

Chapter 3: Adhesion and Anchoring

3.1. Definition and Crucial Role of Adhesion

Adhesion refers to all the bonding forces that develop at the interface between the reinforcing steel and the concrete that encases it. These forces oppose the relative sliding of the steel bar with respect to the concrete matrix.

This adhesion is essential to validate a key assumption in the calculation of reinforced concrete structures: the absence of slippage between steel and concrete. This results in equal deformations in both materials at the same point ($\epsilon_b = \epsilon_s$), where ϵ_b is the deformation of the concrete and ϵ_s is the deformation of the steel.

Adhesion allows for the efficient transmission of forces (mainly tensile) from the concrete to the reinforcement, and vice versa, thus ensuring the behavior **Reinforced concrete is a composite material**. Without bonding, the steel and concrete would work independently, negating the purpose of reinforced concrete.

Adhesion is the bond that develops between reinforcing steel and the surrounding concrete, preventing relative slip between the two materials. It ensures strain compatibility ($\epsilon_b = \epsilon_s$), where ϵ_b and ϵ_s are the strains of concrete and steel, respectively. This bond enables the transfer of forces between concrete and reinforcement, allowing reinforced concrete to behave as a single composite material.

3.2. Physical Origins of Adhesion

Adhesion between steel and concrete results from three complementary mechanisms whose contribution depends on the type of reinforcement.:

3.2.1. Chemical Adhesion (Bonding):

Chemical adhesion is produced by molecular forces at the steel-concrete interface. It is weak and rapidly disappears due to micro-slip, cyclic loading, moisture, or temperature changes. Its contribution is significant only before loading or for smooth bars.

3.2.2. Adhesion by Friction:

Friction develops from the contact between the steel surface and hardened concrete. It is stronger than chemical adhesion and depends on the surface roughness of the bar and the transverse confinement provided by the surrounding concrete or transverse reinforcement.

3.2.3. Adhesion by mechanical meshing (Stamping):

Mechanical interlock is the main bonding mechanism for high-adherence (HA) bars. The ribs interlock with the concrete, transferring forces through compression and shear. This mechanism provides the highest bond strength but may induce radial cracks around the bar.

3.3. Failure modes related to adhesion (Fig. 3.1)

Under increasing tensile load, an anchored bar may fail in one of the following ways::

3.3.1. Tensile fracture of steel:

The reinforcing bar reaches its yield or ultimate strength before bond failure occurs. This represents a perfect anchorage, where the anchorage length is sufficient to fully develop the steel strength.

3.3.2. Bar Pull-Out:

The bond strength is exceeded, causing the bar to slip within the concrete. This failure is generally due to insufficient anchorage length, weak concrete, or poor bond conditions, and should be avoided.

3.3.3. Detachment of a concrete cone (Splitting):

For HA bars, high bond stresses may crack the surrounding concrete, leading to the formation of a concrete cone. This failure is promoted by inadequate concrete cover, low concrete strength, or insufficient transverse reinforcement.

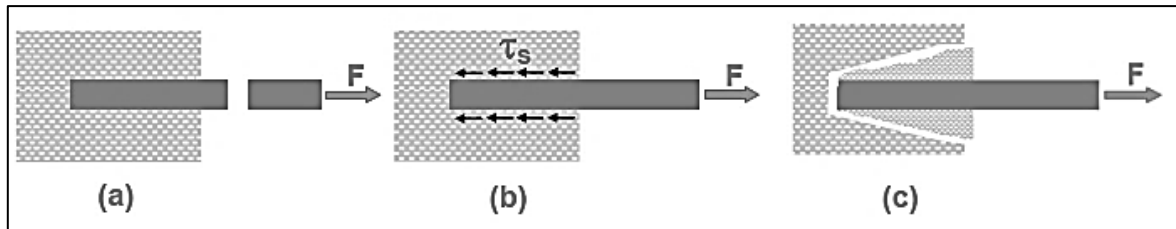


Figure 3.1: Types of failures in a pull-out test of a bar sealed in a concrete block.

3.4. Factors influencing steel-concrete adhesion

The bond strength between steel and concrete depends on several factors:

- **Bar Surface Condition:** HA bars provide better bond than smooth bars due to mechanical interlock.
- **Bar Geometry:** Rib shape, spacing, and height improve interlocking and reduce shear stresses.
- **Bar Spacing:** Closely spaced bars reduce the effective bond area and increase the risk of concrete cracking.
- **Concrete Strength (f_{cj}) or (f_{c28}):** Higher concrete strength improves bond resistance and reduces the risk of pull-out.
- **Transverse Compression:** Confinement from prestressing, support reactions, or transverse reinforcement enhances bond strength.
- **Concrete Cover:** Adequate cover protects reinforcement, ensures proper confinement, and prevents splitting failure

3.5. Bond Stress (τ_s): Local Measurement of the Steel-Concrete Bond

ond stress, denoted τ_s , represents the bond force per unit contact area between reinforcing steel and the surrounding concrete. It is defined by:

$$\tau_s = \frac{\left(\frac{dF}{dx}\right)}{u} \quad (\text{Eq.3.1})$$

or :

dF/dx (N/m or kN /m): axial force gradient along the reinforcing bar. The tensile force (**F**) along the bar per unit length **x** is **physically proportional to the tensile strength along the bar** ($dF/dx < 0$). This means that the force is transmitted to the surrounding concrete via adhesion. Therefore, the absolute value $|dF/dx|$ is directly proportional to the strength of the adhesion force over the length dx .

u (m): effective perimeter of the steel in contact with concrete..

- For an isolated bar of diameter $\emptyset$: $u = \pi \cdot \emptyset$

- For a bundle of bars (generally limited to 2 or 3 identical bars in contact): u is the perimeter of the convex hull (net) of the bundle. *Example:* For 2 bars side by side of diameter $\emptyset$, $u \approx 2 \cdot \emptyset + \pi \cdot \emptyset$ (outer perimeter of the "8" formed by the two circles).

τ_s (MPa or N/mm²): average bond stress acting at the steel–concrete interface.

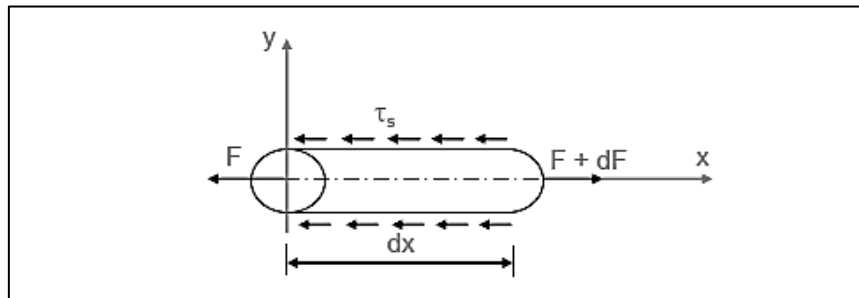


Figure 3.2. Equilibrium of a bar segment of length dx

3.5.1 . Physical Interpretation:

- Force Transfer:**

When a reinforcing bar embedded in concrete is subjected to a tensile force F , this force decreases along the anchorage length as it is transferred to the surrounding concrete through bond stresses. Over an infinitesimal length dx , equilibrium is expressed by:

$dF = \tau_s \cdot u \cdot dx$, where u is the bar perimeter and τ_s is the bond stress. Thus $\tau_s = (dF/dx)/u$.

A larger bar perimeter provides a greater contact area, reducing the bond stress required to transfer a given force.

3.5.2. Practical Importance:

Bond stress is essential for:

- Anchorage design:** determining the required anchorage length to fully develop the reinforcement strength without pull-out.
- Structural verification:** checking that the actual bond stress does not exceed the allowable value, particularly near supports and lap splices.
- Design calculations:** evaluating the ultimate bond stress according to design codes, considering concrete strength, bar type, bar diameter, casting conditions, and transverse compression.

3.6. Limit Bond Stress

The ultimate bond stress (τ_{su}) is the maximum allowable bond stress that prevents reinforcement slippage. According to BAEL::

$$\tau_{su} = 0.6 \cdot \psi_s^2 \cdot f_{tj} \quad (\text{Eq.3.2})$$

The coefficient 0.6 is an overall safety factor, derived from experimental analysis and modeling, which incorporates the variability of material properties and uncertainties related to the transmission of forces.

The term ψ_s^2 , called the sealing coefficient, depends directly on the nature of the steel surface: it is **1** for smooth steels (offering adhesion mainly through friction) and **1.5** for high adhesion (HA) steels (whose asperities generate a more efficient mechanical interlocking mobilizing the strength of the concrete).

Finally, f_{tj} denotes the characteristic tensile strength of the concrete at j days, expressed in MPa. This is itself estimated from the compressive strength of the concrete (f_{cj}) via the following relationship:

$$f_{tj} = 0.6 + 0.06 \cdot f_{cj} \quad (\text{Eq.3.3})$$

The allowable bond stress therefore depends on both the bar surface condition and the tensile strength of the surrounding concrete. Exceeding this limit may lead to reinforcement slip and local concrete damage, reducing the structural performance..

3.7. Anchorage of Reinforcement

Anchorage ensures that a reinforcing bar transfers its tensile force safely to the surrounding concrete through bond stresses, without slip or pull-out..

3.7.1 Straight Anchorage

The straight anchorage length (l_s) is the minimum length required to fully develop the yield strength of a reinforcing bar of diameter ϕ .

$$F_{\text{traction}} = \frac{\pi \cdot \phi^2 \cdot f_e}{4} \quad (\text{Eq.3.4})$$

Total adhesive strength:

$$F_{\text{adherence}} = \pi \phi \cdot l_s \cdot \tau_{su} \quad (\text{Eq.3.5})$$

Or

τ is the limit stress of adhesion defined previously.

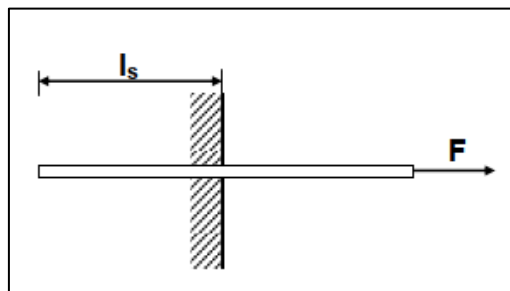


Figure 3.3. Straight anchorage

By solving the equality of equations (Eq.3.4 and Eq.3.5), we obtain the following relationship:

$$l_s = \frac{\phi \cdot f_e}{4 \tau_{su}} \quad (\text{Eq.3.6})$$

The required anchorage length increases with the bar diameter (ϕ) and steel yield strength (f_e), and decreases as the bond strength (τ_{su}) increases.

For practical design, standard codes often recommend simplified values:

- **40 ϕ** for HA Fe E 400 bars.
- **50 ϕ** for HA Fe E 500 and smooth bars.

These values include safety margins and are generally sufficient to prevent bar slippage under normal design conditions.

3.7.2 Straight Anchorage Length for Bar Bundles

Although reinforcing bars may be grouped into bundles for construction convenience, each bar must be anchored individually, as required by BAEL Article A.6.1.21. This requirement is based on the following reasons:

3.7.2.1. Concentration of adhesion stresses :

Bundled bars reduce the effective concrete–steel contact area, increasing bond stresses and the risk of exceeding the allowable bond stress (τ_{su}).

3.7.2.2. Risk of cracking :

Closely spaced bars hinder proper concrete compaction, creating voids that promote radial cracking and reduce bond performance.

3.7.2.3. Collective slip :

If the bundle is anchored as a single unit, bond failure of one bar may trigger slip of the entire bundle, reducing the load-carrying capacity of the member.

Figure 3.4 shows the anchorage length of the bar bundle.

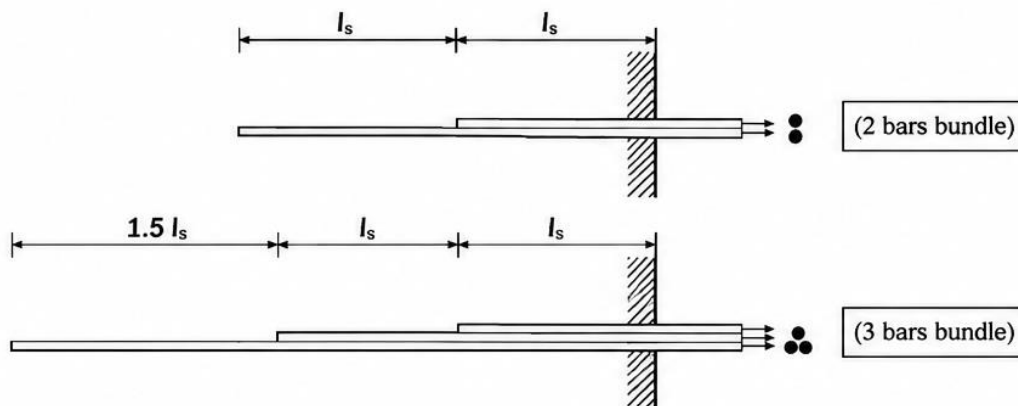


Figure 3.4: Straight anchoring in the case of a 2 or 3 bar bundle

3.7.3. Curved Anchor (or Hook Anchor):

When the available space is insufficient to provide the required straight anchorage length, a curved (hook) anchorage is used. This solution reduces the required anchorage space while ensuring adequate force transfer between the reinforcement and the surrounding concrete:

A curved anchorage consists of three parts (Figure 3.5):

- **Initial straight segment (AB):** Length ℓ_2 , providing the transition from the straight bar to the curved portion.
- **Curved segment (BC):** A circular arc with radius r and central angle θ (typically 90° , 135° , or 180°), which improves force transfer and reduces stress concentration in the concrete.
- **Terminal straight segment (CD):** Length ℓ_1 , providing the final anchorage and contributing significantly to the bond resistance.

Figure 3.5 illustrates the geometry of a curved anchorage.

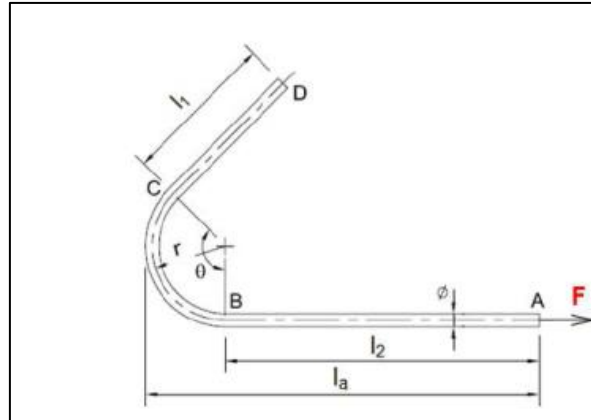


Figure 3.5: Curved anchorage of tension bars

3.7.3.1. Minimum Bend Radius (BAEL Standard A.6.1)

The minimum bend radius is specified to prevent damage to the reinforcing steel during bending and to reduce stress concentrations in the surrounding concrete. The required radius depends on the steel type and the function of the reinforcement.

Table 3.1 presents the minimum bend radii specified by the BAEL standard.

type of steel	Structural element	Minimum radius (r)	Justification
Smooth round bars	Anchor hooks	$r \geq 3\phi$	Reduced risk of cracking (increased brittleness of smooth steels)
	Frames/Stirrups/Pins	$r \geq 2\phi$	Lower mechanical stresses (secondary role in shear)
High-grip (HA) bars	Anchor hooks	$r \geq 2\phi$	Improved ductility of HA steels
	Frames/Stirrups	$r \geq 2\phi$	Standardization and ease of implementation

Example : For an HA bar with diameter $\phi=12$ mm , a hook requires $r \geq 24$ mm .

3.7.3.2. Characteristics of Standard Hooks

The equivalent anchorage length (ℓ_s) represents the straight length that provides the same bond resistance as a curved anchorage. It depends on the hook angle (θ) and includes the following parameters (Table 3.2 and Figure 3.6):

- ℓ_1 : terminal straight segment (CD);
- ℓ_2 : initial straight segment (AB);
- r : bend radius;
- **Curvature coefficients**: factors accounting for the additional anchorage provided by the hook.

Table 3.2. Normative formulas (BAEL) for hooks with curved anchoring

Angle θ	Formula of ℓ_s	Physical explanation
90° (Figure 3.6(a))	$\ell_s = 1.87\ell_1 + \ell_2 + 2.19r$	Minimal anchoring, limited stopping effect
120° (Figure 3.6(b))	$\ell_s = 2.31\ell_1 + \ell_2 + 3.28r$	Size/strength optimization
135° (Figure 3.6(c))	$\ell_s = 2.57\ell_1 + \ell_2 + 3.92r$	Recommended standard (balance of performance/compactness)
180° (Figure 3.6(d))	$\ell_s = 3.51\ell_1 + \ell_2 + 6.28r$	Maximum anchoring (mechanical locking effect)

- ℓ_s : Equivalent straight sealing length (minimum regulatory value).
- $6.28r$: Corresponds to $2\pi r$ (full perimeter of the circle), reflecting the circular anchoring effect.

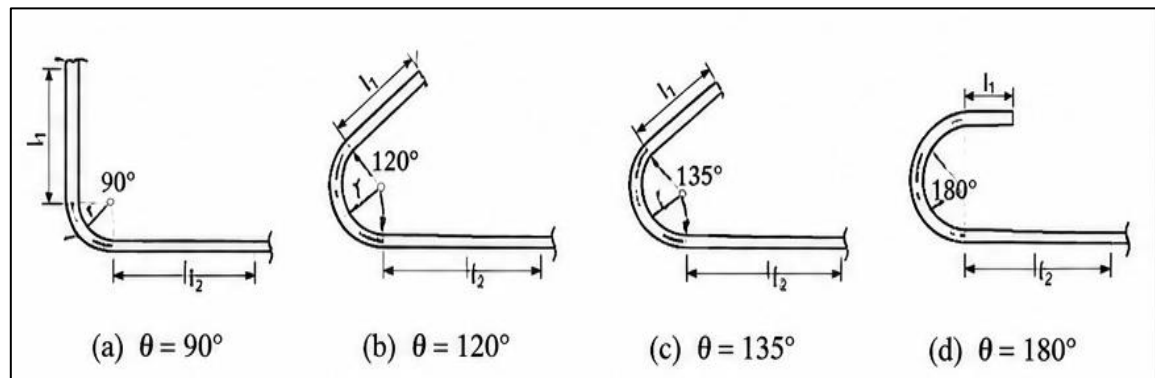


Figure 3.6. Characteristics of standard hooks with curved anchoring

Example:

A 135° bracket with $r = 3\phi$, $\ell_1 = 4\phi$, $\ell_2 = 2\phi$ gives:

$$\ell_s = 2.57 \times 4\phi + 2\phi + 3.92 \times 3\phi = 10.28\phi + 2\phi + 11.76\phi = 24.04\phi$$

This represents a reduction of approximately 30% compared to a straight anchorage ($\ell_s \approx 40\phi$ for HA steel in C25).

3.7.4. Anchorage of Stirrups, Ties, and Hairpins (BAEL A.6.1)

For transverse reinforcement, such as stirrups, ties, and hairpins, anchorage is provided by a bend followed by a straight extension. The bend provides mechanical anchorage, while the straight extension ensures adequate bond with the surrounding concrete.

The design requirements are illustrated in **Table 3.3** and **Figure 3.7**. The main requirements are:

- The bend radius shall satisfy $r \geq 2\phi$.
- The anchorage plane shall not deviate by more than $\pi/8$ (22.5°) from the plane of the main reinforcement.

Table 3.3. Minimum lengths of straight returns :

Angle of curvature	Minimum length of the right return
180° (full bend)	$\geq 5\phi$
135° (standard angle)	$\geq 10\phi$
90° (right angle)	$\geq 15\phi$

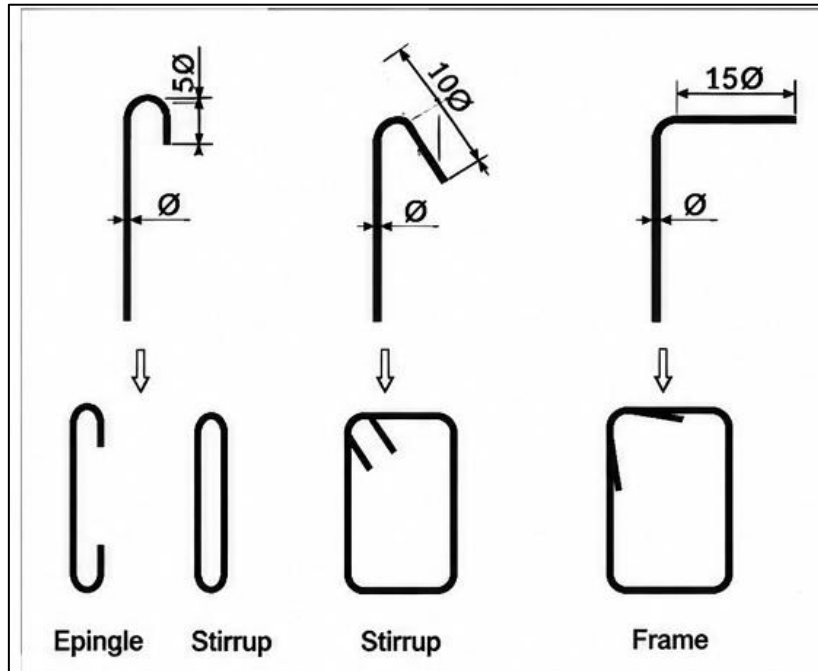


Figure 3.7: Anchoring of frames, stirrups and pins

3.8. Reinforcement Lap Splices

Because reinforcing bars are supplied in standard lengths (typically up to 12 m), long structural members require lap splices to ensure continuity of reinforcement.

The transfer of forces between overlapping bars is achieved by:

- Bond between the steel and the surrounding concrete along the lap length (l_r).
- Direct concrete compression for bars subjected to compression.

An insufficient lap length may result in bar slip or pull-out, leading to premature structural failure.

3.8.1. Straight Bars without Hooks

3.8.1.1. Tension Bars

a) Continuity by Simple Lap Splice

The spacing and detailing requirements for lap splices are illustrated in **Figure 3.8** and summarized in **Table 3.4**.

Table 3.4. Lap Splices for Straight Bars without Hooks.

Case	Distance between axes (c)	Length l_r
Tight alignment	$c \leq 5\phi$	$l_r = l_s$
Bars apart	$c > 5\phi$	$l_r = l_s + c$

- Physical explanation :**

- If $c \leq 5\phi$, the **stress fields** overlap → maximum efficiency.
- If $c > 5\phi$, a **leverage effect** appears → requires an additional length c to balance the moments.

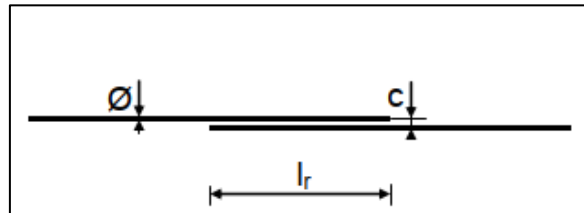


Figure 3.8: Simple overlap of the ends of the bars without hooks

Example : HA500 Ø16 bar ($l_s = 50\phi = 800$ mm):

- $c = 60$ mm (3.75ϕ) → $l_r = 800$ mm
- $c = 100$ mm (6.25ϕ) → $l_r = 800 + 100 = 900$ mm

b) Covering with joint cover

The bars are arranged side by side *without direct contact*, creating a **split transfer zone** (reduced risk of cracking) (Figure 3.9).

$$l_r = 2.l_s$$

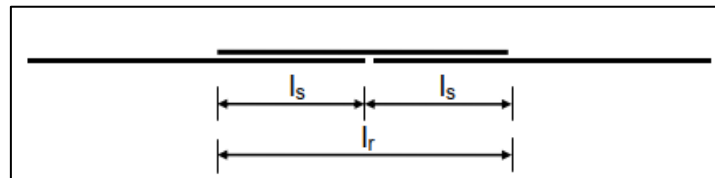


Fig. 3.9: Covering with joint cover

3.8.1.2 Compressed bars

a) Continuity by simple overlap (Figure 3.10)

- **Formula :** $l_r = 0.6.l_s$
 - Compression generates increased lateral steel-concrete friction.
 - Concrete actively participates in the transfer of forces → 40% reduction vs. tension.

Practical values (BAEL):

FeE400 $l_r = 24\phi$

FeE500 $l_r = 30\phi$

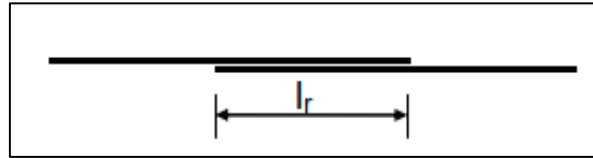


Fig. 3.10: Simple overlap of the ends of the compressed bars

3.8.1.3. Transverse Reinforcement for Lap Splices

Lap splices generate transverse tensile stresses in the surrounding concrete, which may lead to cracking or concrete splitting. To prevent this, transverse reinforcement (stirrups or ties) is provided to confine the splice region and maintain its integrity (Figure 3.11).

The total capacity of the transverse reinforcement shall satisfy:

$$\sum A_t \cdot f_{et} \geq \sum A_s \cdot f_e$$

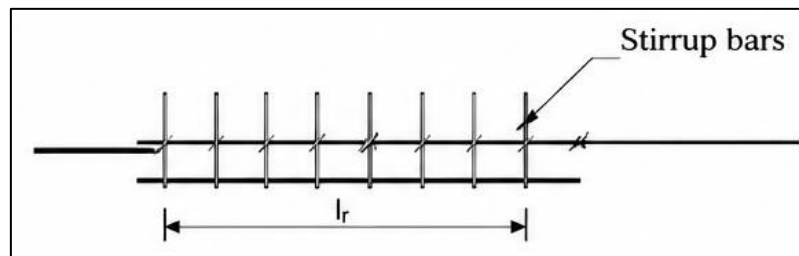


Figure 3.11: Seams of the joints

The diameter of the seam reinforcements must be chosen small enough to ensure a good distribution of these reinforcements throughout the seam.

3.8.2 Overlap of straight bars with normal hooks (BAEL)

Standard hooks optimize anchoring and reduce overlap length thanks to their **mechanical locking effect**.

Normal hook geometry (Figure 3.12)

- **Radius of curvature** : $r \geq 3\phi$ (smooth rounds) / $r \geq 2\phi$ (HA steels)
- **Right return** : $\geq 5\phi$
- **Angle** : $\theta = 180^\circ$

Overlap lengths l_r

- **Smooth circles**: $l_r = 0.6 l_s$, practical values: $l_r = 30 \phi$
- **High-adhesion (HA) steels (FeE400)**: $l_r = 0.4 l_s$, practical values: $l_r = 16 \phi$
- **HA steels (FeE500)**: $l_r = 0.4 l_s$, practical values: $l_r = 20 \phi$

Explanation :

- **Reduction of l_r** : The hook creates a **mechanical support point** in the concrete, decreasing the dependence on linear adhesion (-40% vs straight bars).
- **Difference between smooth steels and HA** : HA bars have better adhesion → additional reduction of 33%.

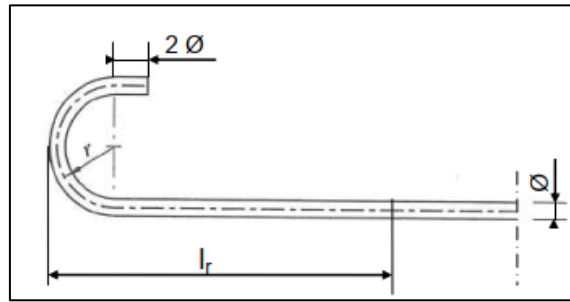


Figure 3.12: Shaping the normal hook

Example

- HA500 bar $\varnothing 16$: $l_r = 20 \times 16 = 320$ mm
- Smooth round $\varnothing 16$: $l_r = 30 \times 16 = 480$ mm

Figure 8.13 shows the construction arrangements for covers with normal hooks .

The arrangement of the hooks in plan and elevation is crucial to avoid stress concentrations and ensure efficient force transfer.

Overlap length rules l_r as a function of spacing c (Table 3.5)

(c = distance between the axes of the bars)

Table 3.5 . Overlaps with normal brackets .

Condition	Smooth circles	High-alloy (HA) steels (FeE400/500)	Physical explanation
$c \leq 5\phi$	$l_r = 0.6$	$l_r = 0.4l_s$	The nearby bars act as a "cohesive group" → direct transfer through mutual adhesion
$c > 5\phi$	$l_r = 0.6l_s + c$	$l_r = 0.4l_s + c$	The spacing creates leverage → requires additional length cc to balance the moment

Practical values :

- **Smooth circles** : $l_r = 30\phi$ (if $c \leq 5\phi$)
- **HA FeE400** : $l_r = 16\phi$
- **HA FeE500** : $l_r = 20\phi$

Example :

Bar HA20 FeE500 ($l_s = 50\phi$):

- $c = 80$ mm (4ϕ) → $l_r = 0.4 \times 50\phi = 20\phi = 400$ mm
- $c = 150$ mm (7.5ϕ) → $l_r = 400 + 150 = 550$ mm

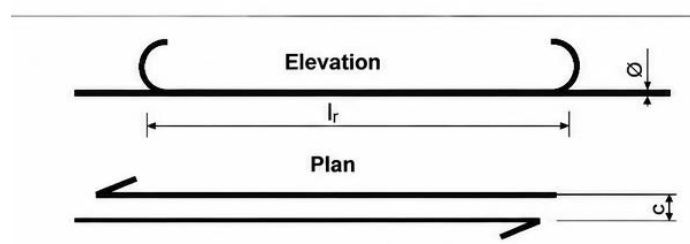


Fig. 3.13: Junction of tension bars with normal hooks