Face And Side Split Mechanism Or Bottom Inside Mechanism

- This mechanism occurs when the outside cover is lesser than half the spacing between the bars.
- This outside splitting occurs first weakening the remaining concrete.
- Horizontal splitting may then occur releasing the bars from the concrete causing failure.

Side cover > bottom cover

and $c_s / 2 > c_e$

Governing cover parameter $c_b = c_e$

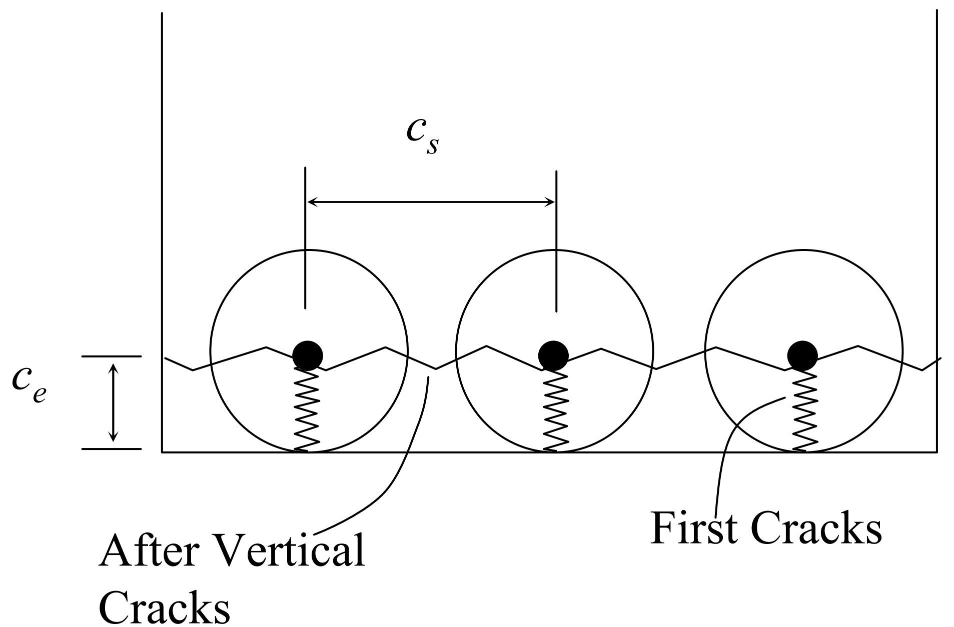


Fig. 11.4.Face And Side Split Bond Failure Mechanism.

V-Notch Mechanism

- In V-notch mechanism, the spacing between the bars is much larger compared with the outside cover.
- splitting in line of bars cannot occur.
- Here first cracks perpendicular to the surface appear followed by cracks at 45° and other angles (Fig. 11.5).
- Hence, after this splitting, the bar looses its anchorage and starts slipping.

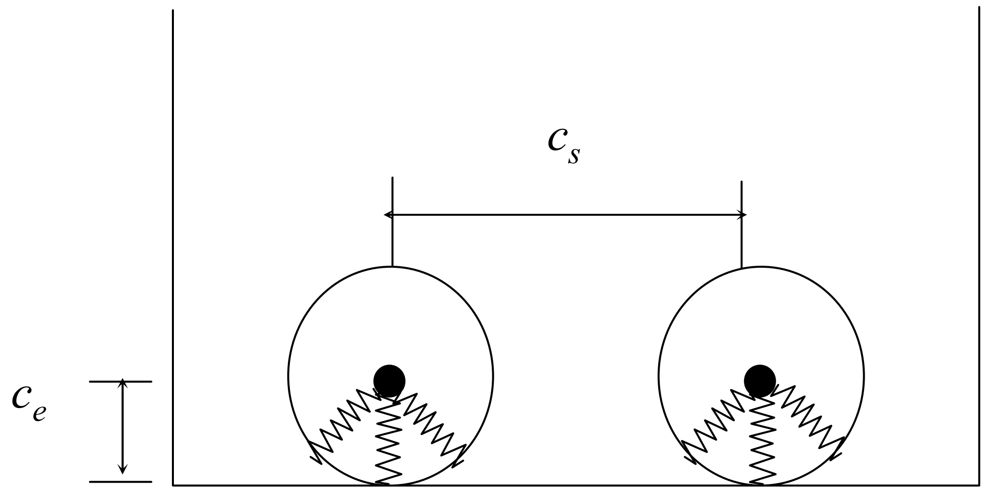


Fig. 11.5.V-Notch Bond Failure Mechanism.

$$c_s / 2 >> \quad c_e$$

$$\text{Governing cover parameter} = c_b = c_e$$

Pullout Mechanism

- When concrete cover to bars is sufficiently larger on each side, no splitting occurs but the bars are pulled out after shearing off the concrete interlocking.
- This mechanism is exactly similar to that of a simple pullout test. In this case both c_s and c_e are sufficiently large.

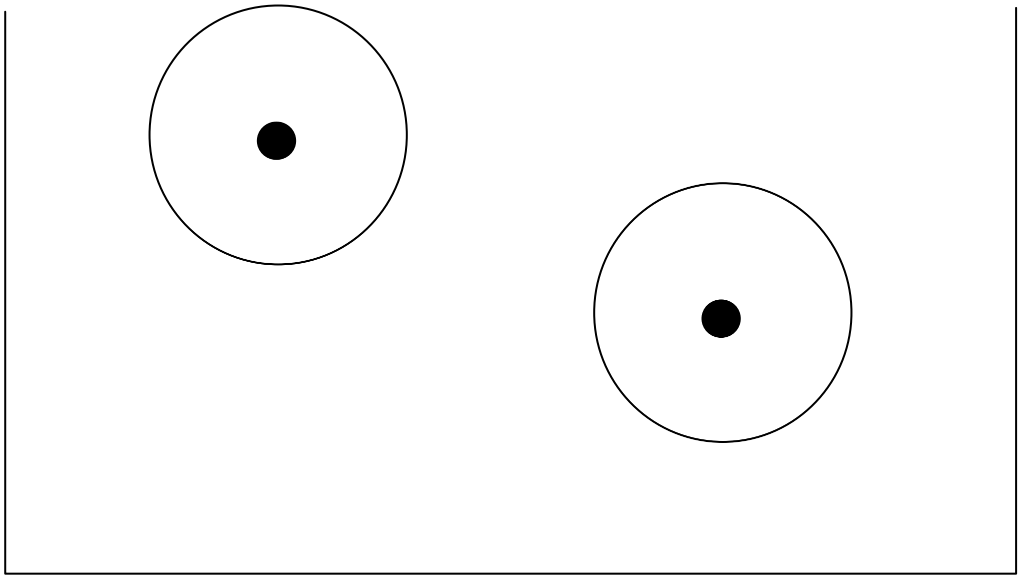


Fig. 11.6.Pullout Failure Mechanism.

EFFECT OF TRANSVERSE REINFORCEMENT

- Shear or flexural-shear diagonal cracks adversely affect the bond strength.
- Transverse reinforcement reduces these cracks and hence improves bond.
- It also prevents splitting of concrete.

DEVELOPMENT OF REINFORCEMENT IN TENSION

- The values of used in this chapter should not exceed 25/3 MPa according to ACI 12.1.2.
- According to ACI 12.2.2, the approximate expression for the required development length is as under:

$$\ell_d \quad = \quad K \frac{f_y \psi_t \psi_e \lambda}{\sqrt{f_c'}} d_b$$

where the constant K is taken from Table 11.1:

Table 11.1. Value of Constant K For Calculation of Development Length.		
	≤ No. 20 and deformed wires	**> No. 20 bars**
Given bar spacing criteria satisfied	$\frac{12}{25} = 0.48$	$\frac{3}{5} = 0.60$
Other cases	$\frac{18}{25} = 0.72$	$\frac{9}{10} = 0.90$

Recommended Bars Spacing Criteria

The required bar spacing criteria are as under:

- Clear spacing of bars being developed or spliced should not be less than d_b.
- Clear cover should not be less than d_b.
- Stirrups or ties should be present throughout the length ℓ_d not less than the code minimum.

OR

- Clear spacing of bars being developed or spliced should not be less than $2d_b$.
- Clear cover should not be less than d_b.

- A more accurate method is given in ACI 12.2.3.
- This method is applicable when exact cover, spacing of bars and details of transverse reinforcement are available.

$$\ell_d = \frac{9}{10}\frac{f_y}{\sqrt{f_c'}}\frac{\psi_t\psi_e\psi_s\lambda}{\left(\dfrac{c_b+K_{tr}}{d_b}\right)}\times d_b$$

where $\dfrac{c_b+K_{tr}}{d_b} \not> 2.5$

The limit of 2.5 on the term $(c_b + K_{tr})/d_b$ is included to safeguard against pullout type failures.

- Ψ_t = Reinforcement location factor. Top reinforcement always have poorly placed concrete around it, reducing the bond.
- = 1.3 if horizontal reinforcement is so placed that more than 300 mm of fresh concrete is cast in the member below the development length or splice.

= 1.0 for other reinforcement.

- Ψ_e = Coating factor
- = 1.5 for epoxy-coated bars or wires with cover less than $3d_b$, or clear spacing less than $6d_b$.
- = 1.2 for all other epoxy-coated bars or wires.

  = 1.0 for uncoated reinforcement.

The produced of Ψ_t and Ψ_e need not be taken greater than 1.7.

λ	=	lightweight aggregate concrete factor.
	=	1.3 when lightweight aggregate is used.
	=	$\frac{1}{1.8}\sqrt{f'_c}/f_{ct}$ <= 1.0 for lightweight aggregate if the average splitting tensile strength (f_{ct}) is known.
	=	1.0 for normal weight concrete.
c_b	=	Spacing or cover dimension, mm. Use the smaller of either the distance from the center of the bar or wire to the nearest concrete surface or one-half the center-to-center spacing of the bars or wires being developed.

K_{tr} = transverse reinforcement index, a factor that represents the contribution of confining reinforcement present across the potential splitting planes.

$$= \frac{A_{tr}\, f_{yt}}{10\, s\, n}$$

here

A_{tr} = total area of all transverse reinforcement which is within the spacing "s" and which crosses the potential plane of splitting through the reinforcement being developed, mm^2.

f_{yt} = f_y of transverse reinforcement.

s = center-to-center maximum spacing of transverse reinforcement within ℓ_d, mm.

n = number of bars or wires being developed along the plane splitting.

It is permitted to use $K_{tr} = 0$ as a design simplification even if transverse reinforcement is present.

The user may construct simple expressions for groups of reinforcement that he/she frequently uses.

For example, in all structures with normal weight concrete ($\lambda = 1.0$), uncoated reinforcement ($\Psi_e = 1.0$), No. 20 or smaller bottom bars ($\Psi_t = 1.0$) with $f'_c = 20$ MPa and Grade 420 reinforcement, the equations reduce to:

Minimum spacing and cover satisfied:

$$\ell_d = \frac{(12)(420)(1.0)(1.0)}{25\sqrt{20}} d_b = 45\, d_b$$

Otherwise, if spacing is not satisfied:

$$\ell_d = \frac{(18)(420)(1.0)(1.0)(1.0)}{25\sqrt{20}} d_b = 68\, d_b$$

Excess reinforcement

- ACI 12.2.5 allows reduction in development length where reinforcement in a flexural member is in excess of that required by analysis, except where anchorage or development for f_y is specially required.

$$\text{Reduced } \ell_{\mathrm{d}} = \frac{A_s\ req.}{A_s\ provided}\ \ell_{\mathrm{d}}$$

DEVELOPMENT LENGTH IN COMPRESSION

$$\ell_{dc} = F_1 F_2 \frac{1}{4} \frac{f_y}{\sqrt{f'_c}} d_b \geq 200 \text{ mm}$$

for $f'_c > 40\ MPa$

$$\geq F_1 F_2 \times 0.04 f_y d_b \geq 200 \text{ mm}$$

for $f'_c \leq 40\ MPa$

where $$F_1 = \frac{A_s\ req.}{A_s\ provided}$$

F_2 = 0.75 if the reinforcement is enclosed with spiral reinforcement of 6 mm minimum diameter at a maximum pitch of 100 mm ***or*** with 13 mm ties satisfying the code requirements at a maximum spacing of 100 mm c/c.

= 1.0 otherwise.

SPLICES OF DEFORMED BARS IN TENSION

- The tension splices are either of Class A or the stronger Class B type.
- All lap splices in tension must be Class B except in the following cases where Class A splices are allowed:

  $A_{prov.} / A_{req.} \geq 2.0$ for the entire length of the splice.

  One-half or less of the total reinforcement is spliced within the required lap length.

The required splice length for the two types is evaluated as follows:

Splice Type	*Splice Length*
Class A	$1.0\ \ell_d \geq 300$ mm
Class B	$1.3\ \ell_d \geq 300$ mm

Where ℓ_d is the development length in tension without reduction for $A_{prov.} / A_{req}$.

Splices in adjacent bars must be staggered by at least 600 mm. Further, the column longitudinal bars must be lapped as illustrated in Fig. 11.7.

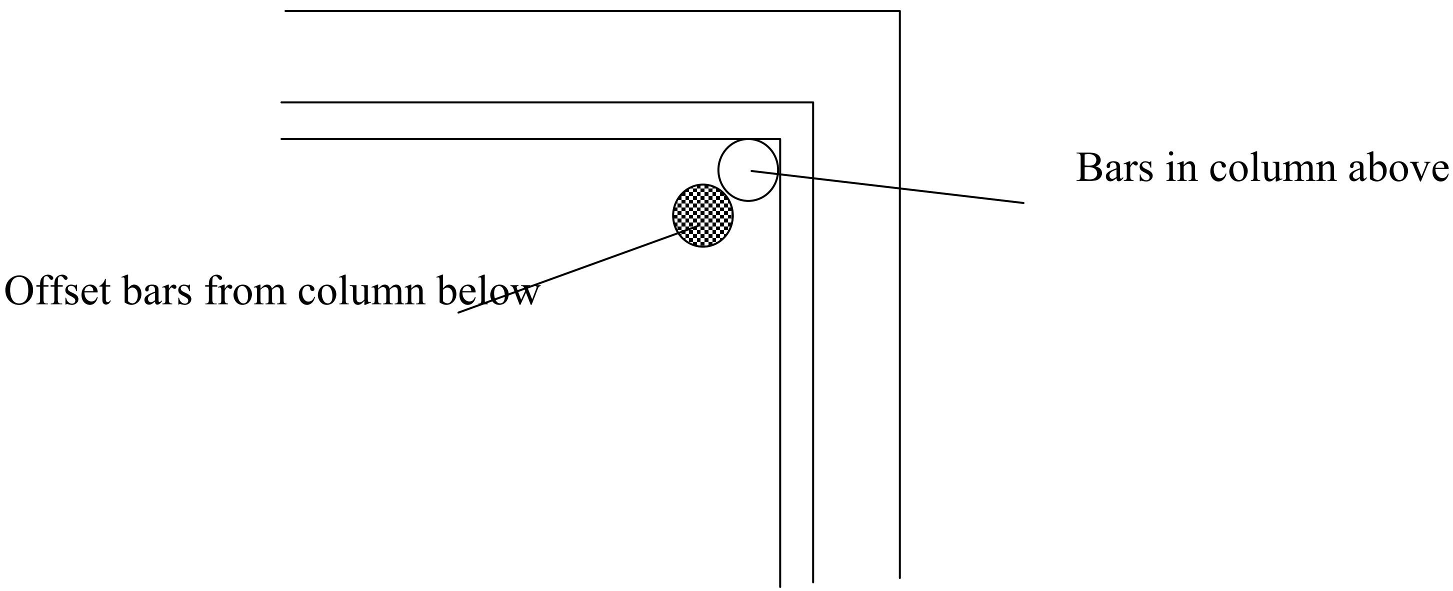


Fig. 11.7. Offset of Overlapped Column Bars.

SPLICES OF DEFORMED BARS IN COMPRESSION

The minimum lap length for splices of deformed bars in compression is as under:

$$\ell = 0.07\,F\,f_y\,d_b \geq 300 \text{ mm} \quad \text{for} \quad f_y \leq 420 \text{ MPa}$$

$$= (0.13 f_y - 24) F\,d_b \geq 300 \text{ mm} \quad \text{for} \quad f_y > 420 \text{ MPa}$$

where $F = 1$ when $f_c' > 20$ MPa

$= 4/3$ when $f_c' \leq 20$ MPa

When bars of different sizes are lap spliced in compression, the splice length is to be taken longer of ℓ_{dc} of larger bar and splice length of smaller bar.

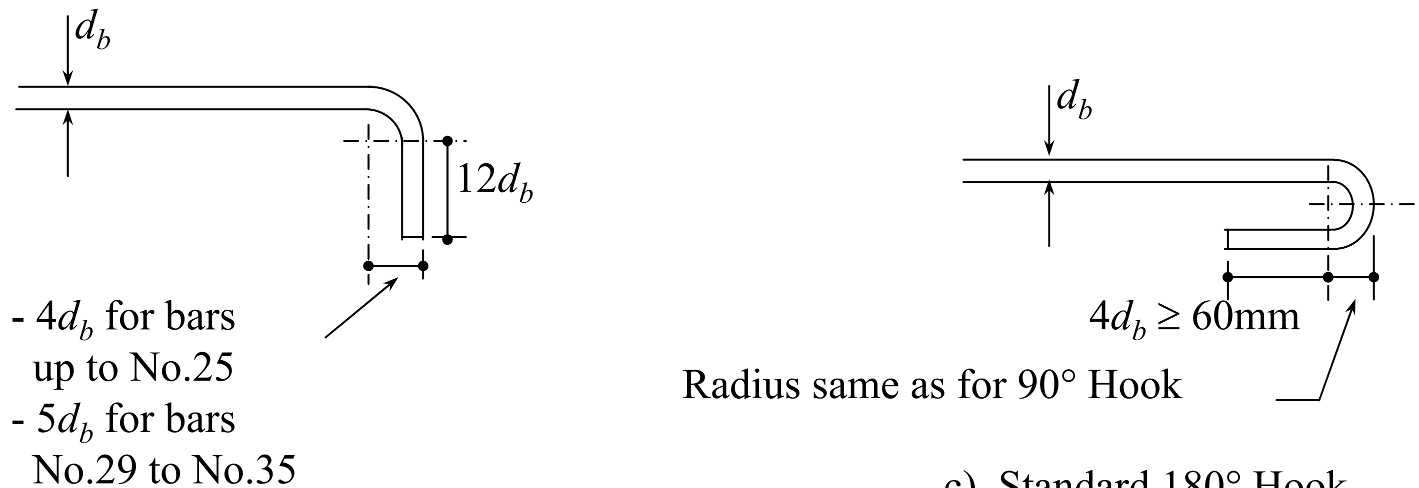
DEVELOPMENT OF BUNDLED BARS

According to ACI 12.4, the development length in tension or compression of bars is to be calculated for individual bars but increased by the following percentages:

- Bundle of three bars - 20 %
- Bundle of four bars - 33 %

DEVELOPMENT LENGTH WITH STANDARD HOOKS

The ACI standard hooks are shown in Fig. 11.8.



c) Standard 180° Hook

b) Standard 90° Hook

Fig. 11.8. Standard ACI Hooks.

According to ACI 12.5, the development length (ℓ_{dh}) for deformed bars having standard hook is given as under:

$$\ell_{dh} = F_1 F_2 \frac{1}{4} \psi_e \lambda \frac{f_y}{\sqrt{f_c'}} d_b \geq 8\, d_b \geq 150 \text{ mm}$$

ψ_e = 1.2 for epoxy-coated reinforcement

= 1.0 for ordinary reinforcement

λ = 1.3 for lightweight aggregate reinforcement

= 1.0 for normal weight concrete

$$F_1 = \frac{A_s \; req.}{A_s \; provided}$$

and

F_2 = 0.7 for No.35 or less size bars having hooks with side covers (normal to the plane of hook) at least equal to 60 mm ***and*** for 90° hook with cover on bar extension beyond hook of at least 50 mm.

= 0.8 for No.35 or less size bars having 90° hooks enclosed within ties or stirrups perpendicular to the bar being developed having a maximum spacing of $3d_b$ along development length (ℓ_{dh}) of the hook ***or*** enclosed within ties or stirrups that are parallel to the bar to be developed having a maximum spacing of $3d_b$ along the length of the tail extension.

= 0.8 for 180° hooks of No.35 or less size bars, which are enclosed within ties or stirrups perpendicular to the bar having a maximum spacing of $3d_b$ within ℓ_{dh}.

BAR CUT-OFF REQUIREMENTS

For a simply supported beam subjected to uniformly distributed load, the bending moment expressed as a percentage of maximum moment at some predefined sections is given in Table 11.2.

Table 11.2. Bending Moment at Various Locations Along the Span of a Simply Supported Beam Subjected to UDL.		
Location, x	Bending Moment	Percentage w.r.t. M_{max}
ℓ / 2	0.125 $w\ \ell^2$	100%
ℓ / 4	0.09375 $w\ \ell^2$	75%
ℓ / 5	0.08 $w\ \ell^2$	64%
ℓ / 7	0.06122 $w\ \ell^2$	49%
ℓ / 10	0.045 $w\ \ell^2$	36%

- According to ACI, there are following critical sections for checking the development of bars:

  Points of maximum stress.

  Points where reinforcement is terminated /bent.

- ACI 12.10.3 requires that reinforcement is to be extended beyond point where it is theoretically no longer required to resist flexure by at least the dimension, ℓ_a, given below:

ℓ_a = additional embedment length at support, or at point of inflection, mm.

= larger of

1) effective depth of member, d

2) $12\ d_b$

- A diagonal tension crack in a flexural member without stirrups may shift the location of the calculated tensile stress approximately a distance d towards the point of zero moment.
- When stirrups are provided, this effect is less severe, although still present up to some extent.
- This requirement needs not to be satisfied at supports of simple spans and at free ends of cantilevers.

Curtailment Of Negative Reinforcement

At least one-third the M^- reinforcement at a support shall have an embedment length beyond the P.I. equal to the following:

$$\text{greater of}\begin{cases} 1) & d \\ 2) & 12d_b \\ 3) & \ell_n / 16 \end{cases}$$

(ℓ_n is the clear span)

At interior supports of deep flexural members, M^- reinforcement should be continuous with that of the adjacent spans (ACI 12.12.4).

Minimum Positive Reinforcement At Support

Fraction of M^+ reinforcement to be carried into the support at least 150 mm from face of the support (ACI 12.11.1) is as under:

Fraction of M^+ reinforcement	
Simple Spans	$^1/_3$
Continuous Spans	¼

If the above member is part of a primary lateral load resisting system, the positive reinforcement should be anchored in the support to give full f_y strength at the face of support.

- ACI 12.10.4 requires that the continuing reinforcement should have an embedment length not less than ℓ_d beyond the point where some reinforcement is terminated or bent.
- The ℓ_d distance must start from the point where the discontinued reinforcement is theoretically not required.
- Peak stresses exist in the remaining bars wherever adjacent bars are cutoff, or bent, in tension regions.
- If bars are cutoff as short as the moment diagram allow, these peak stresses become the full f_y, which requires a full ℓ_d extension.

- Termination of bars in tension zones is to be avoided. However, if it is compulsory to terminate the bars in tension zone, at least one of the following conditions (ACI 12.10.5) is to be satisfied:

(a) $V_{u,\,\text{cutoff}}$ (factored) $\leq$ $^{2}/_{3}\,\phi V_{n}$

(b) Excess stirrups (above that required for shear and torsion) are provided within ¾ distance from the termination point.

Excess stirrup area $A_v \geq \dfrac{0.4 b_w s}{f_y}$

$$s_{max} \leq \frac{d}{8}\beta_b$$

where $\beta_{\mathrm{b}} = \dfrac{A_s \text{ at cut - off}}{\text{Total } A_s \text{ at section}}$

(c) The following conditions are satisfied:

Bar nos.	$\leq$	35
A_s after cutoff	$\geq$	$2\,A_{s,\,req}$.
$V_{u,\,\mathrm{cutoff}}$	$\leq$	$\tfrac{3}{4}\,\phi V_n$

CRITICAL SECTIONS

Let

- Bars present at support for negative moment = a and b
- Negative bars curtailed during first step = a
- Negative bars curtailed later = b
- Bars at mid-span for positive moment = c and d
- Positive bars curtailed = c
- Positive bars continued up to the support = d

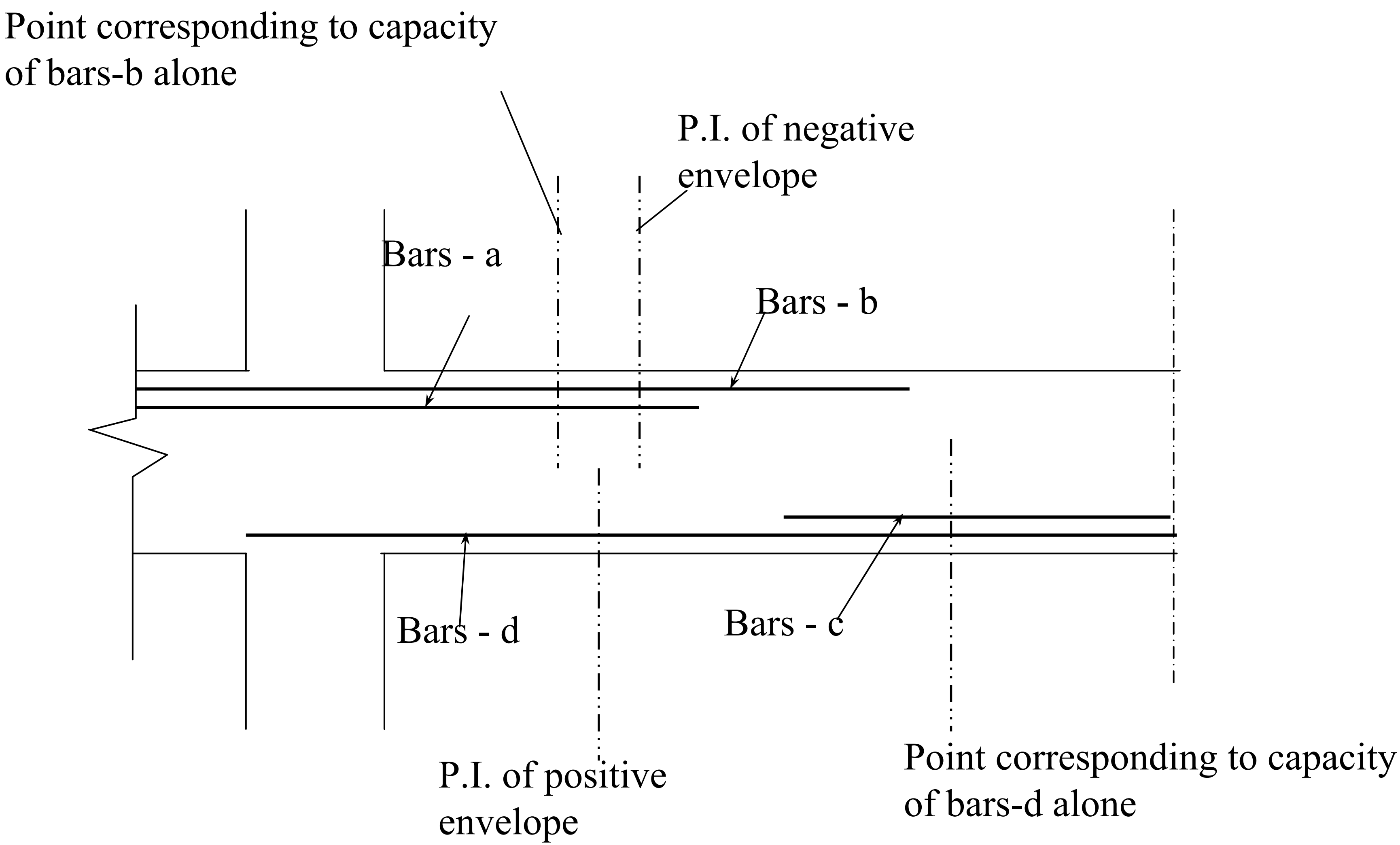


Fig. 11.9. Typical Half Span of a Continuous Beam Showing Flexural Reinforcement.

- Bars-a at face of support must have length greater than or equal to ℓ_d.
- Bars-b must have at least full development length (ℓ_d) beyond the point on negative moment envelop corresponding to flexural capacity of only bars-b.
- Bars-b must extend beyond point of inflection on negative moment envelop for a distance greater than or equal to larger of d, $12d_b$ and $\ell_n/16$.
- Bars-c must at least have full development length starting from mid-span to the point of their curtailment.

- Bars-c must be extended by larger of d and $12d_b$ from point on positive moment envelop corresponding to flexural capacity of bars-d alone.
- Bars-d must have full development length from point on positive moment envelope corresponding to flexural capacity of bard-d alone up to their end within supports.
- Diameter of positive bars is limited at point of inflection on the positive moment envelope, as discussed later.
- Bars-d must extend from face of the support into the support satisfying ACI 12.11.1, ACI 12.11.2 or ℓ_{dc} for compression if these bars are used as compression reinforcement.

Limit On Positive Reinforcement Diameter

According to ACI 12.11.3, at simple supports (SS) and inflection points (PI), positive reinforcement (for M^+) diameter is limited such that:

$$\ell_d \leq K \frac{M_n}{V_u} + \ell_a$$

This means that the rate of development of bond should be more than the rate of increase of moment. The value of the constant *K* is defined as under:

$K = 1.3$ when the ends of reinforcement are confined by a compressive reaction (for example at a support).

The compressive stresses present in concrete increases the bond strength as the splitting of concrete becomes difficult.

$K = 1.0$ otherwise.

ℓ_a at a support = embedment length beyond center of support.

ℓ_a at P.I = greater of 1) d 2) $12d_b$.

Further, this should not exceed the actual bar extension provided.

This condition needs not to be satisfied if positive reinforcement is terminated by a standard book or mechanical anchorage.

Let,

M_n = section capacity at P.I. considering all bars to be yielding.

= section capacity at the critical moment section.

V_u = maximum factored S. F. at the P.I.

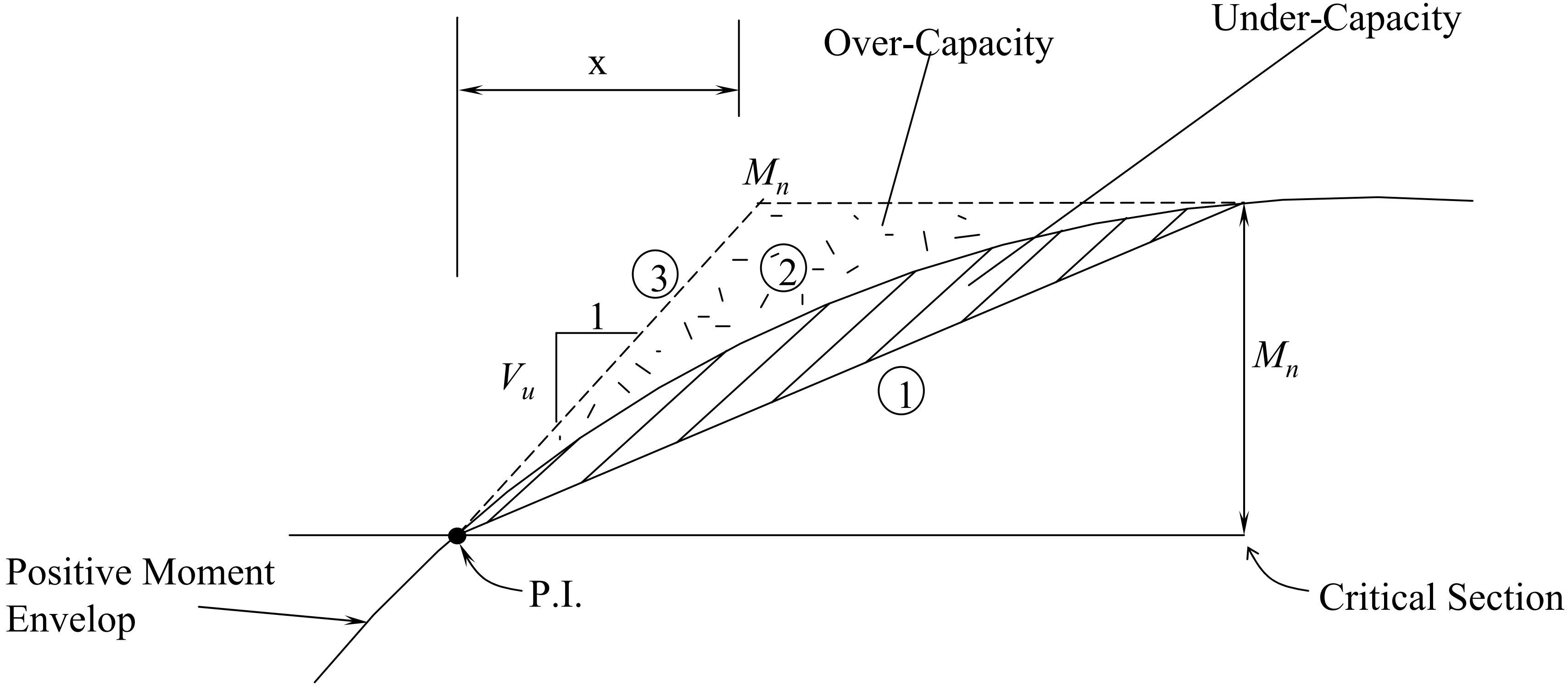


Fig. 11.10. Moment Envelop and Rate of Bond Development.

The three different lines/curves represent the following:

- Moment developed between P.I. to the critical section, showing under-strength for portions in-between in case of parabolic variations of the applied bending moments.
- Actual moment capacity required.
- Moment capacity required to be developed tangent to the actual B.M. diagram.

Slope of B.M.D. required $= V_u$

(From basic mechanics, $\frac{dM}{dx} = V_u$)

$$= \frac{M_u}{x}$$

$$\text{or} \quad x = \frac{M_u}{V_u}$$

Within this distance 'x', bars should be fully developed, so,

$$\ell_d \leq \frac{M_u}{V_u}$$

This development length is definitely required for straight line B. M. diagrams such as that for concentrated loads.

For parabolic moment diagrams, the required rate of development of moment from P.I. is not so sharp and the code allows the minimum distance from the P. I. to a point with fully developed maximum moment capacity be increased by ℓ_a, which is larger of d and 12 d_b.

$$\ell_d \leq \frac{M_u}{V_u} + \ell_a$$

Same situation arises at the cutoff points.

However, if the bar diameter is satisfied at P.I., the criterion will automatically be satisfied at the cutoffs because slope of B.M.D is very steep at P.I. and relatively flat at cutoffs.

Code uses the value of M_n in the numerator to make the expression further on the conservative side.

If the given criterion is not satisfied for a particular reinforcement, the bar diameter is to be reduced.

The top bars at exterior support are extended by ℓ_{dh} into the support with standard hook at the end (ACI 12.12.1).

If available space does not provide the length ℓ_{dh}, the bar is extended such that the total length becomes equal to the development length in tension.

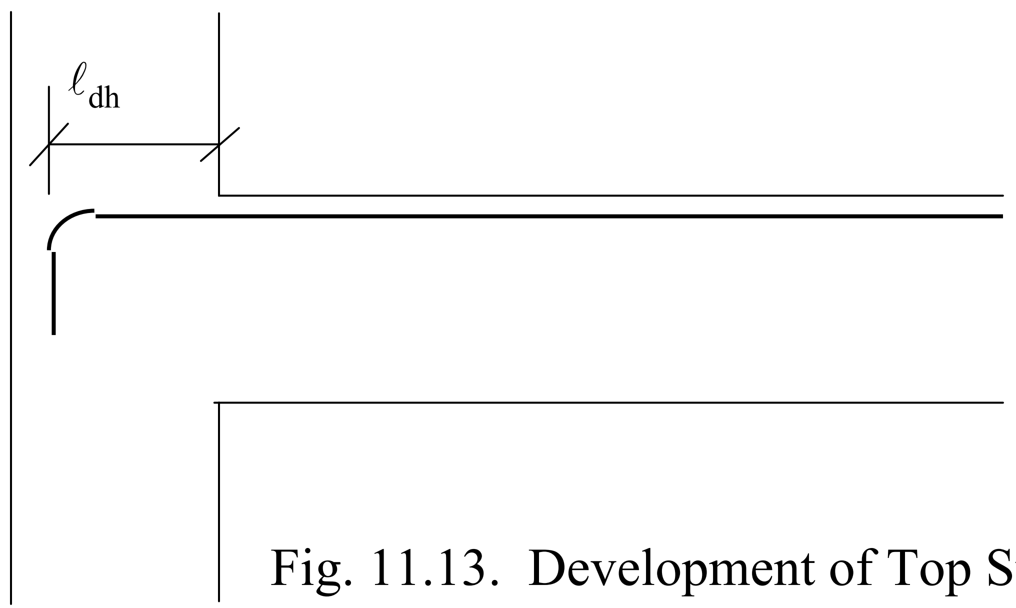


Fig. 11.13. Development of Top Steel at Exterior Support.