CHAPTER 07

Design for Bond in Reinforced Concrete

7.1 Introduction

In the previous chapters, we made an assumption that there exists a perfect bond between the steel and the surrounding concrete in order to have strain compatibility. In this chapter, we will elaborate this assumption along with the concept of development length. We will look into the fact that why anchoring of tensile bars are essential, how tor/deformed bars are better than plain bars, when the question of bond arises? We will understand what does 'bond stress' means along with the concept of 'bond strength'.

7.2 Bond in Reinforced Concrete

'Bond' in reinforced concrete is the adhesion (adhesive force) between the reinforcing steel bar and the surrounding concrete. Due to this bond only it is possible to transfer the axial force from the reinforcing steel to the surrounding concrete thus thereby introducing strain compatibility, composite/combined action of steel and concrete which avoids slippage of reinforcing bars from within the concrete. The basic assumption of flexural theory that plane sections remain plane before and after the bending is valid only if bond between the concrete and the steel is effective.

Remember: In the absence of bond, the reinforcing bar in concrete is just like a string only wherein the stress is constant at all the points on the string.

It is because of the bond only that the axial stress (tensile, compressive) in the reinforcing bar vary along its length from point to point. This is essential to accommodate the variation in bending moment along the length of flexural member.

7.3 Mechanism of Force Transfer Through Bond

Transfer of force due to bond in reinforced concrete is achieved by the following mechanisms:

1. Chemical adhesion due to sticky glue like properties of certain products of hydration of cement in concrete.
2. Frictional resistance due to surface roughness of reinforcement and the grip exerted by the surrounding concrete.
3. Mechanical interlocking due to surface protrusions/ribs on deformed reinforcing bars which is in fact not available for plain reinforcing bars.

7.4 Bond Stress

Bond resistance is achieved by development of tangential (shear) stress along the interface (contact surface) between the reinforcing bars and the concrete. The stress developed at the interface of steel and concrete is called as bond stress.

7.5 Various Types of Bond in Reinforced Concrete

There are two major types of bond according to the types of loading as:

1. **Flexural bond:** It comes into play in flexural members on account of shear or variation in bending moment. This in turn causes a variation in the axial tension along the length of reinforcing bar. Flexural bond is critical at locations where shear ($V = dM/dx$) is significant.
2. **Anchorage/development bond:** It arises over the length of anchorage provided for a bar or at the end of reinforcing bar. This bond resists the pulling out of bar if it is in tension or pushing in of the bar if it is in compression.

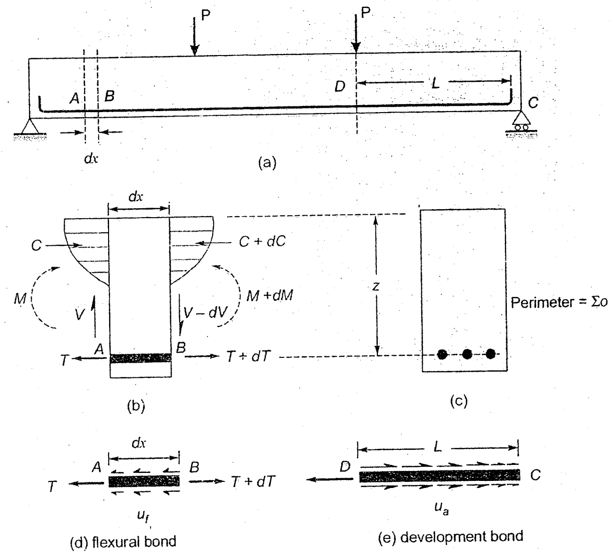


Fig. 7.1 *Different types of bond in reinforced concrete*

7.6 Flexural Bond

The variation in tension along the length of reinforcing bar owing to varying bending moment is due to flexural bond. Consider two sections on a beam distant 'dx' apart as shown in the Fig. 7.1, which are acted upon by a differential moment 'dM'. If 'z' is the lever arm then, At section A, $M = Cz = Tz$

and at section B, $M + dM = (C + dC)z = (T + dT)z$

From above two equations, $dT = \dfrac{dM}{z}$ ...(i)

Therefore, force 'dT' which is the unbalanced force in the bar actually gets transferred to the surrounding concrete. This force transfer through this mechanism is called as **flexural bond**. This force gets developed along the interface of reinforcing bar and the surrounding concrete.

Let, Σo = Total perimeter of all the reinforcing bars at the beam section under consideration

dx = Elementary length of the beam under consideration

u_f = Flexural bond stress

Thus, $u_f(\Sigma o)dx = dT$ ...(ii)

From equations (i) and (ii),

$$u_f = \frac{dM/z}{(\Sigma o)dx} = \frac{V}{(\Sigma o)z} \quad ...(iii)$$

where, V = Transverse shear force at the section = $\dfrac{dM}{dx}$

Thus flexural bond stress is high at locations of high shear force (V) and the term (Σo) in the denominator indicates that flexural bond stress can be reduced by using small diameter of large number of bars.

7.6.1 Factors Affecting The Flexural Bond Stress

The actual flexural bond stress gets affected by the following factors:

1. Appearance of flexural cracking.
2. Local slip of reinforcing bars in concrete.
3. Splitting of concrete and other secondary effects.

Do You Know?

How Flexural Cracking in Reinforced Concrete Affects The Flexural Bond Stress?

From equation (iii) above, it is evident that flexural bond stress (u_f) varies with the transverse shear force (V).

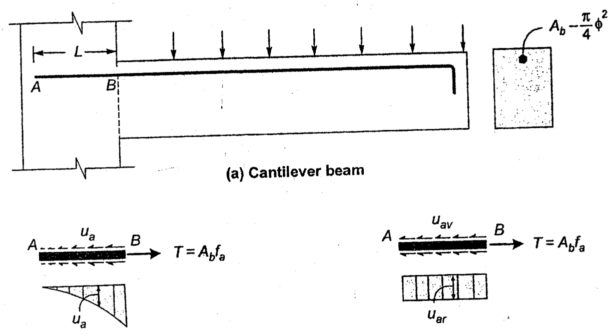
Thus, when, $V = 0,\ u_f = 0$

i.e. no flexural bond stress will be developed at the locations of zero shear force. But in reality, this is NOT true. The tensile force in the reinforcing bar (dT) varies between the flexural crack locations even at the locations of constant bending moments. At the locations of flexural cracks, tension is carried by reinforcing bars only but at locations in between the cracks, concrete do take some tension thereby reducing the tensile stress in reinforcing bar to some extent.

Remember: Flexural cracks are in general NOT present in the compression region of beam.

7.7 Anchorage/Development Bond

This anchorage/development bond gets developed at the extreme cut-off end of the bar subjected to tensile force/ compressive force.



(a) Cantilever beam

(b) Probable variation of anchorage bond stress u_a

(c) Assumed uniform average bond stress u_{ar}

Fig. 7.2 *Anchorage/development bond in reinforced concrete*

In Fig. 7.2 shown above, the stress is zero at the end A of the reinforcing bar and at end B, the bending moment is maximum and hence the tensile stress is maximum at B. This variation of force between the ends A and B is transferred to the surrounding concrete by anchorage bond stress in the beam.

An expression for the average bond stress (u_{avg}) can be obtained by assuming a constant bond stress distribution over the length 'L' of the reinforcing bar.

$$\pi\phi L(u_{avg}) = \frac{\pi}{4}\phi^2 f_s$$

$$u_{avg} = \frac{\phi f_s}{4L}$$

where, f_s = Maximum stress (tensile or compressive) developed at the critical section

7.8 Development Length

As per Cl. 26.2 of IS 456: 2000, development length is:

"The calculated tension or compression in any bar at any section shall be developed on each side of the section by an appropriate development length or end anchorage or a combination thereof."

Development length prevents the bar from pulling out in tension or pushing it in compression. When the required development length cannot be provided due to certain restrictions or other considerations then in that case, bends, hooks or mechanical anchorages are provided to supplement with an equivalent embedment length.

Development length can be calculated as:

$$\pi\phi L\tau_b = \left(\frac{\pi}{4}\right)\phi^2 f_s \Rightarrow L = \frac{\phi f_s}{4\tau_b}$$

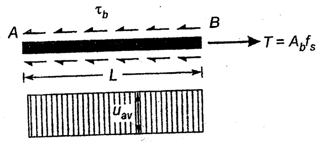


Fig. 7.3 *Assumed uniform average bond stress U_{av}*

where, τ_b = Design bond stress = Permissible value of average anchorage bond stress

The average bond stress is still used in the working stress method of design as given in **Cl. B-2.1.2 of IS 456: 2000**. But in the limit state method of design, this average bond stress is referred to as design bond stress,(τ_{bd})as per Cl. 26.2.1.1 of IS 456: 2000.

The value of bond stress is increased by 60% for deformed bars in tension and a further increase of 25% is made for bars in compression.

Table 7.1: *Design Bond Stress for Different Grades of Concrete (in N/mm²)*

CONCRETE GRADE	M15	M20	M25	M30	M35	M40	M45	M50
LSM (Cl. 26.2.1.1 of IS:456)	—	1.2	1.4	1.5	1.7	1.9	1.9	1.9
WSM (Table 21 of IS:456)	0.6	0.8	0.9	1	1.1	1.2	1.3	1.4

Table 7.2: *Development length of fully stressed (0.87 f_y) single bar in tension (ϕ = Bar diameter)*

Grade of Steel	Concrete Grade		
	M20	M25	M30
Fe 250	46ϕ	39ϕ	37ϕ
Fe 415	47ϕ	41ϕ	38ϕ
Fe 500	57ϕ	49ϕ	46ϕ

For bundled bars, the development length of each bar of bundled bars shall be that of individual bar increased by 10% for two bars in contact, 20% for three bars in contact, 33% for four bars in contact. Such an increase in development length is made because of reduction in the interface area between the steel and surrounding concrete.

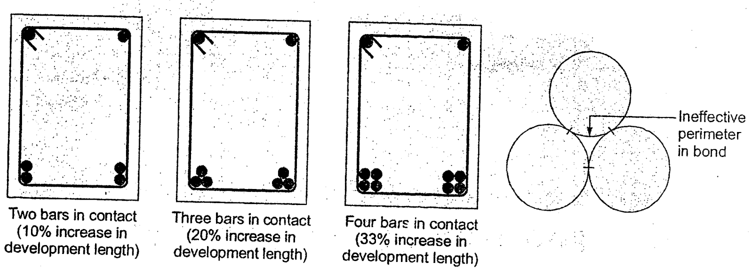


Fig. 7.4 *Bundled Bars in contact*

As per IS 456: 2000 development length is assumed to be satisfied in concrete structure if:

$$L_d \le \frac{M_1}{V} + L_0$$

where, M_1 = Moment of resistance of the section assuming all reinforcing bars to be stressed up to design strength (σ_{st} or 0.87f_y)

V = Shear force at support

L_0 = Length of reinforcement beyond centre of support

Remember: In the above expression, the value of (M_1/V) can be increased by 30% if ends of reinforcement are confined by a compressive reaction.

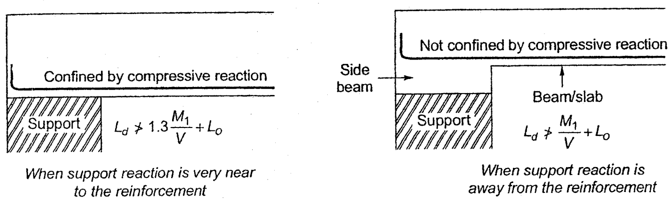


Fig. 7.5 *Confinement of reinforcement ends by compressive support reaction*

The requirement, $L_d \le \frac{M_1}{V} + L_0$

can be satisfied by any of the following methods:

1. Provide more number of bars so that M_1 is increased. This option however adds up the additional reinforcement cost.
2. Increase L_0 but this can be done upto a certain extent since width of support cannot be increased indefinitely.
3. Decrease the diameter of main reinforcing bars.

7.9 Mechanisms of Bond Failure

The bond between the steel and the surrounding concrete may fail in any one or combination of the following:

1. Failure of adhesion between the reinforcing bar and concrete.
2. Splitting of concrete that surrounds the reinforcing bar.
3. Crushing of concrete in front of the bar ribs in case of deformed bars.
4. Shearing of concrete embedded between the ribs along the cylindrical surface surrounding the ribs.

7.10 Factors affecting the Bond Strength

Bond strength is affected by many factors. The following factors attempt to increase the bond strength:

1. Using ribbed/deformed bars instead of plain bars.
2. Using smaller diameter bars.
3. Use of higher concrete grade.
4. Increasing the cover around the bar.
5. Increasing the length of embedment, hooks, bends etc.
6. Using mechanical anchorages.

7.11 Bends, Hooks and Mechanical Anchorages

Bends are provided in order to meet the development length requirements for bars in tension or compression. As per IS 456: 2000, the anchorage value of a bend is taken as 4 times the bar diameter for each 45 degree bend subject to a maximum of 16 times the bar diameter (Cl. 26.2.2.1 (b) of IS 456: 2000).

Bends and hooks introduce bearing stresses in the concrete they bear against. In order that these bearing stresses do not exceed the permissible limits, the turning radius must be large enough.

Mechanical anchorages in the form of nuts, bolts, welded plates etc. can also be provided if they are capable of developing the strength of bar without any damage to concrete.

7.12 Anchoring Bars in Tension

As per Cl. 26.2.2.1 of IS 456: 2000, for anchoring bars in tension, deformed bars may be used without end anchorages provided the development length requirement is satisfied. Hooks should be provided for plain bars in tension. Standard hooks and bends should be as per IS 2502: 1963 or as per Table 67 of SP-16.

7.13 Anchoring Bars in Compression

As per Cl. 26.2.2.2 of IS 456: 2000, for anchoring bars in compression, the anchorage length shall be equal to the development length of the bars in compression. The projected length of hooks, bends and straight lengths beyond bends if provided for a bar in compression, shall only be considered for development length.

7.14 Mechanical Devices for Anchorages

As per Cl. 26.2.2.3 of IS 456: 2000, any mechanical or other device capable of developing the strength of the bar without damage to concrete may be used as anchorage with the approval of engineer-in-charge.

7.15 Anchoring Shear Reinforcement

As per Cl. 26.2.2.4 of IS 456: 2000, for inclined bars, the development length shall be as for bars in tension where this length is measured as:

1. In tension zone, from the end of the sloping or inclined portion of the bar and,
2. In compression zone, from the mid-depth of the beam.

For stirrups and any other secondary reinforcement like transverse ties, complete development length and anchorage shall have to be provided when bar is bent through an angle of at least 90 degree around a bar of at least its own diameter and is continued beyond the end of the curve for a length of at least eight times diameter, or when the bar is bent through an angle of 135 degree and is continued beyond the end of the curve for a length of at least six times bar diameter or when the bar is bent through an angle of 180 degrees and is continued beyond the end of the curve for a length of at least four times bar diameter.

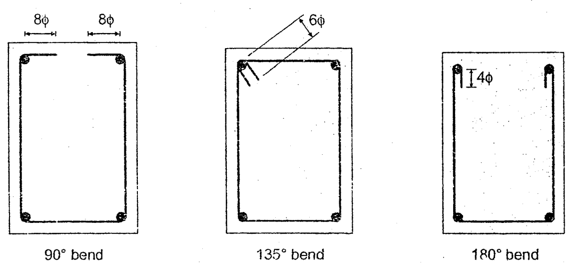


Fig. 7.6 *Anchoring shear reinforcement*

7.16 Reinforcement Splicing

Splicing is required when the bars available are shorter than that required (due to non-availability of longer bars owing to manufacturing or transportation problem), when there is a change in the bar diameter (e.g. in columns) etc. Splicing is done to transfer the axial load from one bar to another with the same line of action. Splicing introduces stress concentrations in the surrounding concrete. To avoid such stress concentrations, **IS 456: 2000 recommends that splices in flexural members should not be at sections where the bending moment is more than 50% of the moment of resistance and not more than half the bars shall be spliced at a particular section.** Splicing is done by lapping of bars, welding of bars or with mechanical connection.

7.16.1 Lap Splices

It is done by overlapping the bars over a certain length, thereby making possible the transfer of axial force from the terminating bar to the connecting bar by the mechanism of anchorage (development) bond with the surrounding concrete. **Lap splices are generally not permitted for very large diameter bars (ϕ > 36 mm), for** which welded splices are recommended. However, where welding is not practicable, **Cl. 26.2.5.1(a) of IS 456: 2000** recommends the use of additional spirals around the lapped bars.

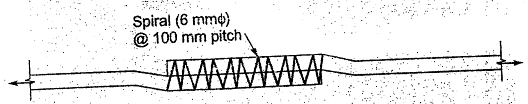


Fig. 7.7 *Lapping of large diameter bars by lap splicing*

It is always desirable to bend the bars slightly (especially for large diameter bars) at the location of splices in order to have a collinear force transfer without any eccentricity. **IS 456: 2000** specifies that straight length of the lap should not be less than 15ϕ or 200 mm (whichever is more). The lap length must be atleast equal to development length. In no case the lap length should be less than 30ϕ for flexural and direct tension and 24ϕ for compression.

When two different diameter bars meet at splice location then lap length should be calculated on the basis of smaller bar diameter. Splices in tension members should be enclosed by spirals made up of bars of diameter not less than 6 mm along with pitch not exceeding 100 mm.

7.16.2 Welded Splices and Mechanical Anchors

Welded splices and mechanical connections are suitable for large diameter bars for which lap splicing is not recommended. This leads to reduced consumption of reinforcing steel. **Cl. 12.4 of IS 456: 2000** specifies that tension tests should be performed on these welded splices in order to check their adequacy.

Welding of cold worked bars (deformed bars) need special attention as there always exists a possibility of loss of strength due to the heat of welding. **Cl. 26.2.5.2 of IS 456: 2000** states that the design strength of welded splice should be limited to 80% of design strength of the bar in tension splice.

Butt welding of bars is generally adopted in welded splices. The bars to be spliced should be of the same diameter. Additional two or three symmetrically positioned small diameter lap bars may also be provided (especially when the bars are subjected to tension) and fillet welded to the main bars. Even in the case of 'lap splices', lap welding (at intervals of 5ϕ) may be provided in order to reduce the lap length.

Cl. 26.2.5.3 of IS: 456-2000 permits the use of end bearing splices for bars in compression.

Example 7.1 A reinforced concrete (M25) simply supported rectangular beam of size 300 mm × 500 mm is reinforced with 3-20 mm diameter bars of Fe 415 steel. The reinforcement bars are bent at 90 degrees at the support. The shear force at the supports is 105 kN under working load conditions. Find the value of anchorage length.

Solution:

Factored shear force (V_u) = 1.5 x 105 kN = 157.5 kN

Let clear cover to reinforcement = 30 mm

$$\text{Thus effective depth of the beam } (d) = 50 - 30 - \frac{20}{2} \text{ mm} = 460 \text{ mm}$$

$$\text{Area of tension steel } (A_{st}) = 3\times\left(\frac{\pi}{4}\right)\times 20^2 \text{mm}^2 = 942.5 \text{ mm}^2$$

Calculation of depth of neutral axis:

$$x_u = \frac{0.87 f_y A_{st}}{0.362 f_{ck} b} = \frac{0.87 x 415 x 942.5}{0.362 x 25 x 300} = 125.34 \text{ mm}$$

Limiting depth of neutral axis ($x_{u\,lim}$) = 0.479d = 0.479 × 460 mm = 220.34 mm $> x_u$ (=125.34 mm)

Thus beam section is under-reinforced and $f_{st} = 0.87 f_y$ is correct in the above calculation of depth of neutral axis.

Calculation of moment of resistance:

Moment of resistance of the beam section (M_r) = $0.87 f_y A_{st}(d - 0.416x_u)$

= 0.87 × 415 × 942.5(460 − 0.416 × 125.34) = 138.79 kNm

For M25 concrete and Fe415, design bond stress (τ_{bd}) = 1.4 x 1.6 N/mm² = 2.24 N/mm²

(Cl. 26.2.1.1 of IS 456: 2000)

Development length:

$$L_d = \frac{0.87 f_y \phi}{4\tau_{bd}} = \frac{0.87 x 415\phi}{4 x 2.24} = 40.296\phi$$

Anchorage length:

For 90 degree bend, anchorage length (L_o) = 8φ = 8 × 20 mm = 160 mm

$$40.296\phi \le 1.3\frac{138.79\times10^6}{157.5\times10^3} + 160$$

$$\phi \le 32.4 \text{ mm}$$

So there is no need to increase the anchorage length.

If the diameter of bar provided was larger than 32.4 mm then in that case, the anchorage length had to be increased either by extending the bar length beyond the anchorage value provided or by providing the anchorage in the form of a *U* bend (anchorage value = 16φ).

Objective Brain Teasers

Q.1 Which of the following option is the best way to have proper bond between the steel and surrounding concrete?
(a) Use small number of large diameter bars
(b) Use large number of small diameter bars
(c) Use of shear stirrups
(d) All of the above

Q.2 When mild steel bars are used in place of deformed bars then bond strength:
(a) Increases
(b) Decreases
(c) Is independent of type of steel
(d) Becomes zero

Q.3 Match List-I and List–II using the codes given below:

List–I
(i) Modulus of rupture of concrete
(ii) Development length
(iii) Modulus of elasticity of concrete
(iv) Nominal shear stress

List–II
(A) $5000\sqrt{f_{ck}}$
(B) $\phi f_s / 4\tau_{bd}$
(C) V_u / bd
(D) $0.7\sqrt{f_{ck}}$

(a) (i)-(D), (ii)-(B), (iii)-(A), (iv)-(C)
(b) (i)-(B), (ii)-(D), (iii)-(C), (iv)-(A)
(c) (i)-(A), (ii)-(C), (iii)-(B), (iv)-(D)
(d) (i)-(C), (ii)-(A), (iii)-(D), (iv)-(B)

Q.4 In limit state design, if τ_{bd} is the design bond stress for plain bars in tension, then the bond stress for deformed bars in compression will be:
(a) $1.6\tau_{bd}$ (b) $1.25\tau_{bd}$
(c) τ_{bd} (d) $2\tau_{bd}$

Q.5 The type of bond which gets developed due to variation of bending moment along the beam is:
(a) Development bond
(b) Anchorage bond
(c) Flexural bond
(d) All of the above

Q.6 The minimum lap length required for reinforcing bars in tension is:
(a) 30 times the bar diameter
(b) 24 times the bar diameter
(c) 16 times the bar diameter
(d) None of the above

Q.7 Lap splicing is generally not permitted if the bar diameter exceeds:
(a) 25 mm (b) 32 mm
(c) 36 mm (d) 40 mm

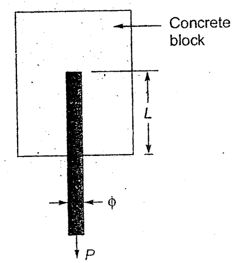
Q.8 The minimum diameter of spirals recommended for splicing in tension members is:
(a) 5 mm (b) 6 mm
(c) 8 mm (d) 10 mm

Q.9 The pitch of the spirals for splicing in tension members should not exceed:
(a) 20 mm (b) 15 mm
(c) 25 mm (d) 100 mm

Q.10 As per IS: 456-2000 recommendations, the design strength of welded splice should be limited to ________ % of design strength of bar in tension splice.
(a) 50 (b) 60
(c) 80 (d) 90

Q.11 The bond strength for M20 concrete as per IS 456: 2000 is 1.2 N/mm². For reinforcing steel of grade Fe 360, the development length in terms of bar diameter (φ) is
(a) 47φ (b) 45φ
(c) 50φ (d) 36φ

Q.12 A bar of diameter φ is embedded in a large concrete block as shown. A force P is being applied to the bar. Let δ_b is the bond strength between the steel and concrete and σ_{st} is the tensile strength of steel bar. Assuming the material of block does not fail, the maximum value of P is



(a) $\text{Max.}\left(\frac{\pi}{4}\phi^2\sigma_b, \pi\phi L\sigma_{st}\right)$

(b) $\text{Max.}\left(\frac{\pi}{4}\phi^2\sigma_{st}, \pi\phi L\sigma_b\right)$

(c) $\text{Min.}\left(\frac{\pi}{4}\phi^2\sigma_{st}, \pi\phi L\sigma_b\right)$

(d) $\text{Min.}\left(\frac{\pi}{4}\phi^2\sigma_b, \pi\phi L\sigma_{st}\right)$

Answers

1. (b) 2. (b) 3. (a) 4. (d) 5. (c)
6. (a) 7. (c) 8. (b) 9. (d) 10. (c)
11. (a) 12. (c)

Hints:

4. (d)
(1.6 for deformed bars) × (1.25 for compression)
$\tau_{bd} = 2\tau_{bd}$

11. (a)
$$L_d = \frac{f_{st}\phi}{4\tau_{bd}} = \frac{360\phi}{4 \times 1.6 \times 1.2} = 46.875\phi \approx 47\phi$$

Conventional Practice Questions

Q.1 A hook of 20 mm dia. plain bar is embedded in concrete for a length of 150 mm. A load of 15 kN is applied on the hook. If the ultimate bond stress of concrete is 1.2 N/mm^2, check whether the load is safe to be carried by the hook.

Ans. [Unsafe, the load will fall down]