CẬP NHẬT VỀ KHẢ NĂNG CHỊU CẮT CỦA BÊ TÔNG TRONG TIÊU CHUẨN EUROCODE 2 – THẾ HỆ THỨ 2 (DỰ KIẾN 2028)

UPDATES ON SHEAR RESISTANCE OF CONCRETE IN EUROCODE 2 – 2nd GENERATION (EXPECTED 2028)

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TÓM TẮT: Lý thuyết Critical Shear Crack Theory (CSCT) đã được phát triển từ năm 1985 nhằm đánh giá khả năng chịu cắt của bê tông cũng như khả năng chống chọc thủng (punching shear) của bê tông cốt thép một cách hợp lý. Ý tưởng chính của CSCT là khả năng chịu cắt được chi phối bởi sự hình thành và phát triển của một khe nứt chịu cắt chính, bao gồm hình học và động học của khe nứt đó. Các dạng đơn giản hóa của mô hình tổng quát này đã được áp dụng trong một số tiêu chuẩn, bao gồm fib Model Code 2010 và gần đây là phiên bản thứ hai của tiêu chuẩn châu Âu cho kết cấu bê tông (Eurocode 2 – dự kiến 2028 áp dụng rộng rãi). Bài viết này sẽ trình bày về lý thuyết và phương pháp tính toán trong phiên bản Eurocode 2 sắp tới sẽ áp dụng).

TỪ KHÓA: Tính toán cắt bê tông, Lý thuyết kiểm toán cắt theo vết nứt tới hạn, Eurocode 2nd Gen.

ABSTRACT: The Critical Shear Crack Theory (CSCT) has been developed since 1985 to rationally evaluate the shear capacity of concrete as well as the punching shear resistance of reinforced concrete. The main concept of CSCT is that the shear capacity is governed by the formation and propagation of a critical shear crack, including its geometry and kinematics. Simplified forms of this general model have been adopted in several design codes, including the fib Model Code 2010, and more recently in the second generation of the European standard for concrete structures (Eurocode 2 – expected to be widely implemented in 2028). This paper presents the theoretical background and calculation method of the forthcoming Eurocode 2 to be applied in Europe.

KEYWORDS: Shear design in Concrete, Critical Shear Crack Theory, Eurocode 2nd Gen.

1. INTRODUCTION

In the new second-generation version of Eurocode 2, shear verification for concrete members is one of the areas that has undergone significant changes. The formulas and approaches have been revised to more accurately reflect the actual behavior of reinforced concrete structures. In addition, the approach has been simplified (based on the CSCT theory) to make it more practical for engineers in design practice.

This paper provides a brief overview of the origins and theoretical basis of the shear verification formulas in concrete. The content focuses on the major changes introduced in the latest updated standard.

2. THEORETICAL BASIS OF CSCT

In a beam without transverse reinforcement, the resistance to shear is provided almost entirely by the concrete itself. Before any cracks appear, the applied shear is mainly carried through the elastic stress distribution of the uncracked section of the beam, where both compression and tension zones participate in transferring forces. This uncracked stress field allows the concrete to sustain the shear action effectively in the initial stage of loading, ensuring that no significant diagonal cracking occurs until the stresses exceed the tensile strength of the material.

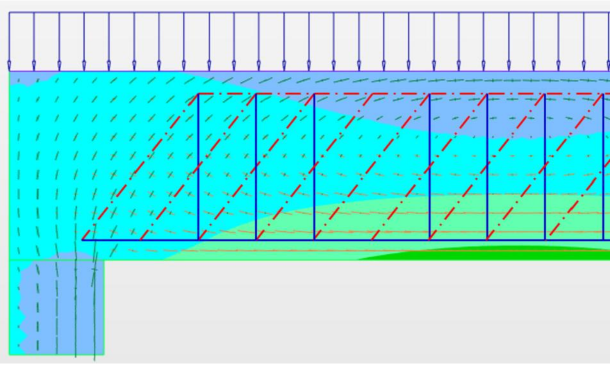

Figure 1: Elastic stress field on a simply supported Reinforced concrete beam subjected to uniformly distributed load (The figure illustrates the elastic stress distribution within an uncracked concrete beam without transverse reinforcement. The arrows represent the principal stress directions in both compression and tension zones, showing how shear forces are transferred through the concrete before diagonal cracking occurs.)

After cracking occurs, several mechanisms come into play to transfer and sustain the shear force within the beam. These include:

- Cantilever action, where portions of the concrete act like small cantilevers bridging the crack (V_c).

- Aggregate interlock, where the rough surfaces of the crack enable aggregates to engage and resist sliding (V_a).

- Dowel action, in which the longitudinal reinforcement bars provide resistance across the crack (V_d).

- Concrete's residual tension, which still contributes to shear transfer even after cracking (V_t).

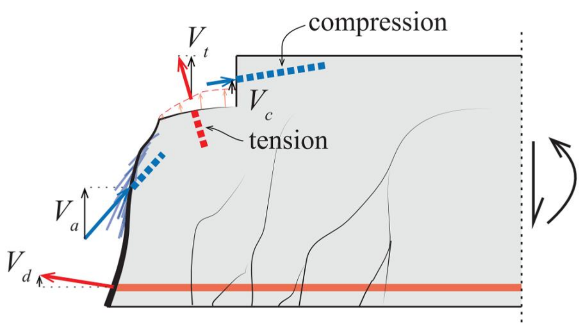

Figure 2: The shear resistance mechanism of concrete (source: Muttoni and Fernández Ruiz)

2.1 Cantilever action

Principle: When flexural cracks have formed, the concrete between two adjacent cracks behaves like a cantilever block. This block is capable of transferring shear forces without the need for stirrups or a complex truss mechanism. Instead, shear is transmitted through the inclination of the compression chord. The stability of this cantilever block is maintained by an inclined tension tie, and the overall shear resistance primarily depends on the tensile strength of the concrete along this tie.

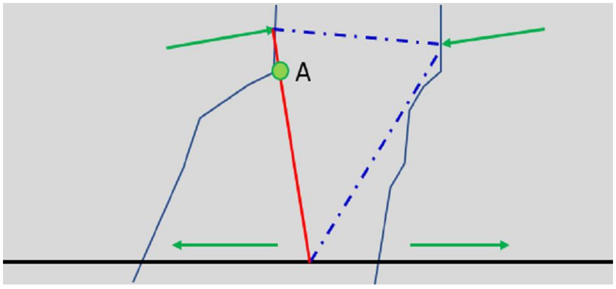

Figure 3: Cantilever action

Limitation of the mechanism: Once the tensile stress in the concrete reaches its tensile strength (at point "A" in Figure 3), a horizontal crack develops. At this stage, the cantilever block fails, and this mechanism ceases to contribute to shear resistance.

Therefore, cantilever action contributes only partially to shear resistance and is typically significant only in the initial stage when the structure has just started to crack.

2.2. Aggregate interlock

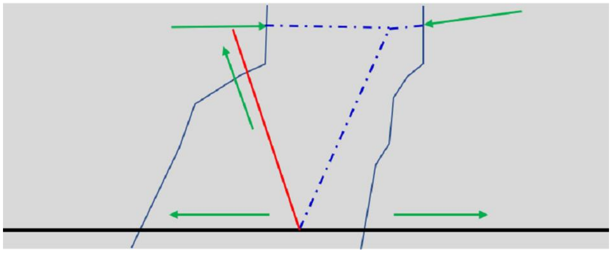

Figure 4: Aggregate interlock

Principle: When concrete cracks due to flexure-shear, the crack surface is not smooth and flat but rather rough because of the distribution of aggregates within the concrete. As the two crack faces tend to slide relative to each other, the aggregates interlock, resisting this sliding action. This resistance provides part of the shear force transfer across the crack.

The condition for this mechanism to occur is the development of flexural cracks (when the cantilever action begins to weaken and exceeds the limit at point A in Figure 3). At that stage, the roughness and the size of the aggregates determine the strength of the mechanism. Therefore, if the concrete contains larger aggregates, the crack surface will be rougher, leading to stronger interlock.

This mechanism remains effective even after the longitudinal reinforcement has yielded, which makes it particularly important in the final stage of shear resistance.

Influencing factors: (according to Walraven 1981, Muttoni 1989, Muttoni & Fernández Ruiz 2008):

- Crack width: narrower cracks → stronger interlock.

- Surface roughness of the crack: rougher surfaces → greater interlock force.

- Aggregate size: larger particles → rougher crack → increased force transfer.

- Concrete strength: higher-strength concrete → smoother crack surfaces (due to finer aggregates and stronger paste) → reduced interlock.

This mechanism is crucial once the concrete has cracked, as it allows the structure to continue resisting shear through the mechanical interlocking of aggregates along the crack surfaces. For this reason, the new Eurocode explicitly incorporates the influence of aggregate size and crack shape into the shear resistance prediction formulas.

2.3. Dowel action

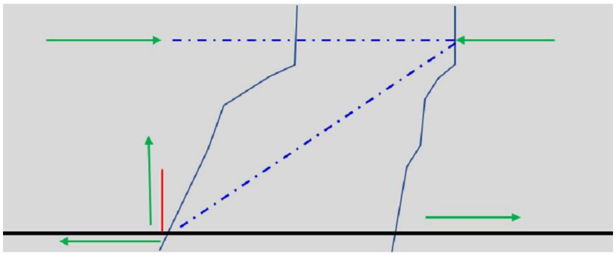

Figure 5: Dowel action

Principle: When a beam or slab cracks, the longitudinal reinforcement (flexural reinforcement) is intersected by the crack. At this stage, the reinforcement acts like a dowel crossing the crack, resisting the relative sliding of the two concrete parts. As a result, part of the shear force can be transferred through shear stresses developed in the reinforcement.

Limitation: When reinforcement acts as a dowel, very high localized tensile stresses develop in the surrounding concrete cover. These stresses cause delamination cracks along the interface between the reinforcement and the concrete, which gradually reduces the ability of the dowel mechanism to transfer shear.

Therefore, although reinforcement can theoretically contribute to shear transfer, in practice its effectiveness is very limited. Mörsch observed this mechanism at an early stage, and modern studies (Muttoni & Fernández Ruiz, 2008) have confirmed that dowel action contributes only marginally to the overall shear resistance in members without stirrups.

For this reason, in modern design codes (Eurocode 2, ACI, etc.), this mechanism is usually neglected or only considered as a very minor contribution to the total shear resistance.

2.4. Concrete's tension

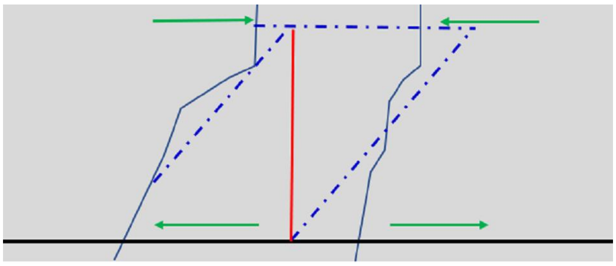

Figure 6: Residual tension

Principle: When beams or slabs are subjected to loading, inclined flexural-shear cracks develop in the shear region. Even after cracking, at the crack tip or when the crack width remains very small, the concrete is still able to provide some residual tensile strength.

Condition: This mechanism is effective only when cracks are narrow. Once the crack widens (due to increasing load or plastic deformations), concrete can no longer sustain tensile stresses, and the mechanism essentially disappears.

It is most relevant in the early stage after cracking, or in members where crack opening is limited (e.g., thin slabs, short beams, or elements with well-distributed reinforcement). In design practice, the contribution of residual tensile strength of concrete is usually not considered separately but rather incorporated into empirical models for overall shear resistance.

2.5. Arching action

In addition, there is the arching action mechanism: if the beam is short and deep (with a small span-to-depth ratio), compressive forces can be transferred through a "compression arch" from the load point to the supports, thereby reducing the demand on reinforcement.

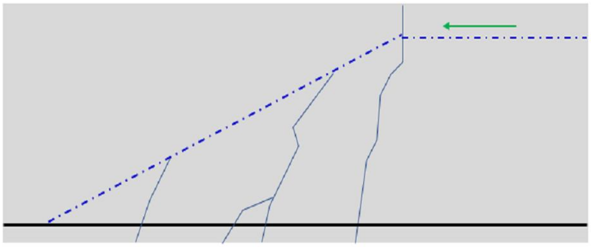

Figure 7: Arching action

When a/d is small (short beams) → the arching action (compression arch) dominates, resulting in very high shear resistance.

When a/d is large (slender beams) → the arching effect diminishes, and shear resistance mainly relies on cantilever action, aggregate interlock, and dowel action, leading to reduced shear capacity.

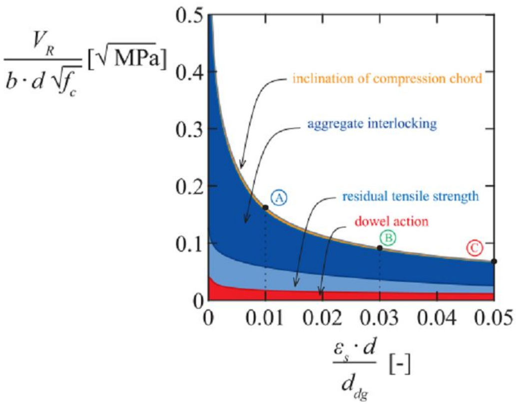

Figure 8: Shear resistance contribution of concrete (source: Muttoni and Fernández Ruiz)

As the deformation increases, the shear resistance of concrete shows a clear change in the relative contribution of different mechanisms. The contribution from compression chord inclination becomes negligible. In contrast, aggregate interlocking increasingly demonstrates its dominant role, becoming the prevailing mechanism in maintaining shear resistance. The residual tensile strength rapidly loses its significance as crack width increases. Dowel action remains relatively stable and decreases only slightly with increasing steel deformation, mainly serving as a supplementary mechanism. At large deformations, the overall shear resistance of concrete decreases significantly, in which aggregate interlocking is almost the only mechanism that still has a noticeable influence. This indicates that the shear resistance of concrete strongly depends on deformation and is governed by multiple mechanisms, with aggregate interlocking being the most important one at the final stage.

3. UPDATE IN EUROCODE 2 – 2nd GEN

3.1. Checking and Calculation Process

Verification of shear resistance may be omitted provided that the shear stress satisfies the condition:

$\tau_{Ed} \leq \tau_{Rdc,min}$ (equivalent to v_{min} in the current version of Eurocode 2).

- No shear reinforcement is required in regions of members where:

$\tau_{Ed} \leq \tau_{Rdc}$ (equivalent to V_{Rdc} in the current Eurocode 2).

- In other cases, shear reinforcement must be calculated, and it is necessary to ensure that brittle crushing of compression struts does not occur by satisfying the condition:

$\tau_{Ed} \leq \tau_{Rd}$ (equivalent to $V_{Rd,max}$ in the current Eurocode).

- The main difference is that the 2nd-Generation Eurocode 2 no longer refers to the conventional reference shear stress $\tau_{Ed}=V_{Ed}/(b.d)$ as before, but replaces d by z – the lever arm, taken as z = 0.9d. The updated formula in the revised standard is:

$$\tau_{Ed} = V_{Ed}/(b \cdot z) \quad (1)$$

The limiting shear stress $\tau_{Rdc,min}$ has been modified to account for the following factors:

- Size effect: The current design provisions underestimate the influence of the size effect, which may lead to unsafe design solutions for members with large effective depths d. Therefore, the size-effect law must be corrected in the next generation of EN 1992-1-1 (this was one of the main drivers for the revision).

- Influence of aggregate size, which was also neglected in the previous version.

- Effect of shear slenderness.

3.2. Minimum shear resistance $\tau_{Rdc,min}$

3.2.1. Critical Crack Theory and Formula for Shear Resistance in Concrete

The initial proposed formula describes the shear resistance of concrete as a function of the strain in the longitudinal tensile reinforcement:

$$V_{Rc} = \frac{0,3}{1+\varepsilon_v.d.k_{dg}}.\sqrt{f_c}.b_w.d \quad (2)$$

where:

- V_{Rc}: Shear resistance;

- ε_v: Strain in the longitudinal reinforcement;

- k_{dg}: Influence of aggregate size, defined as $48/(16+D_{lower})$;

- D_{lower} is the smallest upper sieve size used for the coarsest fraction of aggregates, determined according to EN 206 (or replaced by D_{max} if available - the maximum aggregate size in the concrete mix, determined according to EN 206 based on design and placement requirements);

- f_c: Compressive strength of concrete;

- b_w, d: Section width and effective depth of the member.

Based on Equation (2), it can be seen that as the strain in the reinforcement increases - meaning the crack width becomes larger - the shear resistance of the concrete decreases.

Within the range where the stress–strain relationship of the longitudinal reinforcement remains linear, we have:

$$\varepsilon_v = \frac{M_E}{z.A_S.E_s} = \frac{V_E.a_{cs}}{z.p_1.b_w.d.E_s} \quad (3)$$

where:

- M_E và V_E: The bending moment and shear force at the section under consideration.

- $a_{cs} = |M_E/V_E|$.

- A_s và p_l: The area and reinforcement ratio of the longi. tensile reinforcement,

- E_s: Modulus of elasticity of steel reinforcement.

- z: Lever arm (can be 0.9d).

The direct problem, i.e., calculating $V_{R,c}$ from the longitudinal reinforcement strain when the moment and shear force are known, is relatively straightforward. However, in the inverse problem of determining the shear resistance of concrete $V_{Rd,c}$, it is necessary to solve Equations (2) and (3) simultaneously.

3.2.2 Update of the Simplified Formula

Based on equation (2), Eurocode 2nd Generation has improved the formulation into the following general expression:

$$V_{Rc} = k.\left(\frac{f_c.d_{dg}}{\varepsilon_v.d}\right)^{0.5}.b_w.d \quad (4)$$

where:

- $k = 0.015 .(a_{cs}/d)^{0.25}$.

- $d_{dg} = 16mm + D_{lower} \leq 40mm$.

- a_{cs}/d - the shear slenderness represents the shear span-to-effective depth, indicating the dominant shear transfer mechanism in the member.

It is known that $a_{cs} = |M_E/V_E|$, which becomes difficult in shear verification since it requires checking many positions along a member.

When a_{cs} increases (M/V is large) → the shear span is longer, the beam is less affected by concentrated shear, and its behavior tends more toward pure flexure. Conversely, when a_{cs} decreases → the shear span is shorter, loads are closer to the support, and the behavior is dominated by shear rather than flexure, which reduces the shear resistance of the section.

For these reasons, $\tau_{Rdc,min}$ ensures that the member reaches flexural and shear failure simultaneously. Eurocode 2 simplifies the formula to apply for various loading cases and adopts a reference value of a_{cs} = 4d, based on a large number of combined experimental results. By substituting $\varepsilon_v = f_y / E_s$, E_s = 200.000 Mpa và z = 0.9d and converting into stress form, the following expression is obtained:

$$\tau_{Rdc,min} = \frac{11}{y_v}\left(\frac{f_{ck}.d_{dg}}{f_{yd}.d}\right)^{0.5} \quad (5)$$

where γ_v is the partial safety factor, typically taken as 1.4.

In practice, the longitudinal reinforcement stress at positions with high shear forces (e.g. near supports) is usually higher than the required reinforcement ratio - in fact, Eurocode's detailing provisions require a minimum amount of longitudinal reinforcement near the supports even when the bending moment is zero. Therefore, equation (5) is considered very safe, since it still assumes the reinforcement stress to be f_{yd} instead of the actual (usually lower) stress.

A more refined formula can be applied:

$$\tau_{Rdc,min} = \frac{11}{y_v}\left(\frac{f_{ck}.d_{dg}}{f_{yd}.d}.\frac{p_{pr}}{p_{req}}\right)^{0.5} \quad (6)$$

where:

- ρ_{pr}: Actual longitudinal reinforcement ratio;

- p_{req}: Required longitudinal reinforcement ratio.

For simplicity in practical applications, the new version of Eurocode 2 only proposes equation (5) and does not adopt equation (6).

3.2.3. Comparison with the Current Eurocode 2

Converting into force values, we have:

- Current Eurocode 2:

$V_{Rdc,min} = 0.035 \,.\, k \,.\, f_{ck}^{1/2} \,.\, b.\, d$, with k = 0.15

- New Eurocode 2:

$$\tau_{Rdc,min} = \frac{11}{y_v}\left(\frac{f_{ck}.d_{dg}}{f_{yd}.d}\right)^{0.5}.b.z$$

With b = 1000 mm, f_{ck} = 32 MPa and varying the beam depth from 400 to 1500 mm, the following comparison chart is obtained:

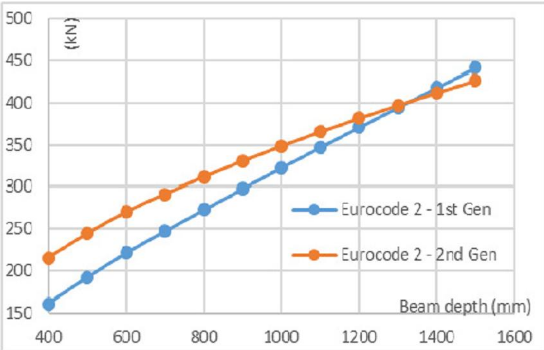

Figure 9: ***$V_{Rdc,min}$ in function of depth (mm)***

3.3 Critical Shear Resistance of Concrete

3.3.1 Formulation Development

From equations (2) and (3), it is possible to solve the system of equations when, at the ultimate state, $V_{Rdc} = V_{Ed}$. This is equivalent to determining V_{Rdc} of a cross-section when the shear force at that section is not yet known.

$$V_{Rc} = k.\left(\frac{f_c.d_{dg}}{\varepsilon_v.d}\right)^{0.5}.b_w.d \qquad (4)$$

where: $k = 0.015 \,.\, (a_{cs}/d)^{0.25}$, $V_E = V_{Rc}$

$$\varepsilon_v = \frac{M_E}{z.A_S.E_s} = \frac{V_E.a_{cs}}{z.p_1.b_w.d.E_s} \qquad (5)$$

Thus:

$$V_{Rc} = 0.015.\left(\frac{f_c.d_g}{V_{Rc}.\sqrt{a_{cs}}.d}.p_1.b.E_s.z\right)^{1/2}.b.d$$

With z = 0.9d, E_s = 200.000MPa, we obtain:

$$V_{Rc} = 0.6.\left(100.p_1.f_c\frac{d_{dg}}{\sqrt{\frac{a_{cs}}{4}}.d}\right)^{1/3}.b.d$$

Eurocode 2 – 2nd Generation provides the following simplified expression (with a_{cs} = 4d):

$$\tau_{Rd,c} = \frac{V_{Rd,c}}{b_w.z} = \frac{0.66}{\gamma_v}.\left(100.p_1.f_{ck}.\frac{d_{dg}}{d}\right)^{1/3} \qquad (7)$$

3.3.2. Comparison with the Current Eurocode 2

Converting into force values, we have:

- Current Eurocode 2:

$$V_{Rdc} = \frac{0.18}{\gamma_c}.k.\left(100.p_1.f_{ck}\right)^{1/3}.b.d\text{ , với } k = 0.15$$

- New Eurocode 2:

$$V_{Rdc} = \frac{0.66}{\gamma_v}.\left(100.p_1.f_{ck}.\frac{d_{dg}}{d}\right)^{1/3}.b.z$$

With b = 1000 mm, f_{ck} = 32 MPa, p_l = 0.5% and varying the beam depth from 400 - 1000 mm, the following comparison chart is obtained:

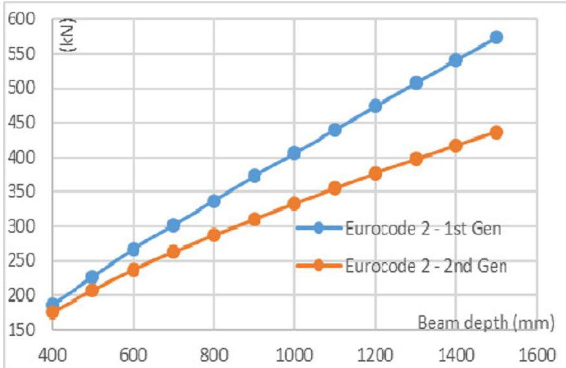

Figure 10: ***V_{Rdc} versus beam depth***

The final shear resistance of the cross-section shall be taken as the greater value between V_{Rdc} (from Figure 10) and $V_{Rdc,min}$ (from Figure 9) comparing the concrete section resistance with the current version:

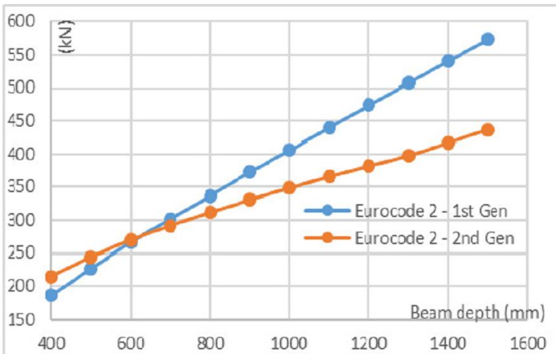

Figure 11. The final V_{Rdc} versus beam depth (greater value from Figure 9 and 10)

The results in Figure 11 highlight the significant influence of member size on the shear resistance V_{Rdc}, particularly for beams with large depths. This is precisely the factor that led to the changes in the new version of Eurocode.

3.4. Design of Shear Reinforcement

In the new version of Eurocode 2, there is no change in the formula for calculating the shear reinforcement:

$$\tau_{Ed} = \frac{A_{sw}}{b.s}.f_{ywd}.\cot\theta \qquad (8)$$

where A_{sw} is the area of shear reinforcement, b is the width of beam, s is the spacing of stirrups, f_{ywd} is the design yield strength of the shear reinforcement, and θ is the angle of the concrete compression strut.

The fact that this formula remains the same in the updated Eurocode is logical because the design approach is still fundamentally based on the Strut-and-Tie model. This theoretical framework models the flow of forces in a concrete member using a truss analogy, where concrete takes the role of compression struts and reinforcement acts as tension ties. Since this underlying concept has not changed, the equation for calculating required shear reinforcement continues to be valid and reliable.

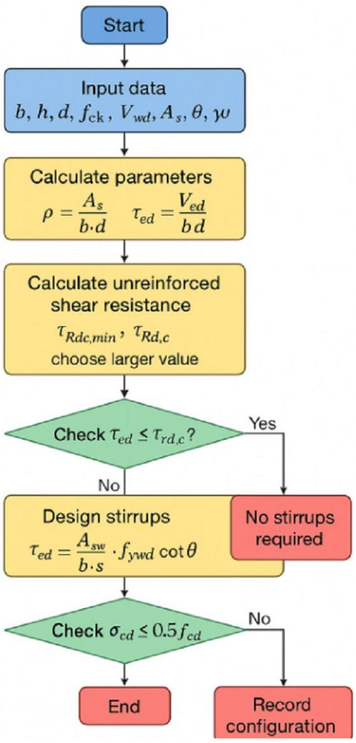

Figure 12: The flow chart

Likewise, based on the anti-bursting concept in the Strut-and-Tie theory, the limitation on shear stress (shear force in the previous code) also remains the same:

$$\tau_{Ed} \le \frac{v.f_{cd}}{\cot\theta + \tan\theta} \qquad (9)$$

where ν is a strength reduction factor and f_{cd} is the design compressive strength of concrete.

Example calculation:

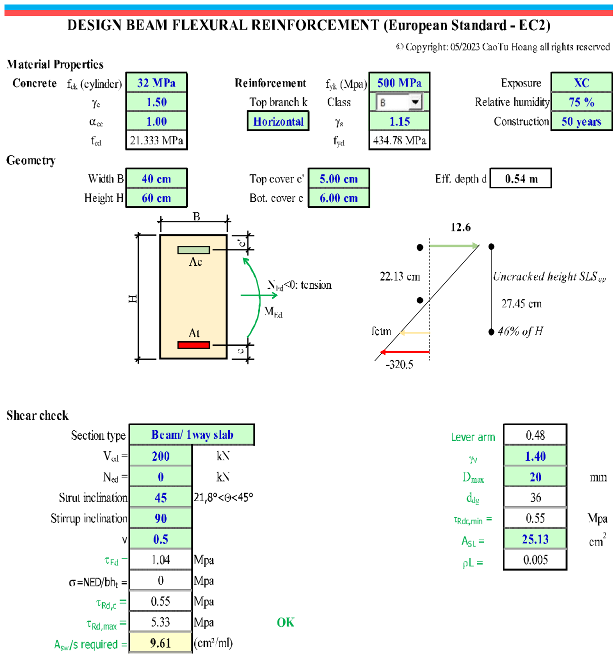

Figure 13: Example shear check for a simple case

3.5. Key Considerations in Checking the Shear Capacity of Structural Members

- Verification in the D-region (discontinuity region near supports or concentrated loads): For members subjected to significant concentrated loads located at a distance less than d from the support, it is recommended to design using the Strut-and-Tie Model (STM) or by reducing the shear stress, as specified in the previous version of Eurocode. This approach is particularly relevant for elements such as corbels or pile caps.

- At the support, attention should be paid to the tensile force induced by shear, which may be distributed equally between the top chord and the bottom chord of the beam.

$$N_{Vd} = |V_{Ed}|.\cot\theta \qquad (10)$$

$$F_{td} = \frac{M_{Ed}}{z} + \frac{N_{Vd} + N_{Ed}}{2} \qquad (11)$$

$$F_{td} = \frac{M_{Ed}}{z} - \frac{N_{Vd} + N_{Ed}}{2} \qquad (12)$$

3.6 French National Annex - Anchorage verification at supports

The distribution of the tensile force induced by diagonal shear at the support is considered relatively sensitive from a design perspective. Some members of the French Eurocode committee have proposed using a different diagonal compression angle, referred to as θ_A, which can be understood as an average diagonal compression angle used to calculate the tensile force generated by shear near the edge support.

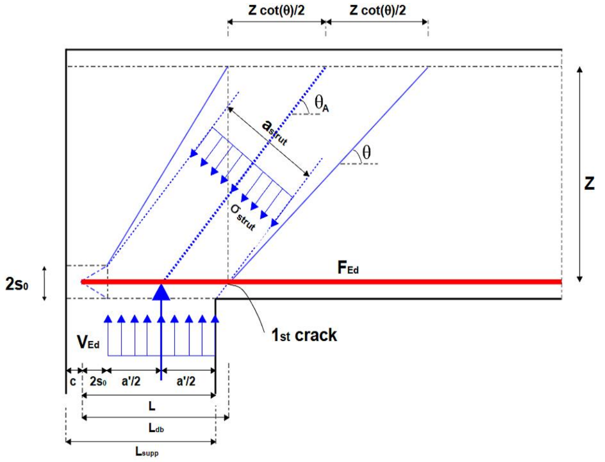

Figure 14: Strut-and-tie model at the edge support

θ_A is calculated using the following formula:

$$\cot_{\theta_A} = \left(a + z\cot_{\theta} - c_{nom}\right) / 2z \quad (13)$$

The tensile force induced by shear:

$$N_{Vd} = \left|V_{Ed}\right|.\cot_{\theta_A} \quad (14)$$

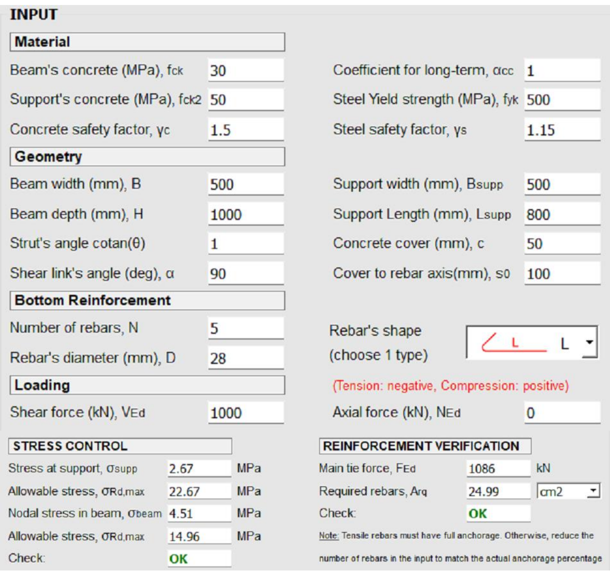

Figure 15: Example of support anchorage check by BTF software

Note: In addition to checking the anchorage forces of longitudinal reinforcement, it is also necessary to verify the stresses at the nodal zones as required by Eurocode for the Strut-and-Tie model. In this example, the C-C-T (compression–compression–tension) node is subject to a significantly reduced maximum allowable stress compared to f_{ck} (according to Eurocode 2).

4. CONCLUSION

The updated shear design provisions in Eurocode 2 are derived from the Critical Shear Crack Theory (CSCT), which provides a more accurate representation of the shear resistance mechanism in concrete. CSCT explains the reduction in shear capacity as cracks develop and widen, while also highlighting the close relationship between deformation, crack width, and the ability of concrete to transfer shear stresses.

A major strength of this approach is that it incorporates practical influencing factors such as aggregate size, member depth, and structural working conditions. As a result, the shear resistance of concrete is no longer treated as a fixed empirical value, but rather described through the physical mechanism and actual deformation behavior of the material.

The implementation of CSCT in Eurocode 2 leads to a design approach that is theoretically more consistent while also ensuring greater practical safety. This is particularly important for members with large spans or those requiring high reliability, where previous empirical formulas often proved either overly conservative or inadequate.

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