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Research Paper

The bond behavior between concrete and rebar under monotonic and cyclic loading

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Abstract

One of the most critical factors contributing to the strength, stiffness, and ductility of reinforced concrete members, particularly under seismic loading, is the bond between concrete and rebar. This research investigates the bond behavior between concrete and rebar in modified beam-end specimens under monotonic and cyclic loading. To this end, ten reinforced concrete specimens with dimensions of 200×300×500 mm and eccentric rebar were constructed. The main variables in the construction of the specimens included rebar size, confinement level, and bond length. The specimens were subjected to monotonic and cyclic loading using a universal testing machine. Results indicated that bond stress and stiffness increased with increasing rebar size. A 25% increase in bond stress was observed when the bar size increased from 14 mm to 22 mm. Furthermore, considering the inverse relationship between bond stress and bond length, a 15% decrease in bond stress was observed when the bond length was reduced from 200 mm to 132 mm. Additionally, under cyclic loading, bond stress and stiffness decreased by up to 30% due to the accumulation of damage in the bond zone.

Keywords: Bond-slip behavior, beam-end specimen, confinement, cyclic loading.

1. Introduction

Given the high compressive and thermal resistance of concrete, its relatively low cost, and the suitable tensile strength and ductility of steel, combining these two materials creates an optimal solution for load-bearing applications. However, the bond between concrete and rebar is one of the most critical factors for the structural performance of reinforced concrete structures. Without sufficient bond between concrete and rebar, the load-bearing capacity and stiffness of the structure would decrease significantly.

Generally, the bond behavior between concrete and rebar is evaluated using bond stress-slip diagrams[2]. The first studies of bond-slip behavior date back almost as long as the history of reinforced concrete [1],[2]. In 1908, Moersch, and 1913, Abrams, presented the first studies on the bond-slip behavior in reinforced concrete members. In 1961, Rehm identified the primary mechanisms for bond behavior in reinforced concrete members [1],[2].

The compatibility of strains between concrete and rebar is required to develop significant strains and stresses in the rebar, which facilitates active participation of rebar in the load-bearing capacity of reinforced concrete components [3]. As illustrated in Figure (1), the primary mechanisms contributing to bond between concrete and rebar include chemical adhesion, surface friction, and shear bond due to the mechanical interlock of rebar ribs and aggregates.

The mechanical interlock at the interface of rebar ribs and concrete is one of the most crucial factors in bond performance. When the bar is pulled with respect to the surrounding concrete, compressive stresses are generated at the contact points between the rebar ribs and the concrete, resulting in circumferential tensile stresses in the concrete cross-section around the rebar and shear stresses in the concrete keys between the ribs [4].

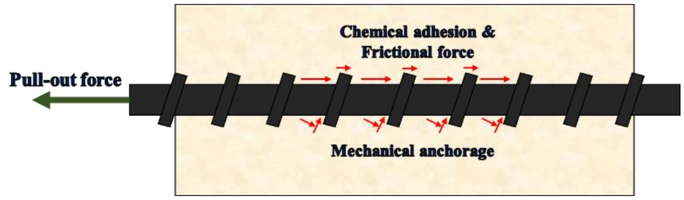


Fig. 1. Bond mechanisms

When the rebar begins to slip with respect to concrete, surface friction is initially the most critical mechanism in this force transfer. This explains why plain or epoxy-coated rebars exhibit reduced bond strength. As the rebar slip within the concrete increases, surface friction diminishes, and mechanical interlocking forces begin to resist the movement. If the concrete cover thickness over the rebar or the lateral spacing between rebars is insufficient, these tensile stresses can cause splitting cracks, leading to "splitting failure". Conversely, if adequate concrete cover, sufficient lateral spacing between rebars, or sufficient transverse reinforcement to prevent splitting is provided, failure occurs due to shear along the rib surface around the rebar, known as "pull-out failure". Typically, splitting failures are more common in most reinforced concrete structures [4].

According to ACI 408R-03 [4], there are four types of tests to determine the bond strength between steel and concrete: 1) pull-out tests, 2) beam anchorage specimen tests, 3) beam splice specimen tests, and 4) beam-end specimen tests. Generally, the pull-out test is less reliable due to the creation of unrealistic compressive stresses in the bond area, which affects the bond strength results. However, it is more commonly used because of its simplicity and speed. The beam splice and beam anchorage tests, on the other hand, require large-scale specimens and extensive laboratory facilities, making them less practical. The beam-end specimen test is practical for determining bond strength because it features off-center rebar, avoids the bearing compressive stress zone, and produces realistic shear and bending stresses similar to those in reinforced concrete members[4]. Factors affecting bond behavior in reinforced concrete specimens include the compressive strength of the concrete, the level of confinement, the concrete cover around the rebar, the type and size of the rebar ribs, the surface and temperature conditions of the concrete, and the type of loading applied to the specimens [5].

A significant number of numerical and experimental studies have been conducted on the bond behavior between concrete and rebar. Alavi-Fard and Marzok conducted an experimental study on the bond behavior between rebar and high-strength concrete containing silica fume under cyclic loading using the pull-out test. Additionally, to investigate the effect of cyclic loading rates on bond behavior, the specimens were subjected to strain-controlled loading at rates of 1.5, 3.75, and 4.25 mm/min. The level of confinement did not significantly affect bond strength but did increase the number of loading cycles required to initiate bond failure. Furthermore, reducing the rebar size led to faster crack propagation, decreasing bond strength in the initial cycles[6].

Delso et al. conducted an experimental study on the bond-slip behavior of rebars with different sizes under monotonic and cyclic loading. For this study, 22 specimens with various rebar sizes and two concrete mix designs with compressive strengths of 34.5 and 55 MPa were tested. As the rebar size increased, the demand for bond stress also increased. Moreover, with increasing compressive strength, the bond strength exhibited an increase that was proportional to the compressive strength to the power of 0.75. Additionally, the study demonstrated that the pulling direction and rebar slip history significantly influenced the bond strength[7].

Shen et al. investigated the bond behavior between concrete and high-strength rebar at early ages using pull-out tests. Concrete specimens with a 28-day compressive strength of 50 MPa were fabricated with dimensions of 160×160×160 mm. These specimens were tested at ages of 1, 3, 7, 14, and 28 days. The results indicated that as the age and compressive strength increased, the bond strength of the specimens increased by up to 25.5 MPa at 28 days. Furthermore, an increase in concrete compressive strength led to a reduction in rebar slip within the concrete. Finally, a model was proposed for the bond behavior of high-strength concrete specimens at early ages [8].

Lin and Zhao conducted a comprehensive study on the bond behavior between concrete and rebar with varying degrees of chemical corrosion under cyclic loading using the pull-out test method. In this study, 43 concrete specimens with dimensions of 150×250×300 mm were prepared, with rebars embedded in the specimens to a length of 100 mm, which was five times the diameter of the rebar. The results indicated that with an increase in stress level, the rebar slip also increased. However, no significant difference was observed in the maximum bond strength between cyclic and monotonic loading for corroded and non-corroded rebars. It was also noted that corrosion could lead to an increase in applied stress levels, resulting in a significant reduction in the fatigue life for bond [9].

Lu and Yuana studied the bond behavior of concrete at early ages under seismic loading after exposure to fire. In this study, 32 groups of specimens with dimensions of 150×150×160 mm were tested after exposure to temperatures of 150, 350, and 550 degrees Celsius at ages of 3, 7, 14, and 28 days using the pull-out test method. The effects of different cooling methods were also considered. The results showed that the bond strength increased when the specimens were exposed to a temperature of 150 degrees Celsius but decreased for greater exposure temperatures. Additionally, it was observed that the specimen age, cooling method, and placement of transverse reinforcements significantly influenced the bond strength [10].

Baktheer et al. conducted a series of experimental and numerical studies on the fatigue behavior of high-strength reinforced concrete beams under cyclic loading. In this study, modified beam-end specimens were used, and cyclic loading consisted solely of compressive loading. In total, 56 beam specimens with varying lengths, concrete strengths, and rebar diameters were subjected to monotonic, cyclic, and fatigue loads. The concrete compressive strengths were 80 and 120 MPa, and rebar diameters of 16 and 25 mm with a yield stress of 500 MPa were used in the specimens. Four types of loading were employed in the experiment: monotonic loading, cyclic loading with force control for 100 cycles, fatigue loading using accelerated loading control, and fatigue loading at a constant load level and a reduced number of cycles. The results showed that for a clear span-to-rebar diameter ratio of 2.5, the behavior under compressive loading was similar to that under tensile loading. The failure mode in this experiment for all monotonic loading tests and most fatigue-loaded specimens was compressive-fracture. In some fatigue-loaded specimens, a compressive failure was observed. Tensile fractures directly affected the ductility behavior under fatigue loading and significantly reduced the ductility. A comparison of the results with the numerical model in *fib MC 2010* showed that the *fib* model was very conservative. Finally, a new numerical model for the bond strength of high-strength concrete was proposed [11].

Asghari Ghajari and Yousefpour conducted a comprehensive experimental study on the effect of exposure to elevated temperature on the bond-slip behavior of modified beam-end specimens. The reinforced concrete beam-end specimens had dimensions of 200 by 300 by 500 mm, which contained a main rebar with a diameter of 14 or 22 mm and two confinement levels. The specimens were subjected to temperatures of 400, 600, and 700 degrees Celsius before the test. The results indicated a significant decrease in bond strength and stiffness for exposure temperatures of 400 and 700 degrees Celsius. Additionally, under cyclic loading, a decrease in bond strength of 25 to 45 percent was observed compared to monotonic loading [12],[13].

Despite these studies, limited data are available on the bond-slip behavior in beam-end specimens, especially under complete load reversals, which may play a critical role in the seismic performance of reinforced concrete members. Moreover, most of the knowledge currently available on the cyclic bond-slip behavior is from pull-out tests, which are known to produce unrealistic results. The objective of this paper is to employ modified beam-end specimens to examine the bond-slip behavior in cyclic loading conditions and its differences with monotonic bond-slip behavior.

2. Methodology

2.1. Materials

The specimens were fabricated using Type 2 portland cement and siliceous aggregates, for which the grading curves are shown in Figure (2). The figure shows that the aggregate grading falls within the permissible range of ASTM C33 [14]. Table 1 presents the mixture proportions used in the reinforced concrete specimens.

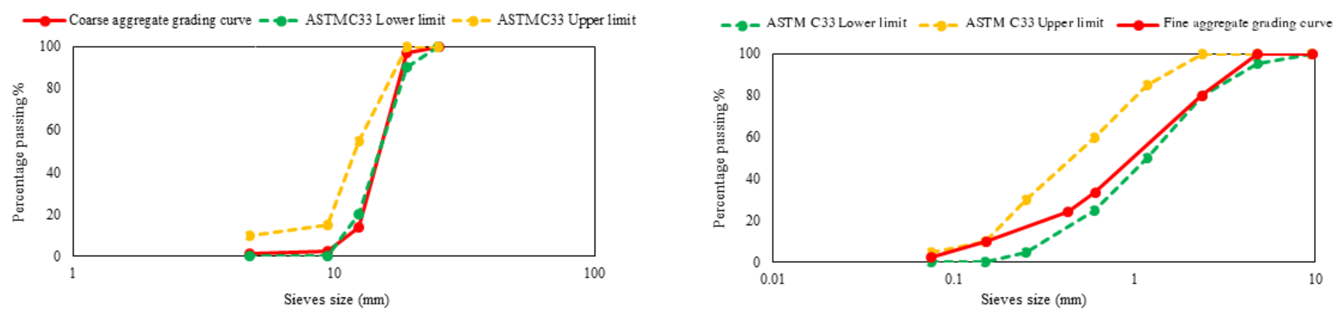


Fig. 2. Grading curves for fine and coarse aggregate

Table 1. Concrete mixture proportions

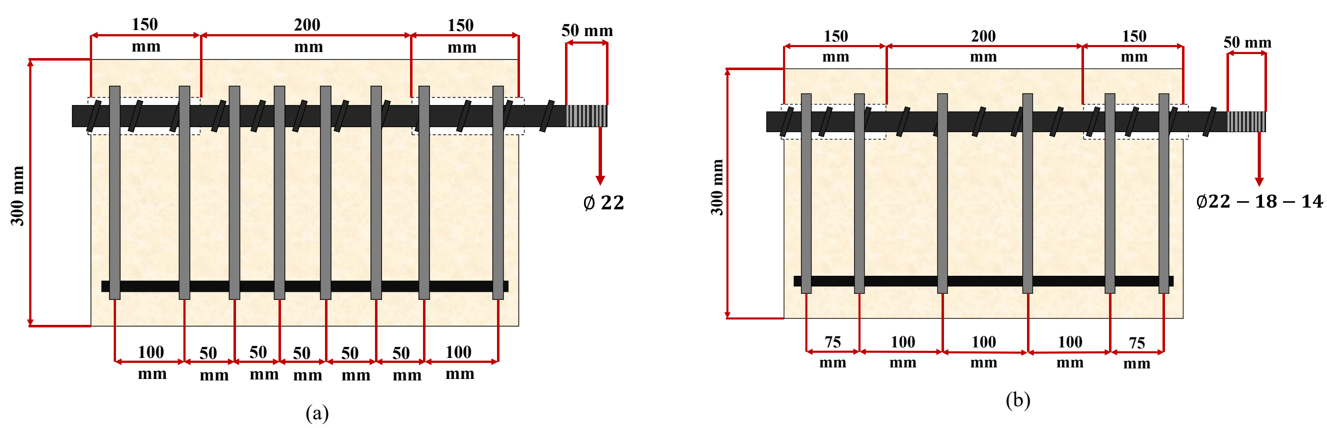
NaOH (kg/m^3)	Water (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	Cement (kg/m^3)
8.4	220	960	615	550

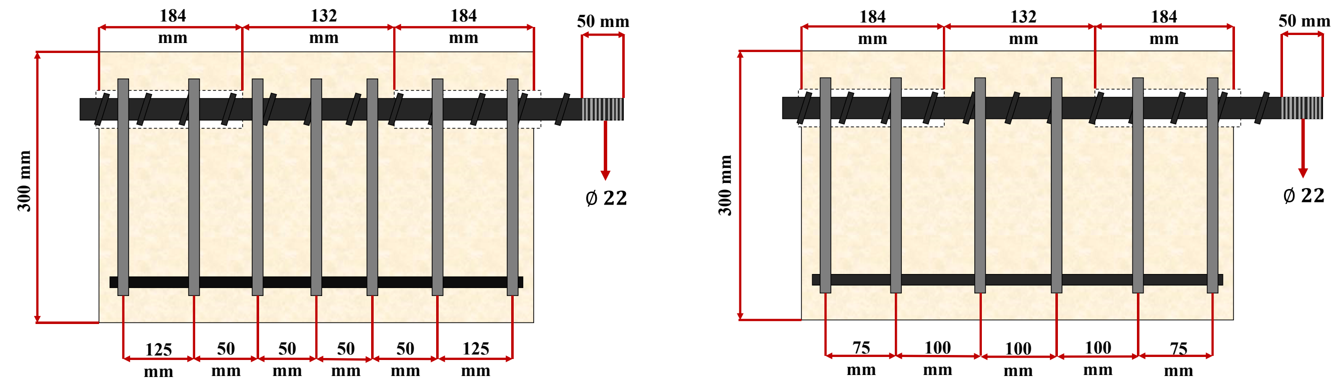
Note: CA=coarse aggregate; FA=fine aggregate.

2.2. Design of Reinforced Concrete Specimens

To examine and compare the bond-slip behavior under various parameters such as rebar size, bond length, concrete compressive strength, level of confinement, and type of loading, reinforced concrete specimens with dimensions of 200 by 300 by 500 mm were designed and constructed, as shown in Figure 3.

As shown in Figure 3(a), four specimens were constructed with a bond length of 200 mm and rebar diameters of 14, 18, and 22 mm with low confinement, featuring two stirrups spaced 100 mm apart in the bond region. Additionally, as shown in Figure 3(b), two specimens had a bond length of 200 mm and a rebar size of 22 mm with high confinement, featuring four stirrups spaced 50 mm apart in the bond region. For a bond length of 132 mm, specimens with a 22-mm main rebar were constructed in both low- and high-confinement conditions; as shown in Figures 3(c) and 3(d), the former containing two stirrups spaced 100 mm apart, and the latter containing three stirrups spaced 50 mm apart.





(c) (d)

Fig. 3. Design of Reinforced Concrete Specimens

Each specimen was identified through a label containing letters and numbers, for example, L22-L200-M. The first letter indicates the level of confinement, either low (L) or high (H). The following number indicates the rebar size, either 14, 18, or 22 mm. The third symbol indicates the bond length, either L132 or L200, representing a bond length of 132 mm or 200 mm. The last letter indicates the type of loading, either monotonic (M) or cyclic (C).

2.3. Construction of Reinforced Concrete Specimens

Figure (4) shows the fabrication of the specimens. As seen in this figure, plastic tubes were used at the ends of the main bar to adjust the required bond length and prevent bonding between the rebar and concrete where needed. As depicted in Figure 4, the formwork for the specimens consisted of a combination of metal forms and wooden block-outs. Besides the main reinforced concrete specimens, concrete cylindrical specimens were constructed for measuring the compressive and tensile strength of the concrete. According to ASTM C192 [15], cylindrical concrete specimens were compacted in two layers using a standard tamping rod, while for reinforced concrete specimens, two layers of concrete were compacted using electric vibrators. Twenty-four hours after concrete casting, the reinforced concrete specimens were removed from the formwork and moist cured in a 25-degree Celsius environment for 28 days. The specimens were subjected to loading at an age of 56 days or later.

Fig. 4. Fabrication of reinforced concrete specimens

2.4. Concrete Compressive and Tensile Strength Test

The compressive and tensile strengths of concrete were determined according to ASTM C39 [16] and ASTM C496 [17], respectively, as shown in Figure (5). Cylindrical specimens for compressive strength testing were capped with sulfur at both ends to ensure uniform stress distribution. Using Equations (1) and (2), the maximum forces obtained from the testing machine were converted to compressive and tensile strengths of concrete.

$$\sigma_c = 4P/(\pi D^2) \quad (1)$$

$$\sigma_t = 2P/\pi DL \quad (2)$$

In the above equations, **P** represents the maximum force (N), **D** denotes the diameter of the specimen (mm), and **L** represents the length of the specimen (mm).

Fig. 5. Testing for the compressive and tensile strengths concrete

2.5. Monotonic Bond Test

To determine the bond strength under monotonic loading, modified beam-end specimens with rebar sizes of 14, 18, and 22 mm; bond lengths of 132 and 200 mm; and two confinement levels of low and high were tested using a 40-ton Universal Testing Machine (UTM) at the Structural Engineering Laboratory at Babol Noshirvani University of Technology. As shown in Figure (6), two methods were used to connect the rebar to the testing machine. For specimens with rebar diameters of 14 and 18 mm, the gripping wedges of the UTM were used to hold and pull the rebar, but for specimens with a rebar diameter of 22 mm, the end of the bar was threaded and a double-ended coupler was used to connect the rebar directly to the machine.

Monotonic tests were conducted in a displacement-controlled fashion at a constant head displacement rate of 2 mm per minute. Using a Linear Potentiometer (LPOT) at the free end of the bar, rebar slippage was simultaneously measured by the machine along with applying the force, and the force-displacement curve was obtained. Using equation (3), the force obtained from the machine at each displacement was converted to bond stress.

$$\sigma_b = P/\pi DL \tag{3}$$

where **P** represents the applied force (N), **D** denotes the diameter of the rebar (mm), and **L** represents the bond length of the rebar (mm).

Fig. 6. Monotonic test setup

2.6. Cyclic Bond Test

Cyclic loading was performed on modified beam-end specimens with a rebar size of 22 mm rebar, which had bond lengths of 132 and 200 mm in two states of low and high confinement. A setup similar to that shown in Figure (6) was used for the cyclic tests. A double-ended coupler was used to connect the threaded end of the rebar to the UTM. Each cyclic bond test consisted of two stages. The first stage was conducted in a force-controlled fashion at a head displacement rate of 1 mm per minute. The rebar is subjected to cyclical compressive and tensile loading, as shown in Figure (7), until the rebar slippage both in tension and compression, measured by the LPOT, reaches a limit of 0.08. Once this bar slip was measured, the load was returned to zero, and the second stage started.

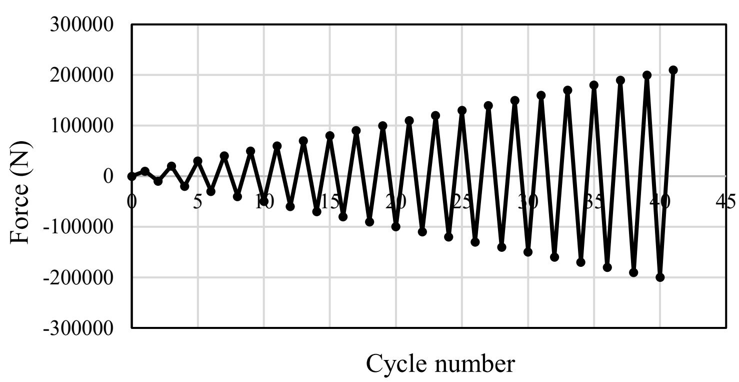


Fig. 7. Loading protocol for the first stage of the cyclic test

In the second stage, a displacement-controlled cyclic loading was applied at a head displacement rate of 2 mm per minute, as shown in Figure (8). This loading protocol was consistent with the requirements of ACI 374.IR [18]. The rebar was subjected to loading under this protocol for each level of slippage, with two loading cycles performed. At the end of the test, the force obtained from the machine at each slippage was converted to bond stress using Equation (3).

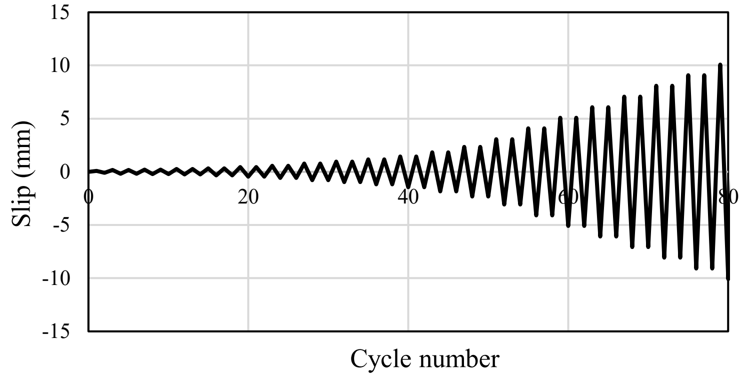


Fig. 8. The loading protocol for cyclic force in the second step

3. Results and Discussion of the Research

3.1. Concrete Compressive and Tensile Strengths

A summary of the results obtained from the compressive and tensile strength tests of cylindrical specimens is depicted in Figure (9). Due to differences in the age of the specimens at the time of loading, the compressive strength of concrete varied between 24 and 33 MPa whereas the tensile strength varied between 2.8 and 3.2 MPa.

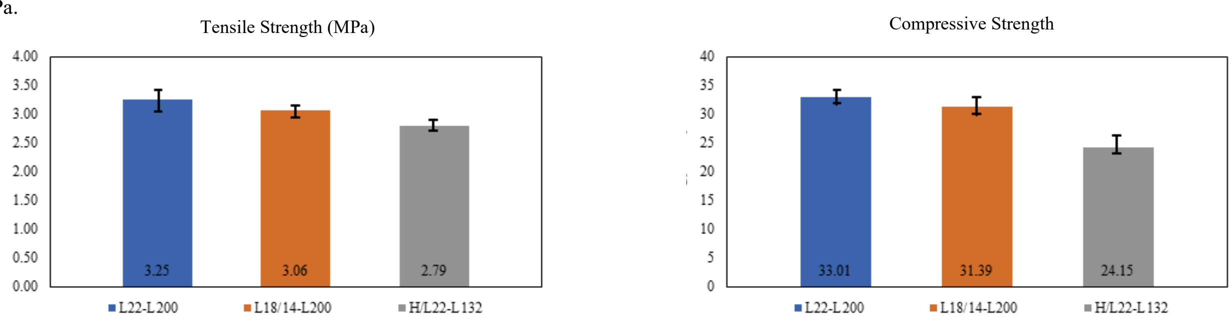


Fig. 9. Results of the compressive and tensile strength tests

3.2. Results of the Monotonic Bond Strength Test

The bond-slip results obtained from the monotonic tests are depicted in Figure (10). It is observed that with an increase in rebar size, the bond strength and stiffness increase. Comparing the specimen with a 22-millimeter rebar to the one with a 14-mm rebar, a 35% increase in bond strength is evident. Additionally, the specimen with an 18-mm rebar reached significant slippage and debonding stress before being pulled out of the concrete. Note that specimen H22-L200-M fractured before significant slip could occur.

For specimens with a bond length of 132 mm, the increase in confinement did not result in a significant change in bond strength. However, it resulted in an increase in bond stiffness, and caused the decrease in bond strength to occur with a delay. Although the compressive strength decreased in the series L22-L132-M compared to L22-L200-M, the average bond stress did not decrease significantly, but the stiffness decreased. The increase in bond stress for the series L22-L132-M compared to L22-L200-M was 15%, which is inversely correlated to the bond length.

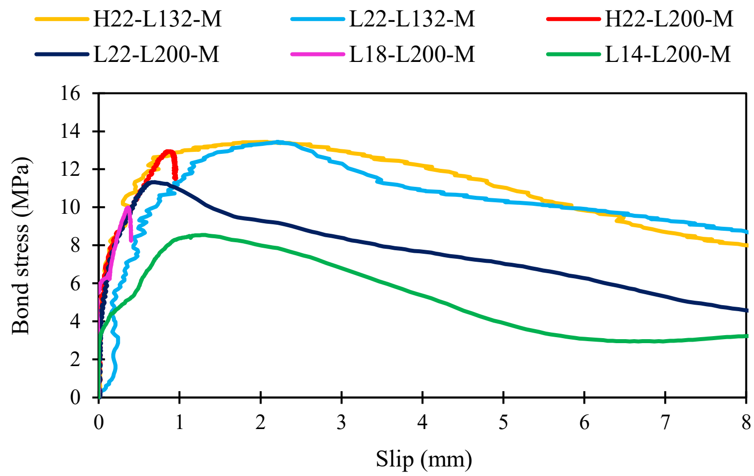
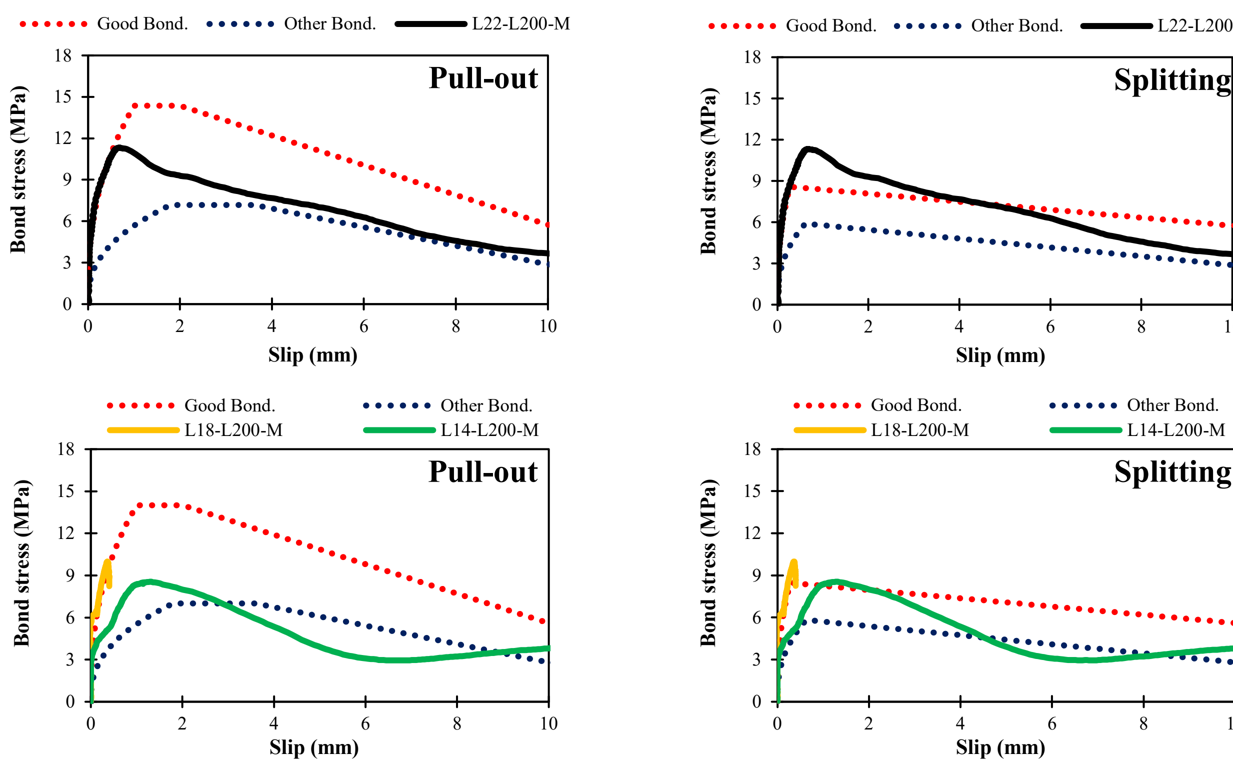


Fig. 10. Bond-slip behavior under monotonic loading

In Figure (11), the results obtained from the monotonic test are compared with the bond-slip model used in *fib* MC 2010 [19] for two failure modes. The results cover a range of specimens with good and other bond conditions. By comparing the results with this model, it is observed that most bond-slip behaviors align well with the pull-out behavior, and not splitting failure.



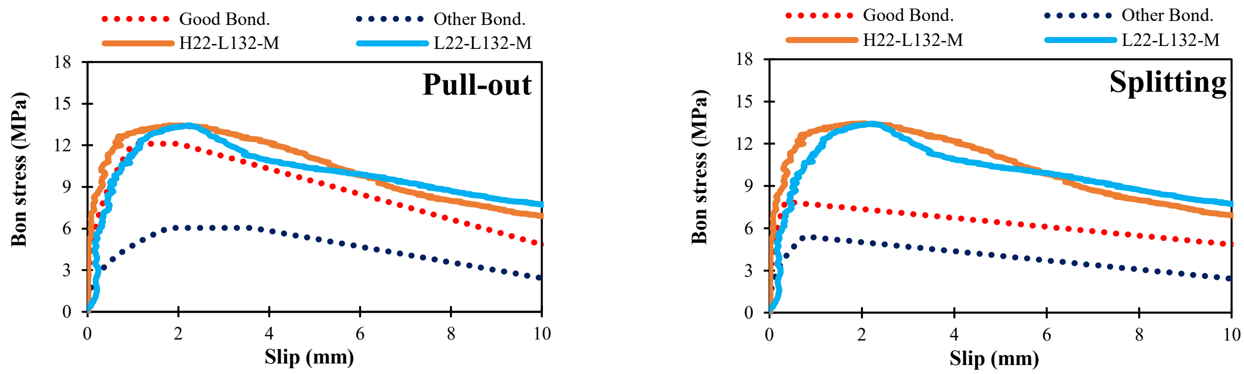


Fig. 11. Comparison of the monotonic test results in this research with the equations in *fib MC 2010*

Larger rebar diameters provide a greater surface area for mechanical interlock with the surrounding concrete. This increased surface area enhances the frictional resistance between the rebar and the concrete, leading to higher bond strength per unit. In addition, Larger rebars may distribute stresses more effectively within the concrete, reducing the likelihood of localized stress concentrations and potential bond failures. However, further experimentation is required to confirm the effect of bar size on bond stress.

The results obtained from this experiment were compared to previous research, such as that of Zhychkovska et al., Asghari and Yousefpour, Baktheer et al., as well as the *fib* MC 2010. The findings showed a good agreement with these references. As an example, Figure (12) presents a comparison of the results obtained in this study with those of the research conducted by Asghari and Yousefpour [12]. The results demonstrate a strong agreement with previous studies.

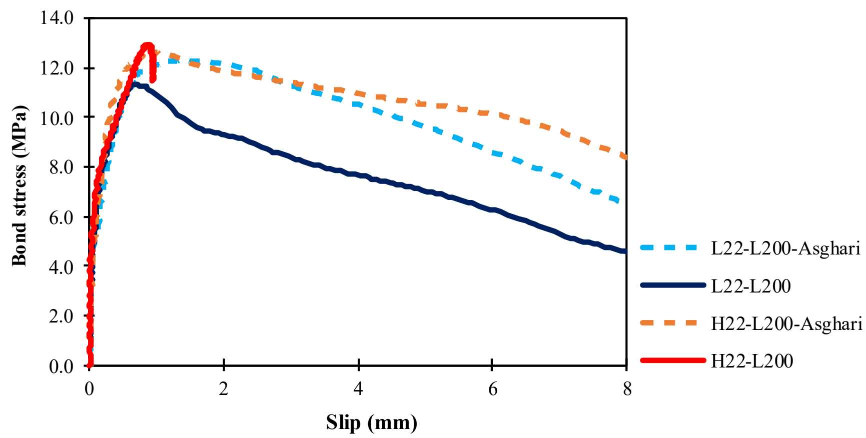


Fig. 12. Comparison of the monotonic test results in this research with Asghari's research

3.3. Cyclic Bond Strength Test

The results obtained from the test to determine bond strength under cyclic loading are depicted in Figures (13-15). At the beginning of loading, due to high bond strength, energy dissipation is based on partial slippage, and bond stiffness remains constant. After increasing damage from cyclic loading at the interface between concrete and rebar, bond strength decreases, and rebar displacement remains in the specimen, resulting in pinching. With an increase in cyclic loading, the displacement amplitude of the rebar increases. According to the results, with an increase in confinement, bond stiffness increases, and cyclical bond strength increases by 45%.

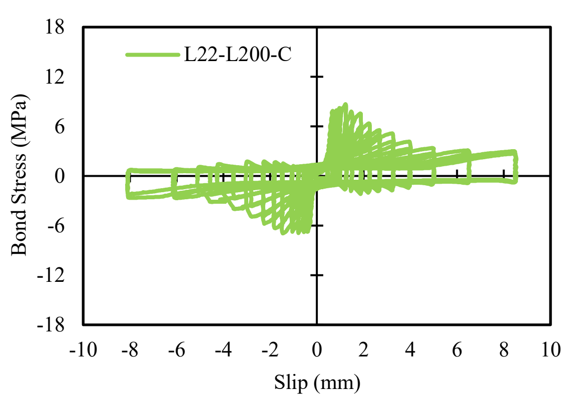


Fig. 13. Bond-slip curves under cyclic loading for L22-L200-C

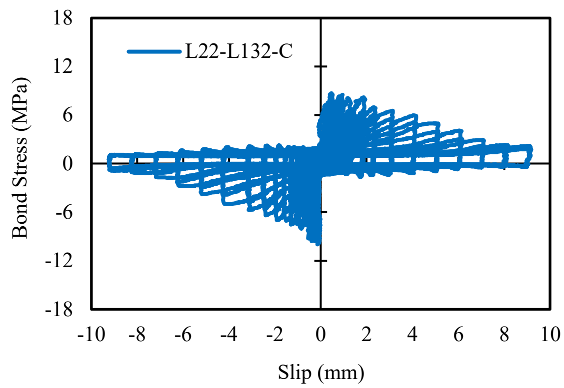


Fig. 14. Bond-slip curves under cyclic loading for L22-L132-C

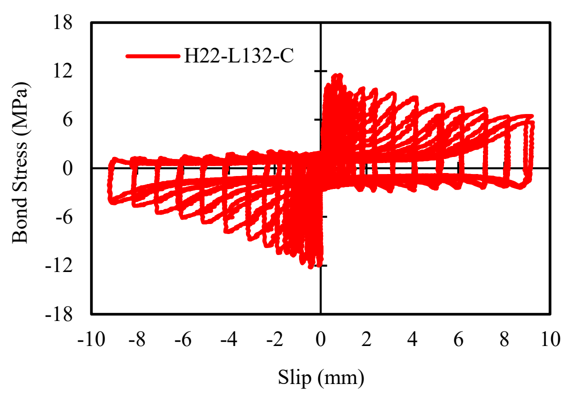


Fig. 15. Bond-slip curves under cyclic loading for H22-L132-C

Backbone curves for the hysteretic behaviors obtained from the specimens are shown in Figures (16-18). The results indicate that with increasing loading cycles and the accumulation of damage in the bond region between the reinforcement bar and concrete, the bond strength and stiffness decrease after each cycle. Additionally, with increased confinement, the bond strength degradation occurs more gradually, and the specimens exhibit greater stiffness and strength compared to those with lower confinement levels. Similar to the monotonic loading case, the H22-L200-C series specimens reached their ultimate stress and fractured at the threaded end before experiencing significant slip and ultimate bond strength.

The test results indicated that for L22-L200-C, the bond stress decreased by 18% under compressive cycles and 25% under tensile cycles. This reduction was 30% and 21%, respectively, for series L22-L132-C, and 31% and 23%, respectively, for series H22-L132-C. It should be noted that this phenomenon is caused by the accumulation of damage in the bond length region.

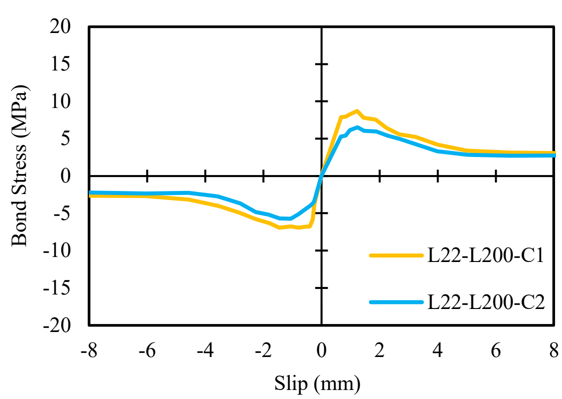


Fig. 16. Back-bone curve of bond-slip under cyclic loading for L22-L200-C

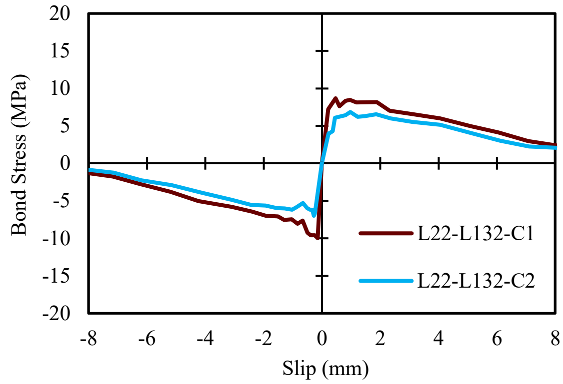


Fig. 17. Back-bone curve of bond-slip under cyclic loading for L22-L132-C

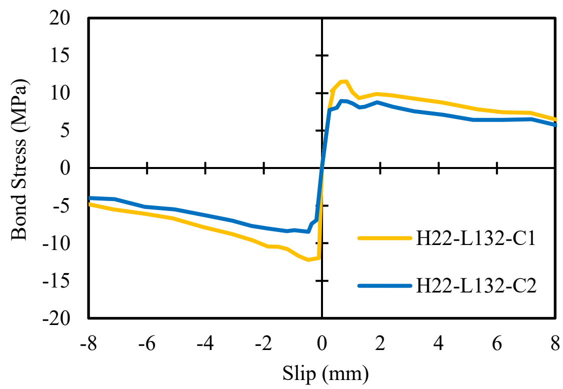


Fig. 18. Back-bone curve of bond-slip under cyclic loading for H22-L132-C

4. Conclusion

This study investigated the bond-slip behavior of modified beam-end reinforced concrete specimens under monotonic and cyclic loading. The results of the monotonic tests showed that increasing the reinforcing bar diameter from 14 to 22 mm increased the bond strength and stiffness by 35%, and the increased rib height played a significant role in increasing the bond strength. Additionally, increasing the confinement level in reinforced concrete specimens played a key role in improving the cyclic bond strength by 35%, and more specifically, in increasing the bond stiffness.

A reduction in bond length from 200 mm to 132 mm results in a 15% decrease in bond stress. Under cyclic loading, a decrease in bond strength was observed in each cycle due to the accumulation of damage at the interface between the reinforcing bar and the concrete caused by loading reversal. A comparison of the monotonic and cyclic test results showed that damage in the cyclic specimens caused a 50% reduction in bond strength. Additionally, under cyclic loading, a reduction of up to 30% in bond stress was observed in both compression and tension cycles.

This research provides valuable data for modeling bond-slip behavior in nonlinear modeling software, such as OpenSEES which can be beneficial in the assessment of reinforced concrete structures, especially where insufficient embedment length is provided. Potential topics for future experimental studies using the same configuration include the following:

-effect of transverse reinforcement on bond behavior.

-behavior of full-scale beams under cyclic loading.

-effects of corrosion on bond behavior.

-bond behavior after yielding of reinforcement.

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