Shear capacity of reinforced concrete members with shear reinforcement inclined more than 90°

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ABSTRACT

According to many codes of practice for reinforced concrete structures, an angle of inclination of the shear reinforcement of more than 90° should be avoided. However, there are no clear design instructions for cases when this angle is greater than 90°. Due to architectural requirements and in some cases also due to structural requirements, inclined columns are used in buildings or inclined piers and towers in bridges. To simplify the reinforcement work on the construction site, the shear reinforcement is often arranged in the horizontal plane and not always perpendicular to the axis of the reinforced concrete components. Although this type of reinforcement arrangement simplifies the work on the construction site, it presents the designer with certain difficulties when verifying the load-bearing capacity of the structural element, in particular the shear and torsional capacity. With shear reinforcement angles greater than 90°, the load-bearing capacity can be critical for the design. This paper presents a mechanically consistent method for calculating the shear resistance of concrete members with arbitrary inclinations of shear reinforcement, focussing on the case where the inclination angle exceeds 90°. Practical examples are provided to illustrate the influencing factors, along with recommendations for practical application.

RESUMEN

Según muchos códigos de práctica para estructuras de hormigón armado, debe evitarse un ángulo de inclinación de la armadura de cortante superior a 90°. Sin embargo, no existen instrucciones de diseño claras para los casos en que este ángulo es superior a 90°. Debido a requisitos arquitectónicos y, en algunos casos, también estructurales, se utilizan pilares inclinados en edificios o pilas y torres inclinadas en puentes. Para simplificar los trabajos de armadura en la obra, la armadura de cortante suele disponerse en el plano horizontal y no siempre perpendicular al eje de los elementos de hormigón armado. Aunque este tipo de disposición de la armadura simplifica el trabajo en la obra, plantea al proyectista ciertas dificultades a la hora de verificar la capacidad portante del elemento estructural, en particular la capacidad a cortante y a torsión. Con ángulos de refuerzo de cortante superiores a 90°, la capacidad de carga puede ser crítica para el diseño. Este artículo presenta un método mecánicamente consistente para calcular la resistencia a cortante de elementos de hormigón con inclinaciones arbitrarias de la armadura de cortante, centrándose en el caso en que el ángulo de inclinación supere los 90°. Se proporcionan ejemplos prácticos para ilustrar los factores que influyen, junto con recomendaciones para su aplicación práctica.

KEYWORDS: shear reinforcement, reinforced concrete, shear design, shear strength

PALABRAS CLAVE: refuerzo para esfuerzo cortante, hormigón armado, diseño para esfuerzo cortante, resistencia al esfuerzo cortante.

1. Introduction

In the Ultimate Limit State (ULS), it is expected that the reinforced concrete section works in cracking state, which can be modelled through Strut and Tie Models (STM) [1] or Stress Field Theory (SFT), for example the Modified Compression-Field Theory (MCFT) [2]. For the design of the shear capacity of concrete members, both STM and SFT are often used complementarily. While STM provides a clear representation of forces via struts and ties, the reinforcement and concrete behaviour can also be considered in a smeared manner, allowing for the application of stress field principles.

The inclination of the shear reinforcement is a decisive factor that influences the shear behaviour of reinforced concrete components. Shear reinforcement that is correctly aligned with the principal tensile stresses significantly improves the shear load-bearing capacity. In practice, however, reinforcement arrangements are often simplified, resulting in the shear reinforcement being arranged mainly in a vertical or horizontal direction. Consequently, the actual angle of inclination α of the shear reinforcement may deviate from 90° relative to the member axis and in many cases may not exactly match the direction of the principal tensile stresses.

There is considerable confusion in the technical design rules regarding the treatment of shear reinforcement with an angle of inclination α greater than 90°. It is still unclear whether such configurations are explicitly permitted or prohibited, or how their effects should be incorporated into the design procedures. Despite this ambiguity, inclined columns and pylons are frequently observed in practice, see an example in Fig. 1. In these cases, the shear reinforcement is often arranged horizontally, parallel to the construction joints, resulting in angles of inclination of the reinforcement with respect to the member axis, with a value $\alpha < 90°$ on one side and $\alpha > 90°$ on the other side, depending on the direction of shear flows due to shear forces and torsion. As the shear forces can change direction depending on load actions, the load-bearing capacity of members with $\alpha > 90°$ can become critical. This risk is often overlooked in the design.

The issue of load reversal further complicates this matter and emphasises the need for uniform treatment in the design regulations. The existing EC2 [4] and the AASHTO LRFD [5] do not limit the inclination angle α in calculating the contribution of shear reinforcement. However, the new generation of EC2 [3] clearly recommends to avoid the use of shear reinforcement with α exceeding 90°. This shows a possible disadvantage of the new generation of the Eurocode on this point.

Figure 1. Arthur Ravenel Jr. Bridge, United States of America (*Foto-source*: peri.ch)

This paper presents an approach to shear design for concrete members with shear reinforcement inclined by more than 90°. Some practical examples are used to illustrate the need for more clarity and guidance for practical applications.

2. Fundamentals of shear design

In general, the shear capacities calculated on the basis of the contributions of shear reinforcement and concrete strut are determined according to [4] as follows:

$$V_{\mathrm{Rd,sy}} = \frac{A_{\mathrm{sw}}}{s_{\mathrm{w}}} \cdot f_{\mathrm{ywd}} \cdot z \cdot \left(\cot\theta + \cot\alpha\right) \cdot \sin\alpha \quad (1)$$

$$V_{\mathrm{Rd,max}} = b_{\mathrm{w}} \cdot z \cdot v \cdot f_{\mathrm{cd}} \cdot \frac{\cot\theta + \cot\alpha}{1+\cot^2\theta} \quad (2)$$

It is noted that, according to EC2 design concept, the shear capacity of reinforced concrete members with *calculated* shear reinforcement primarily depends on the shear reinforcement $V_{\mathrm{Rd,sy}}$, as long as the shear load is still smaller than the maximum shear capacity $V_{\mathrm{Rd,max}}$. For members with very low amount of shear reinforcement or with minimum shear reinforcement, the shear behaviour and shear capacity is quite similar to members without shear reinforcement. Therefore, the provision of minimum shear reinforcement is primarily intended to ensure the required ductile behaviour of member at failure state, and not focus on increasing the shear capacity. This can be considered as fundamental in many design codes.

The additional tensile force in longitudinal reinforcement due to shear force is determined as below:

$$\Delta F_{\mathrm{td}} = \frac{V_{\mathrm{Ed}}}{2}\left(\cot\theta - \cot\alpha\right) \quad (3)$$

The shifted length of tensile force in longitudinal reinforcement due to shear force is calculated as:

$$a_{\ell} = \frac{z}{2}\left(\cot\theta - \cot\alpha\right) \quad (4)$$

For members with different shear reinforcement inclination angles, each type of shear reinforcement can take a portion of shear load corresponding to its capacity. Therefore, the total induced additional tensile force in longitudinal reinforcement can be determined as a sum of different parts calculated by using Eq. (3) for each shear reinforcement group.

In the practice, some engineers still do not believe in the existence of the shifting effect of tensile force in longitudinal reinforcement due to shear force. This may be due to the habit of checking the capacities of reinforced elements in bending and shear separately. As a result, the extension of longitudinal reinforcement due to shear action is often forgotten or neglected in the load-bearing capacity verification.

This effect can be well illustrated through case of the Wieselburg bridge, which collapsed due to shear failure, see Fig. 2. The subsequent analysis [6] showed that the designed capacity was not adequate for the load actions and that the provided reinforcement was insufficient. We calculated the required reinforcement for the bridge slab and also realised that the shifting effect of tensile force had obviously been neglected. The tensile force envelope clearly shows deficits in reinforcement arrangement, and the shear failures occurred exactly at these positions, see Fig. 3.

Figure 2. Shear failure of Wieselburg bridge [6]

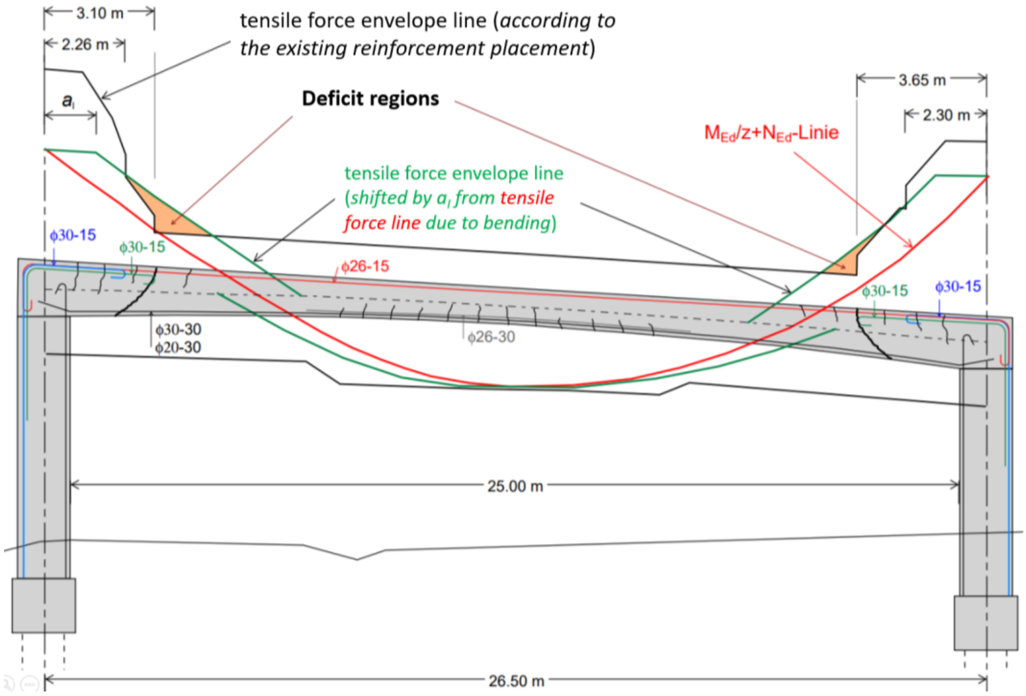

Figure 3. Tensile force in longitudinal reinforcement of Wieselburg bridge

3. Approach to shear design of members with shear reinforcement inclined over 90°

Since Eq. (1) and (2) are derived based on mechanical principles, they can be applied to general cases, including situations where the inclination angle α of shear reinforcement exceeds 90°. In this section, we present a comprehensive shear design for any inclination angle α with a particular focus on investigating the influencing parameters of shear capacity, especially for the cases of α greater than 90°.

In the new generation of EC2 [3], for members with inclined shear reinforcement (45° $\leq \alpha$), the following is defined:

$$\tan\frac{\alpha}{2} \leq \cot\theta \leq \cot\theta_{\min} \tag{5}$$

where the inclination angle α of shear reinforcement is typically limited by 90°.

From Eq. (2), it is seen that the shear contribution from concrete depends on both the inclination angle θ of the concrete strut and the angle α of the shear reinforcement. The capacity of concrete strut in compression is influenced by the cracking state of concrete, which is described through the reduction factor ν of concrete compressive strength. According to the new generation of EC2 [3], this reduction factor can be determined using Eq. (6) and is shown in Fig. 4, taking into account the average concrete strain ε_x of the considered concrete region.

$$\nu = \frac{1}{1+110\left(\varepsilon_x + \left(\varepsilon_x + 0.001\right)\cot^2\theta\right)} \leq 1 \tag{6}$$

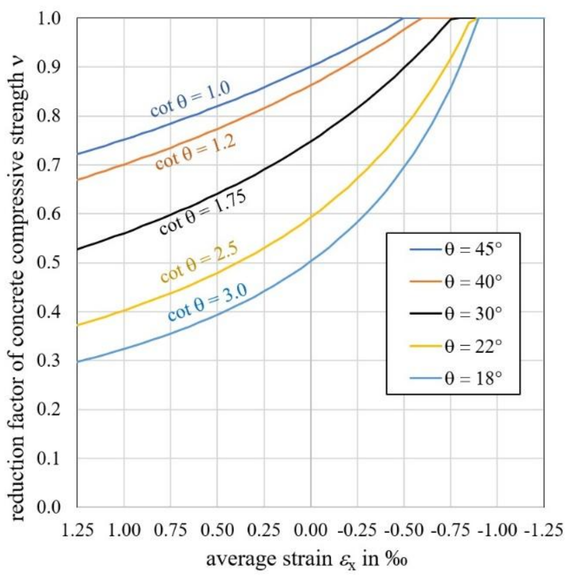

Figure 4. Reduction factor ν

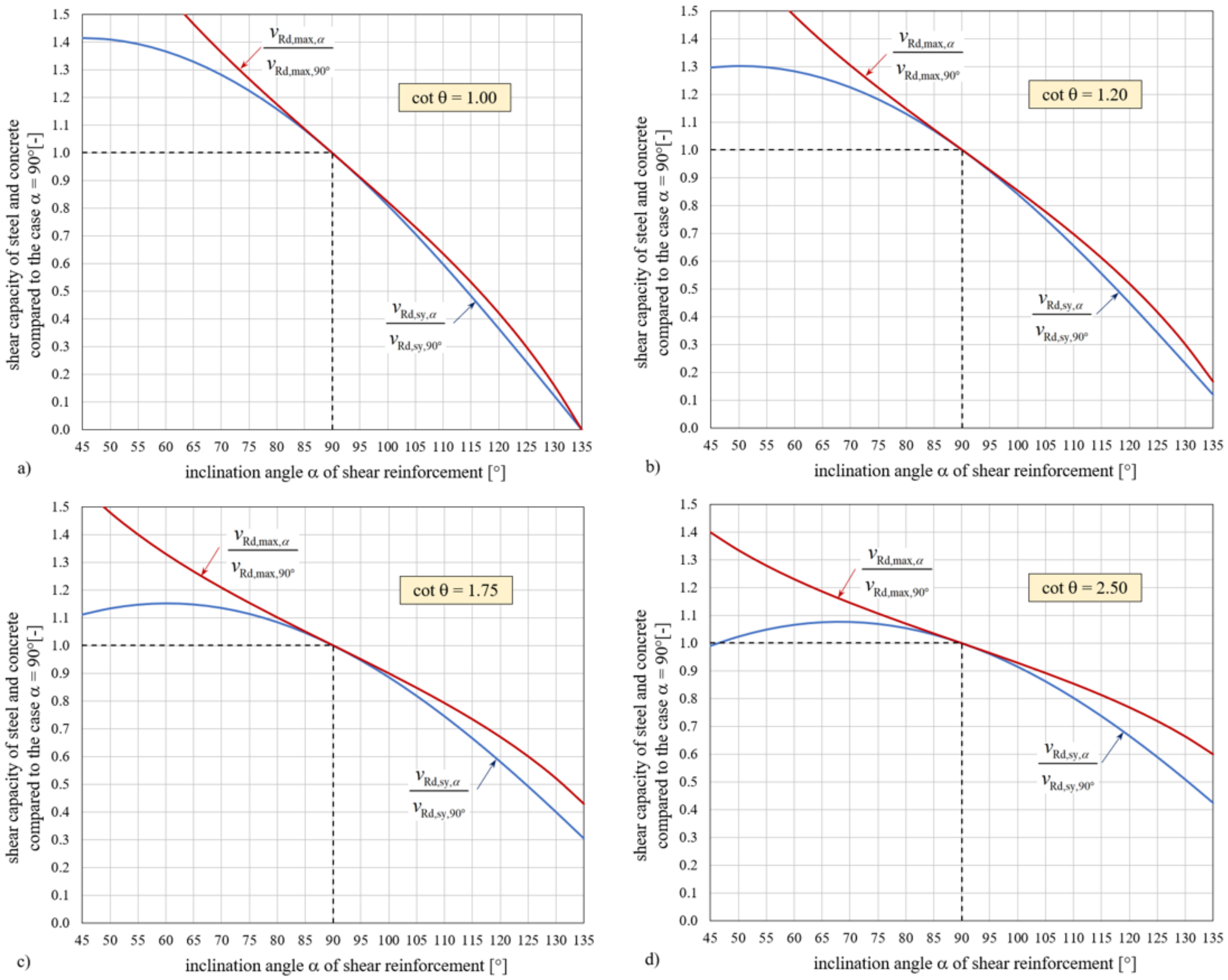

Figure 5. Influence of shear reinforcement inclination angle α on the shear capacity

For design, it is often expected that the shear reinforcement will yield before shear failure occurs due to concrete strut, ensuring the ductile behaviour of reinforced concrete structures. Therefore, the inclination angle θ of concrete strut shall be larger than certain threshold. For example, for bridge structure, DIN EN 1992-2/NA [7] defines a maximum value of $\cot\theta_{min}$ = 1.75, while for building structures, a larger limiting value of $\cot\theta_{min}$ = 3 can be used. The designer must decide whether to use more longitudinal reinforcement or more shear reinforcement when choosing the inclination angle θ of the concrete strut.

According to the Simplified Modified Compression Field Theory (SMCFT) developed by Bentz et al. [8], the inclination angle θ of concrete strut can be determined as follows, which exhibits a similar limiting value $\cot\theta_{min} \approx 1.8$ as defined for bridge design in [7]:

$$\theta = \left(29° + 7000\varepsilon_x\right)\left(0.88 + \frac{s_{xe}}{2500}\right) \le 75° \qquad (7)$$

According to EC2 [3], compression field inclinations with a value of $\cot\theta < \tan(\alpha/2)$ are permissible, if the yield strength f_{ywd} in Eq. (1) is replaced by the stress $\sigma_{swd} \le f_{ywd}$ in the shear reinforcement calculated according to:

$$\sigma_{swd} = E_s\left[\left(\varepsilon_x + 0.001\right)\frac{\left(\cot\theta + \cot\alpha\right)^2}{1 + \cot^2\alpha} - 0.001\right] \qquad (8)$$

where ε_x represents the average strain of the bottom and top chords.

It can be seen that with the increasing inclination angle α > 90°, both the shear capacities calculated with steel reinforcement and concrete compressive strut decrease significantly, as shown in the Fig. 5 and Fig. 6.

It is worth noting that the maximum capacity $V_{Rd,max}$ is reached at a given inclination angle α when $\cot\theta = \tan(\alpha/2)$.

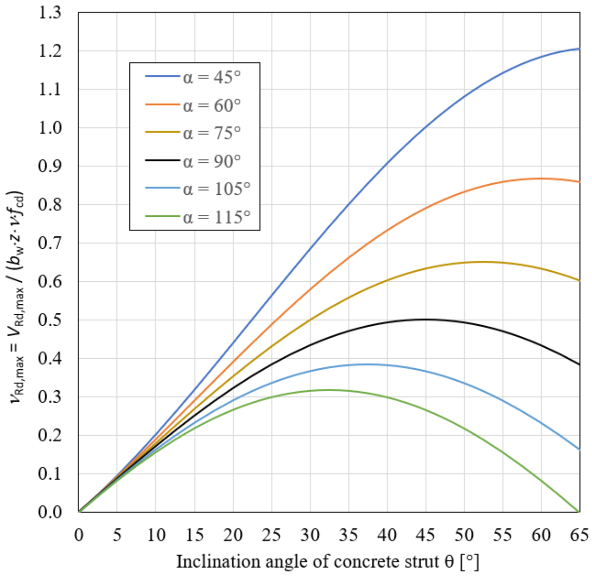

Figure 6. Shear capacity depending on angle θ

To determine the required shear reinforcement, the following condition must be satisfied.

$$\cot\theta \le \sqrt{\frac{s_w b_w}{A_{sw}} \cdot \frac{v \cdot f_{cd}}{f_{ywd} \cdot \sin\alpha} - 1} \tag{9}$$

By defining the mechanical shear reinforcement ratio as below

$$\omega_w = \frac{A_{sw}}{s_w b_w} \cdot \frac{f_{ywd}}{v \cdot f_{cd}} \tag{10}$$

and applying Eq. (5), we obtain:

$$1 \le \tan\frac{\alpha}{2} \le \cot\theta \le \sqrt{\frac{1}{\omega_w \sin\alpha} - 1} \le \cot\theta_{min} \tag{11}$$

The maximum shear reinforcement ratio $\omega_{w,max}$ can be determined as:

$$\omega_{w,max} = \frac{1}{\left(1 + \tan^2\frac{\alpha}{2}\right)\sin\alpha} \tag{12}$$

Note that if more shear reinforcement is provided than the calculated maximum shear reinforcement, the shear strength does not increase, as the governing failure mode will be concrete failure. From the load action:

$$v_{Ed} = \frac{V_{Ed}}{b_w z \cdot v \cdot f_{cd}} = \omega_w \left(\cot\theta + \cot\alpha\right)\sin\alpha \tag{13}$$

the minimum shear reinforcement ratio $\omega_{w,min}$ is determined using the following inequality:

$$v_{Ed} a \ge \sqrt{a-1} + c \tag{14}$$

with

$$a = \frac{1}{\omega_w \sin\alpha} \tag{15}$$

and

$$c = \cot\alpha \tag{16}$$

The inequality (14) leads to:

$$v_{Ed}^2 a^2 - \left(2v_{Ed}c + 1\right)a + \left(c^2 + 1\right) \ge 0 \tag{17}$$

Finally, the minimum value $\omega_{w,min}$ of the mechanical shear reinforcement is determined by solving Eq. (17), considering the maximum limiting value $\cot\theta_{min}$ used with Eq. (13).

$$\omega_{w,min} = \frac{1}{a_{max}\sin\alpha} \ge \frac{v_{Ed}}{\left(\cot\theta_{min} + \cot\alpha\right)\sin\alpha} \tag{18}$$

with

$$a_{max} = \frac{\left(2v_{Ed}c + 1\right)}{2v_{Ed}^2}\left(1 + \sqrt{1 - \frac{4v_{Ed}^2\left(c^2+1\right)}{\left(2v_{Ed}c+1\right)^2}}\right) \tag{19}$$

The relationship between the mechanical shear force and $\omega_{w,min}$ is presented in Fig. 7.

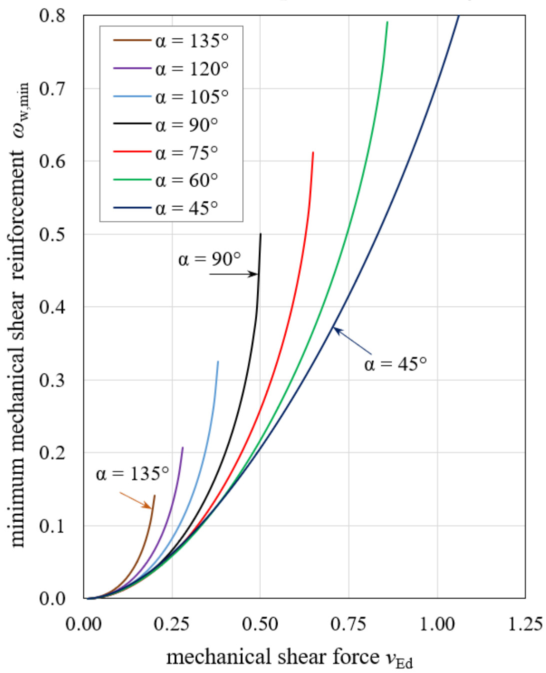

Figure 7. Minimum mechanical shear reinforcement

4. Examples

4.1 Transverse beam

A reinforced concrete transeverse beam of an existing concrete arch bridge is investigated, see Fig. 8. The transverse beam supports the bridge deck and connects two vertical walls placed on two arches. The beam has a shear cross section of b x h = 0.32m x 1.05m, is made of concrete C25/30, and is subjected to a shear force V_{Ed} = ±500 kN. The reinforcement has a characteristic value of the yield strength of 220 MPa. The shear reinforcement was constructed by bending some longitudinal bars with a bending angle of 60° and by providing stirrups (inclination angle of 90°).

It appears that the bent bars used as shear reinforcement were primarily designed to resist the shear force caused by traffic loads on the middle lanes of the bridge (located between the two concrete arches). However, the critical case of shear loading may arise from restraint deformation caused by differential displacement between the two concrete arches. This occurs when the traffic load is concentrated in only one moving direction, creating an eccentricity in the transverse direction of the bridge. Consequently, the induced shear forces act in opposing directions at the two ends of the transverse beam. The bent bars, serving as shear reinforcement, exhibit alternating inclination angle α = 60° and α = 120°, depending on the direction of the acting shear force.

For the case of a member without normal force and to illustrate the influence of shear reinforcement angle α, a concrete strut inclination of $\cot\theta$ = 1.2 and a lever arm z = 0.8h are assumed for shear capacity verification. The shear resistance of the member with respect to the shear reinforcement contributions is determined as the sum of the contributions of both types of shear reinforcement (bent bars and vertical stirrups). Eq. (1) is used for each type of reinforcement to calculate its contribution.

When the acting shear force corresponds to an inclination angle of α = 60° for bent bars (as illustrated on the left side of the beam in Fig. 8), the shear capacity is calculated as:

$$\begin{aligned} V_{\mathrm{Rd,sy}} &= V_{\mathrm{Rd,sy,60°}} + V_{\mathrm{Rd,sy,90°}} \\ &= 372.4\,\mathrm{kN} + 174.2\,\mathrm{kN} = 546.6\,\mathrm{kN} \end{aligned} \tag{20}$$

showing that the shear capacity is sufficient.

On the opposite side, where the inclination angle of bent bars is α = 120°, the shear capacity of the member is calculated as:

$$\begin{aligned} V_{\mathrm{Rd,sy}} &= V_{\mathrm{Rd,sy,120°}} + V_{\mathrm{Rd,sy,90°}} \\ &= 130.5\,\mathrm{kN} + 174.2\,\mathrm{kN} = 304.7\,\mathrm{kN} \end{aligned} \tag{21}$$

In this case, the calculated shear resistance is significantly lower than the applied design load, indicating that the structural safety is insufficient. A strengthening of shear capacity by providing more shear reinforcement is required.

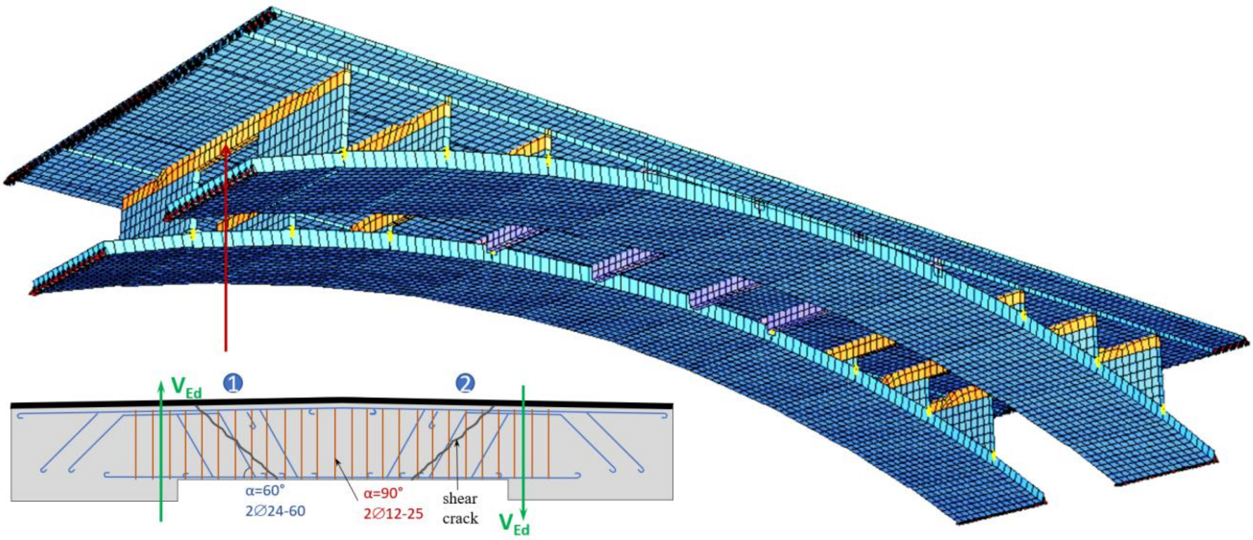

Figure 8. Shear action and shear reinforcement in transverse beams of bridges

When only vertical stirrups are provided (with an inclination angle α of 90° to the axis), the required shear reinforcement is calculated using Eq. (1) as follows:

$$a_{sw} = \frac{V_{Ed}}{f_{ywd} \cdot z \cdot \cot\theta} = 26 \text{ cm}^2/\text{m} \qquad (22)$$

This calculation result corresponds to shear reinforcement consisting of two legs ∅16 mm bars, with a spacing of 15 cm.

Therefore, for members subjected to reverse shear loads, it is recommended that the main portion of the shear reinforcement be arranged at an inclination angle of 90°.

4.2 Inclined pylon

A column or pylon leg with an inclination angle of 15° as showed in Fig. 9 is investigated, in which the shear reinforcement is placed horizontally and thus shows an inclination angle of $\alpha = 75°$ as well as $\alpha = 105°$ depending on the direction of shear load action. The pylon leg is subjected to a combination of compressive load N, bending moment M and shear force V.

Due to the reversal load actions, e.g. wind load or seismic load, the shear force as well as the companying force components acting in the inclined member can be critical for the shear capacity if its direction corresponds to the case of shear reinforcement with an inclination angle α larger than 90°. For illustration purpose, a mechanical shear force $\nu_{Ed} = 0.3$ is assumed.

To determine the minimum required shear reinforcement, the inclination angle θ of the concrete strut is selected with the limiting value of $\cot\theta = 1.75$, corresponding to $\theta = 29.7°$, which is defined according to DIN EN 1992-2/NA [2]. The minimum required shear reinforcement is calculated using Eq. (13) as follows:

$$\omega_w = \frac{\nu_{Ed}}{(\cot\theta + \cot\alpha)\sin\alpha} \qquad (23)$$

For shear reinforcement inclined at an angle of $\alpha = 105°$ of shear reinforcement, the required shear reinforcement is given by:

$$\omega_{w,105°} = \frac{0.3}{(1.75 + \cot 105°)\sin 105°} = 0.209 \qquad (24)$$

If the inclination angle of the reinforcement is not considered (assumed to be $\alpha = 90°$), the calculated required shear reinforcement is:

$$\omega_{w,90°} = \frac{0.3}{(1.75 + \cot 90°)\sin 90°} = 0.171 \qquad (25)$$

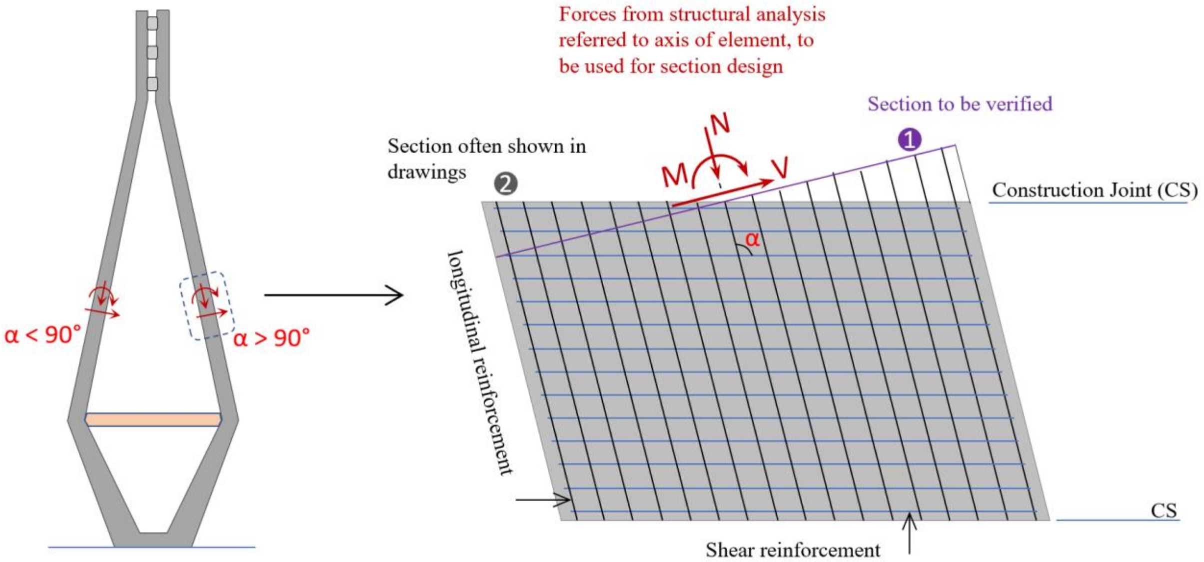

Figure 9. Shear resistance of inclined members

The ratio of the required shear reinforcement between two cases is $\omega_{w,90°}/\omega_{w,105°} = 0.82$. This result can also be obtained by using diagram 5c. Based on the calculation using Eq. (23) as the reference, the missing shear reinforcement is 18% when the inclination angle of shear reinforcement is incorrectly considered with a value of $\alpha = 90°$.

It is important to note that the shifted length a_l of the tensile force in longitudinal reinforcement, due to shear force, increases significantly when the shear reinforcement is inclined at an angle α greater than 90°. This effect is particularly pronounced when the minimum inclination angle θ_{min} of the concrete strut is used in the shear capacity design, see Eq. (4). For this case, with a consideration of the concrete strut inclination of $\cot\theta = 1.75$, the ratio of shifted length of tensile force between two calculations is $a_{l,105°}/a_{l,90°} = 1.15$. Additionally, as the shear reinforcement inclination angle α increases, the contribution of concrete in shear capacity decreases, as indicated in Eq. (2). The ratio of the maximum shear capacity, contributed solely by the concrete, between the two calculation cases is $V_{Rd,max,105°}/V_{Rd,max,90°} = 0.85$, see also Fig. (6).

It should be noted that in cases where the longitudinal reinforcement is uniformly distributed in the cross section, such as in box sections, the shifted length of the tensile force shall not be determined using Eq. (4). Instead, it can be accurately calculated through sectional analysis, considering the equivalent normal force and bending moments induced by shear forces. Details on this approach can be found in [9, 10].

As a result, a larger inclination angle α necessitates both additional shear reinforcement and more longitudinal reinforcement. In practice design, the effects of the actual inclination angle of shear reinforcement, arising from the real arrangement of the shear reinforcement on construction side, must be properly accounted for to ensure accurate and reliable shear capacity design.

5. Conclusions

Shear capacity verification is an important task of designing reinforced concrete members, where the inclination angle α of shear reinforcement significantly affects shear capacity. While inclination angles α greater than 90° are typically not expected, and thus not clearly defined in the design codes, they are frequently encountered in practice, especially in inclined concrete members subjected to reversal shear loads. In such cases, shear reinforcement is often placed horizontally rather than perpendicular to the axis of the concrete members.

The findings of this study are summarized as follows:

- Inclination angles of shear reinforcement greater than 90° are often seen in practice, particularly in inclined elements subjected to reversal shear loads.
- When α exceeds 90°, there is a significant increase in the required amount of shear reinforcement, longitudinal reinforcement, and the shifted length of tensile forces.
- The maximum shear capacity based on the contribution of concrete is notably reduced for inclination angles α of shear reinforcement greater than 90°.
- The extended formulation for calculating shear capacity aligns with the design principles of the new generation of Eurocode 2, ensuring consistency and applicability to practical scenarios.
- It is strongly recommended to carefully model and design members with shear reinforcement inclination angles greater than 90° to ensure structural safety and efficiency.
- It is recommended to introduce detailed design rules in the new generation of the

Eurocode 2 to clearly cover this case of practical application.

In summary, priority must be given to the structural modelling and verification of load-bearing capacity of such reinforced concrete members with shear reinforcement inclined over 90° to overcome the challenges of this particular case and to ensure compliance with safety standards and design principles.

Notations

a_l	the shifted length of the tensile force in the longitudinal reinforcement due to shear force
a_{sw}	relative amount of shear reinforcement
b_w	effective width of concrete web
b	width of rectangular cross section
h	depth of cross section
f_{cd}	designed concrete compressive strength
f_{ywd}	designed tensile strength of shear reinforcement
s_{xe}	effective crack spacing
s_w	spacing of shear reinforcement
z	lever arm of cross section
A_{sw}	cross sectional area of shear reinforcement
E_s	elastic modulus of steel reinforcement
M	bending moment
N	normal force
V_{Ed}	factored shear force
$V_{Rd,sy}$	factored shear resistance based on contribution of shear reinforcement
$V_{Rd,max}$	factored shear resistance based on the contribution of concrete strut
ΔF_{td}	additional tensile force in longitudinal reinforcement due to the shear force
α	shear reinforcement inclination angle
ε_x	average strain of cross section
ω_w	mechanical shear reinforcement
ν	reduction factor of strut concrete
ν_{Ed}	designed shear force
θ	concrete strut inclination angle
θ_{min}	the minimum inclination angle of concrete strut defined for design.

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