



Influence of Concrete Cover and Bar Diameter on Development Length in Seismic Zones

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Annotation

The goal of this academic work is to evaluate and analyze the effect of concrete cover and reinforcing bar diameter on the needed development length (L_d) for optimal reinforcement anchoring in seismic zones. Adequate bond strength between concrete and reinforcing steel is critical to ensuring seismic performance and structural safety, especially in areas where plastic hinges develop and large stresses are concentrated.

According to research findings, adding the concrete cover improves the amount of confinement, hence boosting bond strength and resistance to splitting failure. In contrast, as the bar diameter grows, bond strength decreases, needing a longer development time.

Design regulations, like ACI 318, integrate modification factors that account for these impacts and impose extra criteria to assure ductile behavior of reinforced concrete components under seismic stress situations.

Keywords: bond strength, development length, concrete cover, bar diameter, seismic, confinement.



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1. Introduction

For corrosion initiation and cracking, the concrete cover, quality, and bar size have a significant influence. The impact of these three parameters on corrosion protection for reinforcing steel is quantified. It is observed that the cover-to-bar-diameter (c/d) ratio serves as a more reliable protection criterion for corrosion cracking than simply using cover or bar diameter alone.

Given the significance of the c/d ratio, clear cover specifications that disregard bar size result in insufficient and deceptive corrosion protection design, particularly in concrete where internal chlorides are present from the time of manufacturing. As a result, the corrosion propagation time before cracking is a crucial stage in the service life of structures.

A concept of corrosion cracking resistance factor, $cf'c/d$ or c/dw , incorporating cover, bar diameter, and concrete quality either in terms of strength ($f'c$) or water-cement ratio (w) has been developed to quantify the relative corrosion protection provided by a particular set of detailing and strength parameters [1].

Adequate bonding between the concrete and steel reinforcements is essential for managing the complex behavior of concrete with reinforcement, ensuring the transfer of stresses between them. The development length and the cover of the reinforcement influence bond strength. Bond strength characteristics were studied by testing twisted steel bars that met BS 4461 standards within high-strength concrete. The post-peak bond behavior was analyzed using a universal displacement-controlled testing apparatus. Results for both small- and large-diameter twisted steel bars showed that increasing the cover-to-diameter ratio improved the bond and reduced slippage. This enhanced containment lessened the uneven distribution of stress along the development length. The stress concentration at the front key—the concrete area between two ribs—was decreased because it extended continuously along the twisted bars. Consequently, this strengthened the connection and provided maximum resistance to bond failure. Similarly, bond strength and the related slip increased with longer embedment lengths. A noticeable pattern across all images and samples was the sudden drop in bond strength when the initial concrete key failed due to the development of longitudinal splitting cracks, which could be seen on the cylinder's exterior. When a key fails, failure rapidly propagates [2]. This review is based on a comprehensive analysis of academic studies regarding the bonding behavior between reinforcing bars and concrete.

Research published between [Start Year] and [End Year] (e.g., 1990–2024) is the scientific focus. To ensure thorough and specific coverage of the paper's scientific scope, studies were carefully selected if they addressed the key parameters of restriction, splitting failure, and the effect of cyclic seismic loading on the necessary Development Length (L_d) in critical structural elements (like joints and connections).

2. Concept and Importance of Development Length

The length of the piece of reinforcing (bar) that must be inserted or pushed into the column to achieve the required strength of the bond between the steel and the concrete (or any additional two types of structural material) is known as the development length.

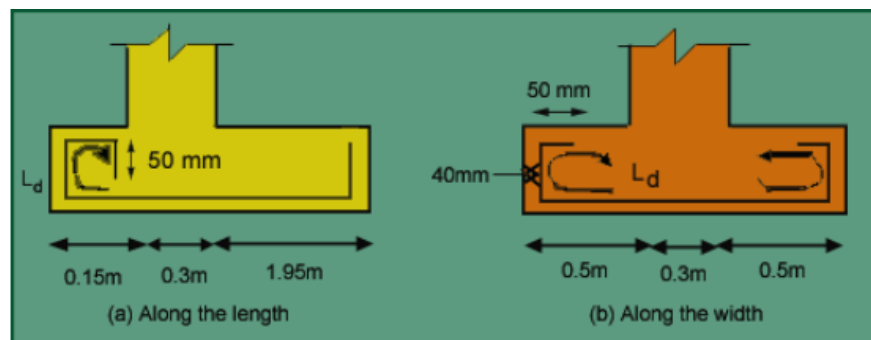


Fig .1

2.1 Reason for providing the Development length

- To provide a secure connection between the concrete and the bar surface so that the bar won't slip and fall under extreme load circumstances.
- Additionally, the additional length of the bar that is supplied as the development length is in charge of transmitting the stresses that are created in any area to the adjacent sections (for example, at the column-beam junction, the increased length of bars supplied from the beam to the column).

2.2 Importance

A key aspect of safe construction methods is the supply of suitable development. The steel grade taken into account for the design should determine the appropriate development length for

reinforcement bars. The structures may be more likely to fail because of joint, bond, anchor, and lap slippage if a shorter development length than necessary is provided. In these situations, failure will happen at the joints and laps before the reinforcement bars approach their yield point, rather than the reinforcement bars yielding first.

2.3 Calculation of Development Length

$$L_d = \frac{\phi \sigma_s}{4 \tau_{bd}}$$

Where, ϕ = nominal dia of reinforcement bar

σ_s = Stress in bar at the section considered at design load

t_{bd} = Design bond stress

Development Length for fully stressed bars deformed bars conforming to IS 1786 For Bars in Tension (Working Stress Design) $\sigma_s = 230 \text{ N/mm}^2$							
Dia	M20	M25	M30	M35	M40	M45	M50
8	360	320	290	265	240	225	210
10	450	400	360	330	300	280	260
12	540	480	435	395	360	335	310
16	720	640	575	525	480	445	415
20	900	800	720	655	600	555	515
25	1125	1000	900	820	750	695	645
32	1440	1280	1150	1050	960	885	825

**Note:
All above values are in mm
All above values are rounded up to nearest multiple of 5

Fig 2: Development length as per IS 1786

For every given bar diameter, the formula mentioned earlier is used to determine the necessary development length in millimeters; the same formula is applied to the limiting state method and the working stress method. The only explanation for the difference in the two methods of calculations is the different design bond stress values; the design bond strengths for working stress and Limit State are as follows:

Table No 1: Design Bond Stress in Limit State Method

Design Bond Stress in Limit State Method						
	M20	M25	M30	M35	M40 and above	-
Concrete Grade	1.2	1.4	1.5	1.7	1.9	For Plain Bars in Tension
Design Bond Stress (? $t_{bd}, \text{N/mm}^2$)	1.92	2.24	2.4	2.72	3.04	For deformed bars in tension

Fig3

Table No 2: Design Bond Stress in Working Stress Method

Design Bond Stress in Working Stress Method								
-	M20	M25	M30	M35	M40	M45	M50	-
Concrete Grade	0.8	0.9	1	1.1	1.2	1.3	1.4	For Plain Bars in tension
Design Bond Stress (N/mm ²)	1.28	1.44	1.6	1.76	1.92	2.08	2.24	For deformed bars in tension

Fig4

Generally, in practice, the development length requirement is expressed as '41 times \emptyset ' or '41 \emptyset ' where 41 is the factor calculated using the above formula & \emptyset is the dia of the bar [3].

3. Effect of Bar Diameter on Development Length

Bar diameter has a significant impact on bond behavior in reinforced concrete, although its impact on pulling-out tests is still up for debate. In C 35/45 concrete, ribbed bars with diameters of 10, 12, and sixteen millimeters have been exposed to experimental and numerical studies in this work. The concrete damaged plasticity model and the contact cohesive behavior approach were used in FEA modeling, which faithfully captured the actions of experimental bonds. While analytical models tend to underestimate maximum bond stress, the results indicate that bar diameter has an important effect on bond stress–slip behavior, failure mode, and bond strength.

The interaction of reinforcing bars in tension zones and concrete, which has a low tensile strength, results in a bond. Rigid bars create approximately eighty percent of the binding by mechanical interlocking, with adhesion and friction providing the remaining portion. Forces acting on the bar produce friction parallel to the ribs and pressure perpendicular to them, producing vertical components that could break the concrete and horizontal elements that transfer forces that compress it. [4].

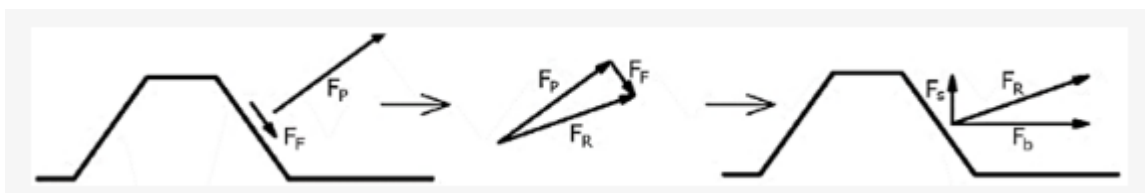


Fig4

Two of the fundamental quantities in bond analysis are the difference in displacement between the building material and the bar, or slip (s), and the bond stress (τ_b). Frequently, the bond's stress–slip curve $\tau_b(s)$ is one of the fundamental outcomes of bond analysis. The stress–strain curves for steel or concrete are examples of fundamental laws for bonds, according to Rehm [5]. Bond failure type is indicated by the curve's form. Bonding failure may be divided into two distinct groups: splitting failure (SF) and pull-out failure (POF).

[6,7]. An example of $\tau_b(s)$ curves depending on the type of failure is shown in **Figure 5**.

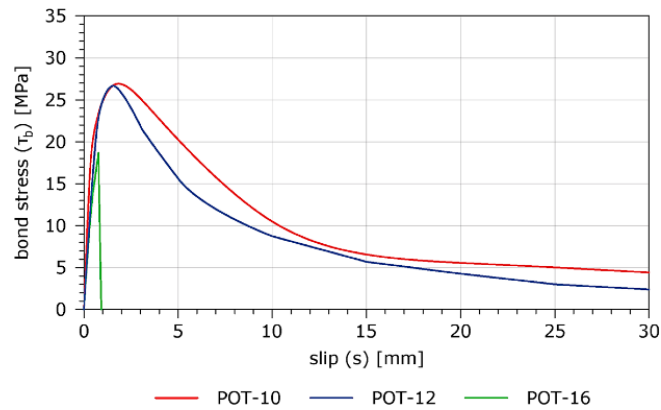


Fig 5. Comparison of representative curves obtained from pull-out tests.

In contrast to the POT-10 series, the POT-12 series exhibits a faster rate of post-peak bond stress degradation. Because the concrete is sheared off between the ribs, the bond stiffness is degrading more quickly. Because of the denser concrete cover, there is more bar confinement as a result. The slower stiffness deterioration following the peak was observed on the smaller diameter. The slightly varying ribbing of the bar, which differs depending on the diameter, could have an impact on this. At a slip value of 15 millimeters, the POT-10 and POT-12 series' $\tau_b(s)$ curves start to stabilize and achieve residual bond stress (τ_{bf}), around 20% of the maximum bond pressure.

This observed difference in post-peak behavior highlights a crucial finding: greater bar diameter significantly impairs bond strength under high slip demands. The proposal to use more smaller-diameter bars in seismic design to ensure more stable and ductile anchorage performance during inelastic cycles is thus strongly backed by this experimental evidence.

4. Seismic Design And Seismic Performance

The foundation to selecting loads, materials, analytical techniques, and structural systems that provide economy and safety is design philosophy. Since engineers take greater risks than other loads, a logical mindset is crucial in seismic design. According to current regulations, earthquake intensities with return times ranging from 100 to 500 years generate forces that are greater than the elastic capacity of materials. Thus, just 15–25% of elastic strength is intended for structures, permitting inelastic deformations and dissipating energy. In contrast to 0.01% under gravity stresses, buildings may attain maximum strength during smaller and more frequent earthquakes, which have a yearly likelihood of 1-3 percent.

When inertial effects were first identified in the 1920s and 1930s, earthquake design methods were introduced. Engineers developed a simplified lateral-force technique due to a lack of data, assuming forces of roughly ten percent of the building's mass, with actual lateral strength often [8].

5. The Influence of Reinforcement Bar Diameter (d_b)

One of the main factors affecting the required growth duration is the diameter of the reinforcement bar, and the connection between them may be explained by two main factors:

5.1. Relationship between Area and Diameter

The bar diameter, d_b , is approximately proportional to the required development length, L_d . [9]. But in the context of bonding, the connection is more complicated:

- **Peripheral Stress:** The bond surface area (proportional to πdb) rises more slowly than the total force that has to be transmitted (proportional to the bar area, $A_b \propto db^2$) [10]. Put another way, a larger risk of splitting failure results from an increase in the bond stress needed to generate the yield strength as d_b increases.

Surface Deformations: Under identical cover and confinement conditions, smaller diameter bars have a higher unit bond strength than larger diameter bars [11,12], as experimental research has demonstrated that the effectiveness of the bar's deformations in producing bond strength diminishes with increasing diameter [13].

5.2. Reinforcement Size Factor

The ACI 318 code reflects this effect through the modification factor ψ_s (Reinforcement Size Factor):

$\psi_s = 0.8$ for smaller bars (Size #6 or 20 mm and smaller).

$\psi_s = 1.0$ for larger bars (Size #7 or 22 mm and larger).

This reinforces the relative decrease in bond strength for large bars [14] by suggesting that the computed development length (L_d) for bars with larger diameters rises by 25% in comparison to the fundamental formula (all other things being equal). To attain greater overall strength of bonds and a more uniform fracture distribution, engineers prefer to use many smaller-diameter bars in seismic zones rather than a few larger-diameter bars [15].

6. Specific Considerations in Seismic Zones

Unlike normal gravity stresses, seismic loads have unique demands on the development period [16].

6.1. Effect of Cyclic and Reversing Loads

Especially in the flexible hinge areas, cyclic and reversing stresses applied to structural joints in seismic zones induce a gradual and ongoing weakening of the bond [17]. As a result, it is essential to:

Extend Development Length: To make up for the bond strength loss brought on by the seismic damage [18].

The ACI 318 code requires concrete confinement by means of the use of transverse reinforcement (stirrups/ties) in specific areas (e.g., the end of columns and beams in high-seismicity zones). This effective confinement increases the K_{tr} value, which reduces the necessary development length and prevents premature splitting failure [19].

6.2. Joint Performance

To guarantee that the bars stay attached even after concrete cracking inside the joint, the beam reinforcement needs to be built within the column-to-beam joints [20]. The relationship between the cover (c), bar diameter (d_b), and transverse reinforcement (K_{tr}) greatly influences the development length requirements at joints [21]. Hooked development lengths or enclosed joints are ideal to ensure ductile behavior because they take advantage of the extra confinement that the crossing member offers [22].

Global design regulations agree that bond deterioration happens as bar diameter increases, although they take different tacks in mitigating this adverse effect. For larger-diameter bars, the ACI 318 code uses a Reinforcement Size Factor (ψ_s) to increase the development length (L_d); however, Eurocode 2 directly accounts for the effect of bar diameter in the design bond stress (t_{bd}) calculation.

Importantly, as far as seismic design, both Eurocode 8 and ACI 318 (Chapter 18) go above standard cover standards by requiring extensive transverse reinforcement for Mandatory Confinement in crucial joint and anchorage areas. In order to reduce the possibility of brittle splitting failure and guarantee the ductile performance of connections under cyclic seismic loading, this approach is the best engineering solution accessible.

7. Literature Review

A steady transition from basic corrosion-related studies to complex seismic applications and cutting-edge materials like ultra-high-performance concrete (UHPC) and mechanical splices can be seen in the growth of research on bond behavior, anchorage, and splice performance in reinforced concrete (RC).

The cover-to-diameter ratio (c/d) was recognized as a crucial indicator of corrosion resistance in the early foundational work by Rasheeduzzafar et al. (1992), which established the relationship among concrete cover, bar diameter, and concrete quality. In order to measure the longevity of RC elements, the authors developed the idea of a corrosion cracking resistance factor through the integration of geometric and mechanical data [23]. The foundation for comprehending how material and geometric parameters influence the bond behavior and long-term performance of reinforced concrete was established by this study.

The dynamic behavior of RC and bridge systems under seismic loads became the main focus of later studies. In order to project the seismic response of bridge piers supported by pile foundations, Tuna and Akbas (2014) highlighted the significance of soil–structure interaction (SSI). They showed that neglecting SSI might result in an underestimate of displacements and rocking effects, particularly with soft soils [24]. simultaneously, Kim et al. (2016) investigated the seismic behavior of RC columns with lap splices inside plastic hinge sections, demonstrating that inadequate detailing or splice lengths considerably lower ductility and strength under cyclic loading [25]. These results demonstrated how vulnerable old splicing techniques in earthquake design are.

Lee et al. (2017) examined weak-axis beam-to-column connections in compact steel structures, emphasizing the degree to which bolt designs and geometry limitations affect cyclic performance in the context of steel and RC connections [26]. Mechtcherine (2017) carried out groundbreaking experiments on anchorage design for large-diameter bars around the same time period, demonstrating that the distribution of bond stress is quite irregular and that sufficient confinement can shorten the necessary development lengths without sacrificing ductility [27]. In their analysis of the seismic performance of broad bars in bridge columns, Zhao et al. (2018) expanded on this knowledge by suggesting better development length formulations that were confirmed by probabilistic simulations [28].

Al-Ghamdi et al. (2019) investigated bar development lengths in UHPC in light of the growing popularity of UHPC and expedited manufacturing procedures. They discovered that while increased compressive strength increases total bond capacity, bonding stresses decrease as embedment length rises [29]. Their findings offered crucial information for improving the anchorage design of UHPC components.

Kaya and Ulucan (2022) enhanced the discussion of lap splice performance in substandard RC columns by showing through their experimental investigation that inadequate splice detailing, which is prevalent in developing regions, leads to limited ductility and premature bond failures. Strength and energy dissipation were partially restored with the addition of 180° hooks, providing helpful retrofitting insights [30]. The impact of rebar diameter on the seismic response of precast columns with grouted sleeve connections was also assessed by Zhao et al. (2022), who found a strength–ductility trade-off since larger bars increased load capacity but sped up bond breakdown [31].

In keeping with this line of research, Li et al. (2023) examined high-pressure grouted sleeve connections in short precast columns and found that incorrect sleeve placement can cause shear

failure by shifting the plastic hinge zone. In order to prevent brittle reactions, their numerical models provided recommendations for determining the critical sleeve height [32].

Alrubaie et al. (2024) presented and verified novel mechanical and friction-welded splices as substitutes for traditional lap splicing in the latest stage. Rotating friction-welded threaded couplers (RFWTC) greatly improved strength, ductility, and energy absorption, meeting or surpassing ACI 318-19 earthquake criteria, according to their extensive experimental campaign [33, 34]. In support of these efforts, Graybeal et al. (2024) looked into the splice lengths for large-diameter bars inserted in UHPC for prefabricated bridge systems. Their research helped develop Accelerated Bridge Construction (ABC) procedures by offering specific design ranges (6–13 db) [35].

Together, these works show a distinct research path from the basics of corrosion and bonds to complex seismic anchorage systems with cutting-edge materials. Understanding bond mechanisms as well as improving splice performance have advanced significantly, but there are still issues with estimating long-term behavior in combined corrosion and seismic conditions and maximizing the use of mechanical and UHPC splices for full-scale applications in construction.

8. Conclusion

In accordance with this review, the bond strength and ductile behavior of reinforced concrete buildings in seismic zones are primarily controlled by three connected factors: concrete cover, bar diameter, and development length. While higher bar diameters decrease bond efficiency, more concrete cover increases confinement and bond strength. Consequently, during seismic loading, the use of many smaller bars improves ductility and energy dissipation. Modification factors with confinement criteria are used by design codes like ACI 318 and Eurocode 8 to mitigate these impacts; however, additional improvement is required to accommodate contemporary materials and connecting technologies. To guarantee long-term structural safety and robustness, future research should concentrate on bond performance under combined corrosion and seismic effects.

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