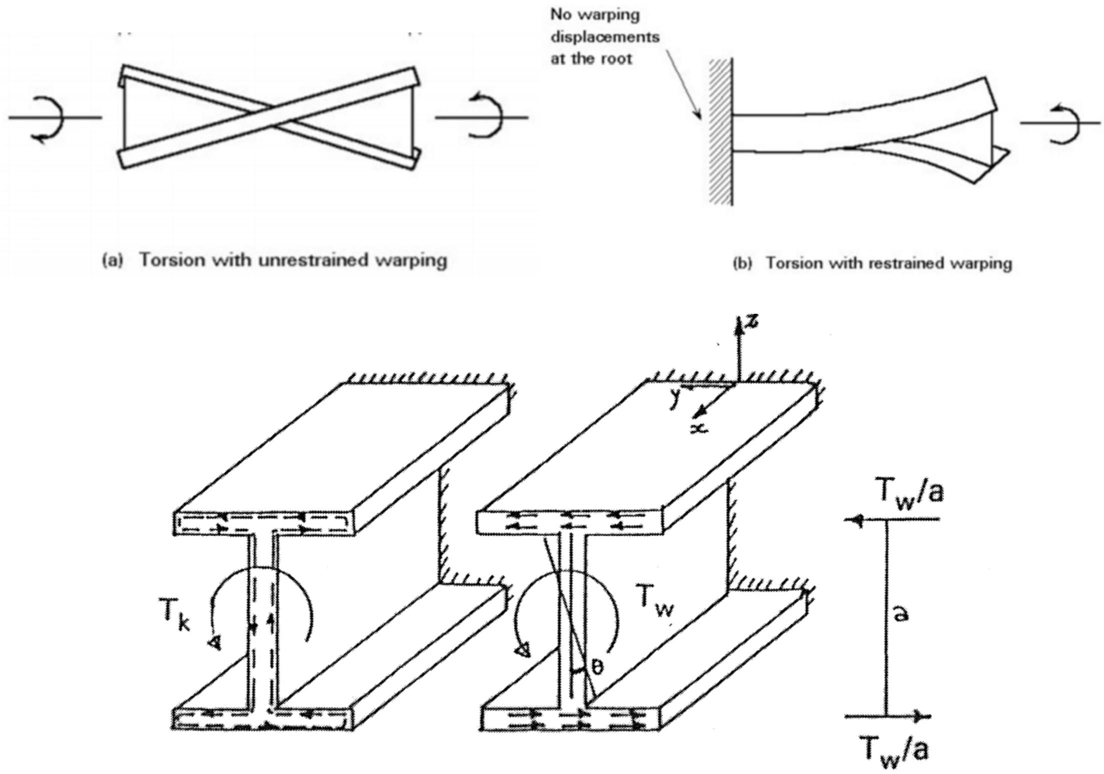


Fig. 11.12 St. Venant torsion (left) and warping (right) of an I-shaped cross section

In a beam with a box cross-section (Figure 11.13, left) the torsional moment will be mainly transferred by St. Venant torsion even though warping will occur between stiffeners. In a beam with an U-shaped cross-section (Fig. 11.13, right) the torsional moment will be mainly transferred by warping, although the composing elements will also develop a certain level of St. Venant torsion. To which extend St. Venant torsion or warping occurs, depends on the specific cross section.

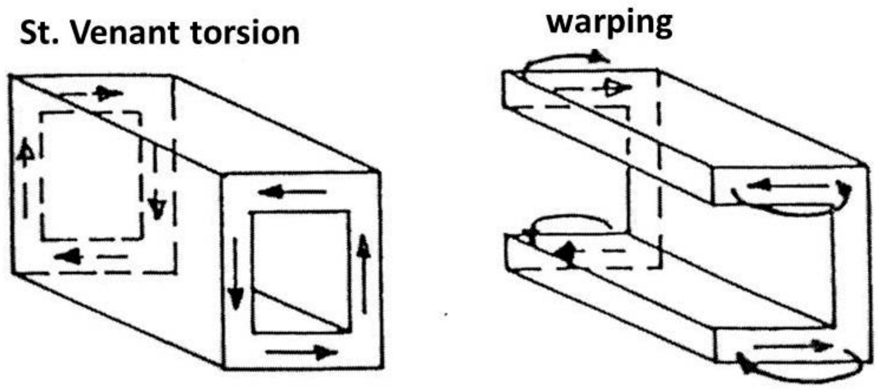


Fig. 11.13 Cross section with mainly St. Venant torsion (left) and warping (right)

In most cases one defines the dominating torsional mechanism and designs the structure assuming that it is the only torsion mode.

11.4. Shear stresses from torsion

For the deformation of a structural element subjected to pure torsion it holds:

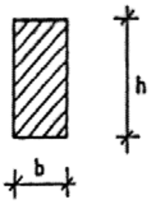
$$\frac{d\theta}{dx} = \frac{T_{Ed}}{G_c \cdot I_t}$$

where I_t is the torsion constant of the cross-section.

Concrete structures often have a rectangular or box-shaped cross-section. For a rectangular, solid cross-section it holds:

$$I_t = \alpha \cdot h \cdot b^3$$

where α is a function of the ratio h/b (Fig. 11.14).

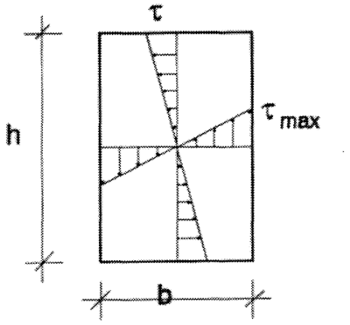


$$I_t = \alpha \cdot h \cdot b^3 \quad (h > b)$$

h/b	1,0	1,4	1,8	2,0	3,0	4,0	6,0	8,0	10,0	∞
α	0,141	0,187	0,217	0,229	0,263	0,281	0,299	0,307	0,313	0,333

Fig. 11.14 Torsion constant for a solid, rectangular cross-section

The shear stresses in a solid, rectangular cross-section are greatest along the long edges. In the centre of gravity the shear stresses are zero (Fig. 11.15).



$$\tau_{max} = \left[3 + \frac{2{,}6}{\left(0.45 + \frac{h}{b}\right)}\right] \cdot \frac{T_{Ed}}{b^2 \cdot h}$$

Fig. 11.15 Shear stresses in a solid, rectangular cross-section

Box-shaped cross-sections are typically applied in bridge construction (Figs. 11.16 and 11.17). The possible eccentricity in bridge structures due to traffic loads sets high standards for the torsional stiffness, which makes the choice for a box cross-section obvious. The torsion constant for these types of cross-sections is (see also Fig. 11.16):

$$I_t = \frac{4 \cdot z_1^2 \cdot z_2^2}{2 \cdot \frac{z_2}{t_1} + \frac{z_1}{t_2} + \frac{z_1}{t_3}}$$

equation (11.2)

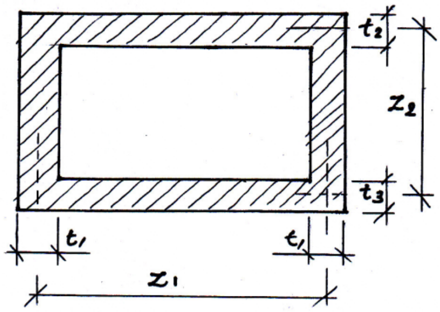


Fig. 11.16. Box-shaped cross-section with notations from equation (11.2)

Fig 11.17 Box girders under construction (Doha, Qatar)

When determining the shear stresses one can assume a constant shear flow:

$\tau_1 \cdot t_1 = \tau_2 \cdot t_2 = \tau_3 \cdot t_3 = \tau_4 \cdot t_4$

Where t_1, t_2, t_3, t_4 are the thicknesses of walls and flanges (Fig. 11.18).

This illustrates that the highest shear stresses occur in the thinnest cross-section walls.

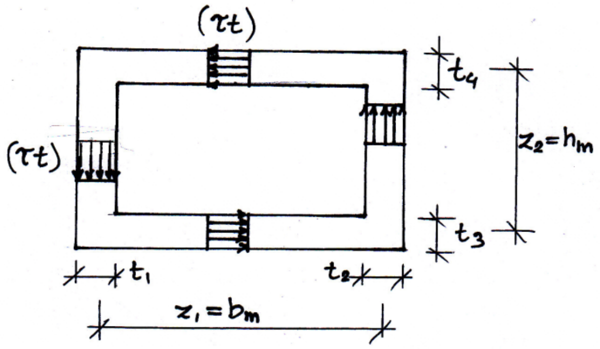


Fig. 11.18 Constant shear flow ($\tau_i \cdot t_i$) in box cross-section

The torsional moment T_{Ed} is partly resisted up by the long planar elements (webs) ($\tau \cdot t \cdot b_m \cdot h_m$) and partly by the vertical planar elements (webs) ($\tau \cdot t \cdot h_m \cdot b_m$). For the cross-section it holds:

$$T_{Ed} = \tau_i \cdot t_i \cdot (b_m \cdot h_m + h_m \cdot b_m)$$

or:

$$\tau_i \cdot t_i = \frac{T_{Ed}}{2 \cdot b_m \cdot h_m}$$

The shear force for the horizontal elements is:

$$V_{Ed} = \tau_i \cdot t_i \cdot b_m$$

The shear force for the vertical elements is:

$$V_{Ed} = \tau_i \cdot t_i \cdot h_m$$

equation (11.3a)

The maximum shear stress occurs in the thinnest cross-section wall:

$$\tau_{max} = \frac{T_{Ed}}{2 \cdot b_m \cdot h_m \cdot t_{min}} = \frac{T_{Ed}}{2 \cdot A_k \cdot t_{min}}$$

equation (11.3b; Bredt formula)

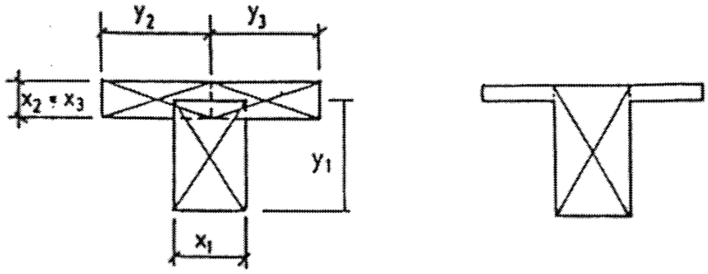


Fig. 11.19 Cross-sections consisting of multiple rectangles

Cross sections composed of multiple rectangular parts (Fig 11.19, left) can be designed assuming that the torsional moment is distributed over the composing, individual rectangles and proportional with the values $\alpha_i \cdot x_i^3 \cdot y_i$, so:

$$T_{Ed,i} = T_{Ed} \cdot \frac{\alpha_i \cdot x_i^3 \cdot y_i}{\sum \alpha_i \cdot x_i^3 \cdot y_i}$$

Where

$T_{Ed,i}$	is the part of the total torsional moment resisted by the ith rectangle
x_i	is the smallest size of the ith rectangle
y_i	is the greatest size of the ith rectangle

Each rectangle can now be designed as a separate cross-section subjected to a torsional moment $T_{Ed,i}$. If one of the composing rectangles has a significantly larger value of $\alpha_i \cdot x_i^3 \cdot y_i$ compared to other rectangles, one can assume that the total torsional moment is carried by this single rectangle (Fig. 11.19, right).

11.5. Torsion in the cracked phase

When discussing the ultimate limit state (ULS) load bearing capacity of a cross-section loaded in torsion, the following assumptions are important:

- In compatibility torsion the torsional moments will diminish due to cracking. For structural elements that are exposed to compatibility torsion, the assumption is made that the torsional stiffness is zero: they are not designed for torsion (for instance edge beams of a slab)
- When there is equilibrium torsion, the structure or structural elements need to be designed for torsion (for instance box girders)

Structures loaded in pure torsion are rare. In almost all cases a combination of torsion (T_{Ed}), shear (V_{Ed}) and bending (M_{Ed}) occurs. In prestressed structures there will also be a normal compression force present (N_p). The consequences of these combinations of forces are illustrated in Fig 11.20.

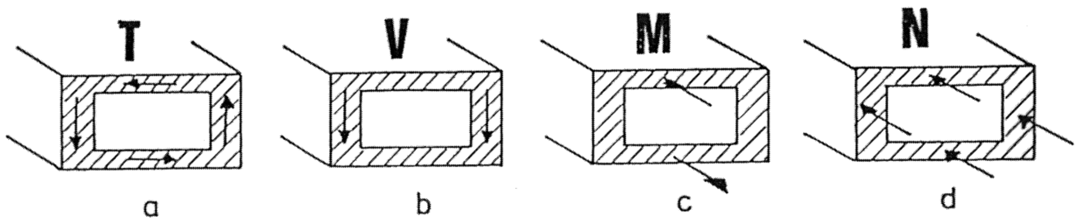


Fig. 11.20 Forces on a box cross-section from torsion (a), shear (b), bending (c) and compression (d)

- The torsional moment, T_{Ed}, results in shear forces in the four planar elements of the box (Fig 11.20a). The values of these shear forces can be determined using equation 11.2a
- The shear force, V_{Ed}, results in shear forces in the vertical planar elements only. The flanges of the cross-section are, in the direction considered, relatively flexible which makes their contribution to the transfer of shear rather small (Fig. 11.20b)
- The bending moment, M_{Ed}, results in a normal compressive force in the top flange and a normal tensile force in the bottom flange (Fig. 11.20.c).: $N'_{Ed} = N_{Ed} = \frac{M_{Ed}}{z}$
- An optional normal compression force, N_p, is distributed over the four planar elements (Fig. 11.20d).

Dimensioning for torsion is now reduced to dimensioning four in-plane loaded planar elements. This will be discussed for a box girder with a rectangular cross-section, see Fig. 11.21.

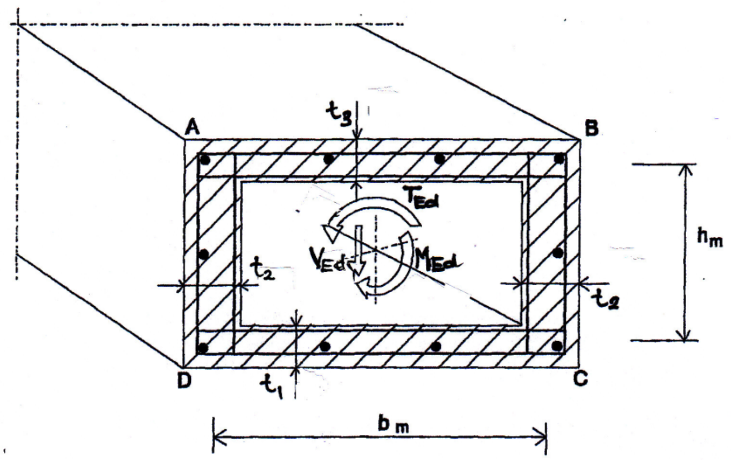


Fig. 11.21 Box cross-section loaded by a combination of a torsional moment, T_{Ed}, a shear force, V_{Ed}, and a bending moment, M_{Ed}

First planar element AD is considered. This part is loaded by a shear force which has to two separate components:

- The shear force, V_{Ed}, will be equally distributed over the two vertical planar elements. Each element is therefore loaded by a force

$$\frac{V_{Ed}}{2}$$

- The torsional moment, T_{Ed}, according to equation 11.2b, results in the vertical planar elements with a shear stress:

$$\tau_{T,AD} = \frac{T_{Ed}}{2 \cdot b_m \cdot h_m \cdot t_2}$$

- The shear force from to torsion in element AD is (equation 11.3a):

$$V_{Ed,T,AD} = \tau_{T,AD} \cdot t_2 \cdot h_m = \frac{T_{Ed}}{2 \cdot b_m}$$

The overall shear force that occurs in planar element AD is:

$$V_{Ed,AD} = \frac{V_{Ed}}{2} + \frac{T_{Ed}}{2 \cdot b_m}$$

Fig. 11.22 gives a side view of planar element AD. The shear force $V_{Ed,AD}$ introduces sloped cracks. The inclination angle of these cracks is denoted as θ.

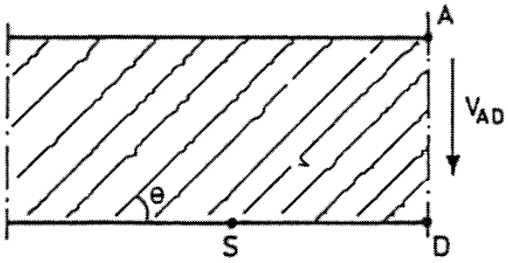


Fig. 11.22 Planar element AD in side view

We now consider several sections in this planar element. Fig. 11.23a considers the triangle ADS loaded by the shear force $V_{Ed,AD}$. To have vertical force equilibrium, the force in the vertical shear reinforcement has to equal the occurring shear force:

$$\frac{A_{sw} \cdot f_{yd}}{s_w} \cdot h_m \cdot \cot\theta = V_{Ed,AD}$$

The required amount of reinforcement:

$$\frac{A_{sw}}{s_w} = \frac{V_{Ed,AD}}{f_{yd} \cdot h_m \cdot \cot\theta}$$

equation (11.4)

where:
A_{sw} = cross-sectional area of each stirrup
s_w = spacing of the stirrups

In a different section the compressive struts are crossed perpendicular to their longitudinal axis direction (Fig. 11.23b). When considering the force equilibrium of triangle ADS in horizontal direction, the required amount of longitudinal reinforcement, A_{sl}, is determined:

$$\sum A_{sl} \cdot f_{yd} = V_{Ed,AD} \cdot \cot\theta$$

equation (11.5)

This reinforcement has to be distributed over the height of the planar element AD.

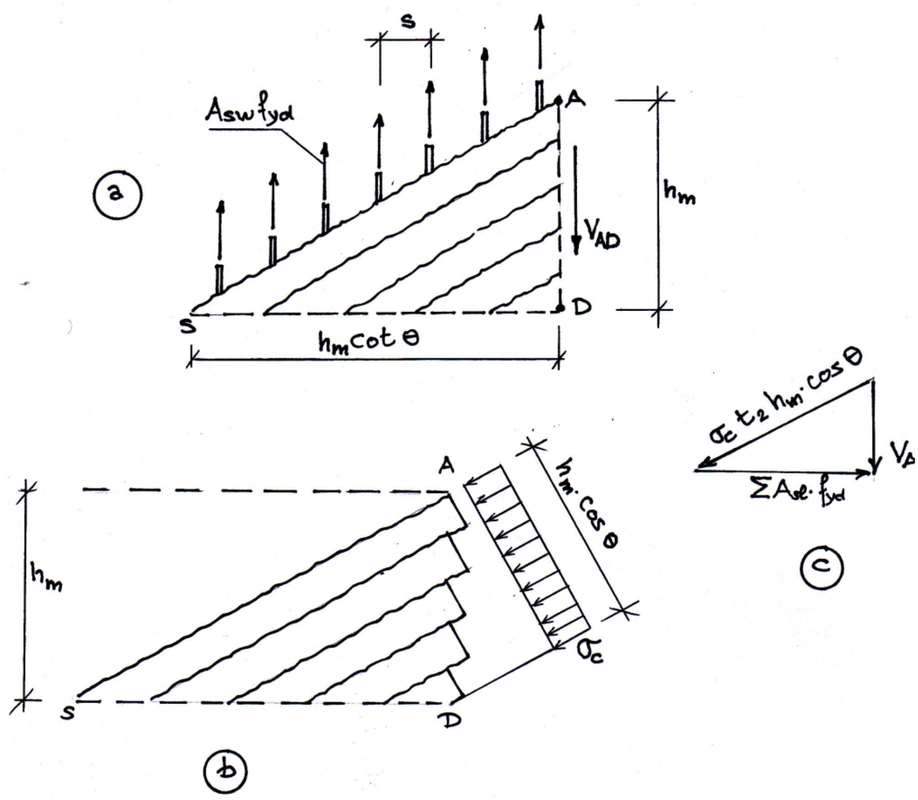


Fig. 11.23 Sections from wall AD to calculate the required reinforcement

Note that the shift of the bending moment line in cases where both torsion and shear occur is not necessary, because the additional longitudinal reinforcement, due to torsion, resulting from equation 11.5 for the bottom flange is equal to the additional reinforcement caused by the shift of the moment line.

Finally it needs to be checked whether the compressive stress in the struts, σ_{Ed} (Fig. 11.23b), does not exceed the maximum allowed stress. Based on equilibrium the occurring stress can be determined:

$$\sigma_{Ed} = \frac{V_{Ed,AD}}{t_2 \cdot h_m \cdot \sin\theta \cdot \cos\theta}$$

equation (11.6)

The occurring stress needs to smaller than the limit value for the compressive stress in these struts:

$$\sigma_{Ed} \leq \nu \cdot f_{cd}$$

equation (11.7)

where:

$$\nu = 0{,}6 \cdot (1 - \frac{f_{ck}}{250})$$

In this calculation one remark has to be made. The assumption is made that in determining the compressive stress, σ_{Ed},the full width, t_2, of the cross-section can be taken into account. For thicker walls this assumption can result in an unsafe structure. Although in the considered case there is clearly St. Venant torsion, a certain amount of warping will occur in the planar elements. This results in an unequally distributed compressive stress over the thickness of the planar element (Fig. 11.24). By using the effective wall thickness, t_{eff}, this effect can be taken into account. Test results show that the effective thickness, can be estimated as:

$$t_{eff} = \frac{A}{u}$$

equation (11.8)

where:

u = the outer perimeter of the cross-section

A = the surface within the outer perimeter of the cross-section schematized

If the wall thickness is smaller than the effective thickness, t_{eff}, calculations must be based on the actual wall thickness. If the wall thickness is larger than the effective thickness, calculations should be based on the effective wall thickness.

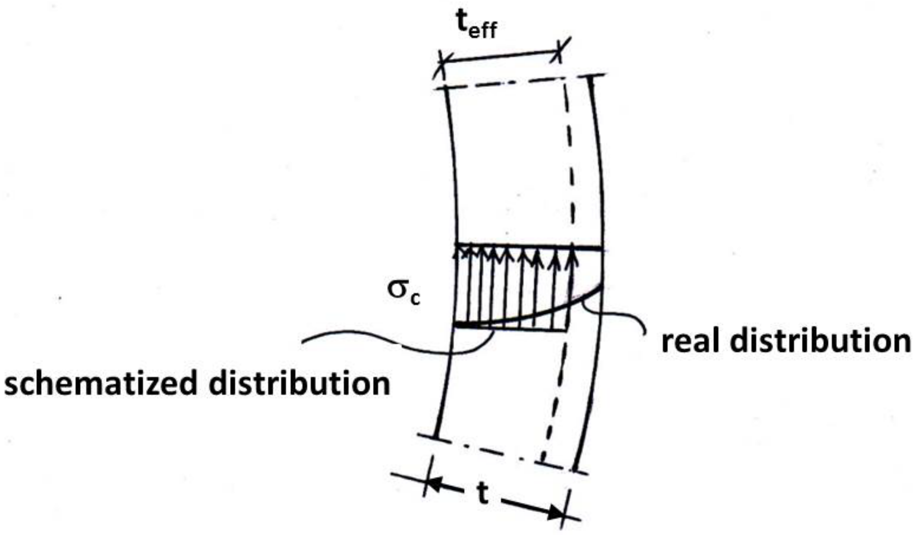


Fig. 11.24 Definition of the effective wall thickness t_{eff}

The calculations for the top and bottom flange of the box girder (planar elements AB and CD, Fig. 11.21) are performed in a similar way. The top flange ia loaded by a compressive force caused by bending ($N'_{Ed} = \frac{M_{Ed}}{z}$). Therefore, in most cases, the application of longitudinal tensile reinforcement (based on equation 11.5) is not required.

In the bottom flange both bending and torsion tensile forces occur which make the application of longitudinal reinforcement necessary.

Finally, determining of the boundaries for the angle θ for the compressive struts remains. Identical to structures loaded in shear, the designer is free to use the interval $1 \leq \cot\theta \leq 2{,}5$ (or $21{,}8^{\circ} \leq \theta \leq 45^{\circ}$). The smallest amount of stirrups is required when θ = 21,8°. In that case, the concrete strut compressive stress is maximum.

For solid, rectangular cross-sections the calculation method now is similar to the calculation method presented for box girders. In pure torsion, at a certain moment, an outer effective layer occurs (Fig. 11.8 and 11.9) causing a behaviour identical to the behaviour of a box girder. For the thickness of this layer the effective thickness, $t_{eff} = \frac{A}{u}$, can be used.

When a combination of torsion and shear occurs, it might be preferable to use an alternative design procedure for solid cross-sections. The top figures in figure 11.25 show the design procedure presented before. Torsion is carried by the effective layers and shear is carried by the full cross-section. However, the left web layer is now subjected to a relatively high shear stress (right figure). When distributing the shear force over the part of the cross-section surrounded by the effective layers (figure 11.25, bottom figures), the shear force stresses and torsional moment stresses don’t have to be combined. This might result in an optimized design. It is noted that this approach is n ot addressed in EN 1992-1-1.

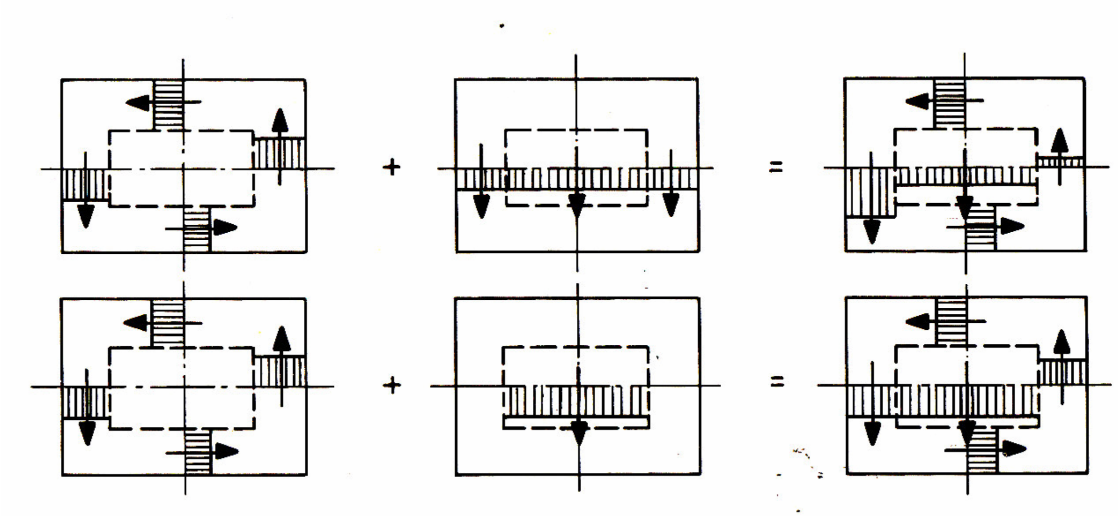


Fig. 11.25 Alternative addition of torsion and shear stresses in a solid cross-section

In the same way a normal force may be distributed over the full cross section or over the outer layer only.

When a structural element is exposed to a combination of shear and torsion, the load bearing capacity might be reached when the compressive struts fail before the reinforcement yields. To avoid this failure mode, the following requirement must be met:

$$\frac{T_{Ed}}{T_{Rd,max}} + \frac{V_{Ed}}{V_{Rd,max}} \leq 1{,}0$$

equation (11.9)

where:

$T_{Rd,max}$ is the capacity for pure torsion:

$$T_{Rd,max} = 2 \cdot \nu \cdot f_{cd} \cdot A_k \cdot t_{eff,i} \cdot \sin\theta \cdot \cos\theta$$

equation (11.10)

$V_{Rd,max}$ is the capacity for pure shear:

$$V_{Rd,max} = \frac{(z/d) \cdot \nu \cdot f_{cd} \cdot b \cdot d}{\cot\theta + \tan\theta}$$

EN 1992-1-1 calculates $V_{Rd,max}$ using the full width b of a solid cross-section. $T_{Rd,max}$ is calculated using the effective thickness (Fig. 11.25, top).

Another question to be answered is at which combination of shear and torsion reinforcement has to be designed and, in line with that question, when is only minimum reinforcement required. EN 1992-1-1 gives the following unity check expression (cl. 6.3.4(5)):

$$\frac{T_{Ed}}{T_{Rd,c}} + \frac{V_{Ed}}{V_{Rd,c}} \leq 1{,}0$$

equation (11.11)

where:

$T_{Rd,c}$ the torsional cracking moment for pure torsion, to be determined by assuming $\tau_{T,i} = f_{ctd}$

$V_{Rd,c}$ the shear force causing shear failure of an element without shear reinforcement

$$V_{Rd,c} = \max\left(0{,}035 \cdot k^{3/2} \cdot \sqrt{f_{ck}} \cdot b \cdot d;\ 0{,}12 \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^{1/3} \cdot b \cdot d\right) + 0{,}15 \cdot \sigma_{cp} \cdot b \cdot d$$

$$k = \min(1 + \sqrt{\frac{200}{d}}; 2)$$

d effective height in mm

ρ_l reinforcement ratio; $\rho_l = \min(\frac{A_{sl}}{b \cdot d}; 0{,}02)$

σ_{cp} compressive or tensile stress; $\sigma_{cp} = \min(\frac{N_{Ed}}{A_c}; 0{,}2 f_{cd})$

11.6. Reinforcement of cross-sections loaded in torsion

The longitudinal reinforcement for torsion, according to section 11.5, can be equally distributed over the perimeter of the cross-section or concentrated in the corners. The stirrups need to be closed and make an angle of 90 degrees with the axis of the considered element. The centre-to-centre distance of stirrups needs to be limited to make that the compressive struts transfer their force to the reinforcement: Too great centre-to-centre distances may result in breaking out of the corners of the cross-section (Fig. 11.26) since the force in the compressive struts is inadequately (only locally) counteracted by the tensile forces in the steel.

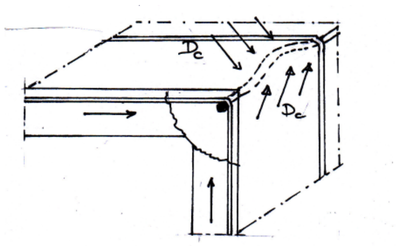


Fig. 11.26. Breaking out of longitudinal corner bar when the centre-to-centre distance of stirrups is too large

EN 1992-1-1 requires for stirrups a maximum centre-to-centre spacing of $u/8$, where u is the outer perimeter of the cross-section. The maximum centre-to-centre spacing should also not exceed $0{,}75d$ and has to be smaller than the minimum dimension of the cross-section.

To guide the forces in the compressive struts through the corners of the cross-section, at least one longitudinal rebar has to be placed in every corner of the cross-section. The remaining longitudinal reinforcement can be distributed over the cross-section, applying a maximum centre-to-centre spacing of 350 mm (EN 1992-1-1 cl. 9.2.3 (4)).

In box girders the transverse and longitudinal reinforcement can be divided over the inner and the outer surface of the walls, provided that the thickness of these walls is not larger than t_{eff} (equation 11.8). For thicker walls the reinforcement placed on the inner side is assumed not to be able to resist the torsional moment acting on the cross-section (Fig. 11.27).

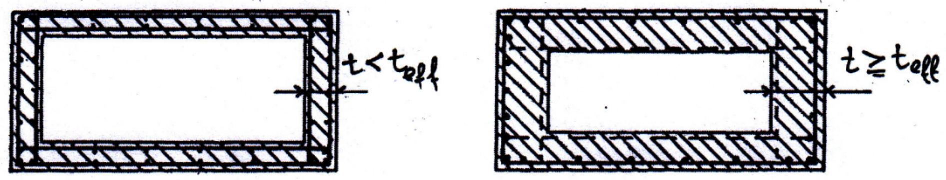


Fig. 11.27 Reinforcement in box girder loaded in torsion