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Experimental investigation of the Moment Bolted Coupler (MBT) with steel on the bond strength under different monotonic pull-out tests

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Abstract
The bond strength between steel reinforcement bars and mechanical bolted couplers (MBT) is essential for the structural integrity of reinforced concrete structures. However, various pull-out test methods yield inconsistent results when assessing this bond strength. This research examines the impact of reinforcement bar diameter (12mm, 16mm, and 20mm) and three different pull-out test configurations (M1, M2, and M3) on the bond strength of MBT couplers. The M2 method, employing direct tensile loading and a short clamp zone, consistently produced the highest bond strength values across all bar diameters. Its simplicity, reliability, and adherence to standardized procedures make it the preferred method for determining the maximum bond capacity of MBTs. While the M1 and M3 methods offer insights into coupler behavior under complex loading scenarios, they exhibit lower bond strength values compared to M1. The M2 pull-out test method is recommended as the primary method for evaluating the bond strength of MBT in practical applications, with M3 testing as a potential supplement for a more comprehensive understanding of coupler behavior.

Keywords:
Bond Strength;
Failure mode;
Maximum load capacity;
Mechanical Bolted Coupler;
Pull Out Test;

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INTRODUCTION

Steel is a fundamental material in modern construction due to its strength, durability, and adaptability. Steel connections, including bolted, welded, and mechanical splice connections, are crucial for ensuring the stability and safety of the steel structure. Mechanical splice connections, such as couplers, provide huge advantages in terms of ease of assembly and design flexibility. Couplers are clearly advantageous over traditional lap splicing, as it can directly transfer loads between reinforced bars and reduce steel consumption, thus minimizing congestion at joints [1-5].

Mechanical couplers are commonly used in construction as an alternative to the traditional lap splicing method. Mechanical couplers offer significant advantages, particularly in term of cost reduction for reinforcement bars and fabrication expenses, as well as reduced congestion at joints. The concept of connection for mechanical couplers typically involves a threaded annual sleeve that fits the bar at the junction, connecting a different rebar in the sleeve region using grout or a screw as a connector.

There are various types of mechanical couplers available nowadays with specific applications and characteristics. Hybrid couplers, for instance, incorporate two distinct connection mechanisms, while transition couplers are designed to connect reinforcement bars of different diameters. For shear screw couplers, utilize screws designed to break at a predetermined torque, enabling controlled separation under shear stress [6]. Grouted couplers enhance structural stability by filing the steel sleeve with cementitious material, providing a robust connection for reinforcing bars [7]. Threaded couplers are well-known for their exceptional structural performance in concrete structures, enhancing load-bearing capacity and ductility [8].

On the upside, the mechanical coupler offers abundant benefits, but it is essential to consider the downsides and potential limitations. For instance, the bond strength between the coupler and the rebar can be influenced by factors such as the cleanliness of the rebar surface (i.e., the presence of ribs), as well as the presence of contaminants [9]. Additionally, steel diameter can significantly affect bond strength as well as bond failure [10]. A large diameter can increase the likelihood of bond failure. This failure can manifest as either slippage failure, where the steel reinforcement slides within the concrete, or pull-out failure, where the steel reinforcement bar is completely extracted from the concrete.

Excessive slippage between the coupler and the reinforcement bar under dynamic or static loading indicates poor coupling efficiency and can be affected by a few factors, for example, thread pitch, thread angle, bar diameter, and temperature [11]. Understanding these limitations is crucial for ensuring the proper selection, design, and installation of mechanical couplers to ensure the structural integrity and long-term performance of RC structures. Ensuring the reliability and efficiency of mechanical coupler steel connections, especially under extreme environmental scenarios and dynamic loading, is quite challenging in construction projects.

An earthquake event can induce vibrations in structures, potentially causing slippage failure between couplers and reinforcement bars. In reinforced concrete (RC) structures, the continuity of reinforcement in the inelastic zone is crucial for maintaining structural integrity under high dynamic loads like earthquakes. Traditional lap splicing may lead to over-reinforcement and non-ductile behavior due to stress concentration at the lap ends, inadvertently altering the deformation capacity of the reinforced structure [12].

The vital challenge to comprehending the reliability and efficiency of mechanical couplers is to understand their bond behavior in terms of bond strength. Experimental configuration setups for evaluating the bond strength of mechanical couplers have been plagued by inconsistencies and significant variation in results, such as bond strength and failure, depending on the test setup [13]. The numerous types of testing methodologies, including the uniform pullout test (UPT) [14-17], direct pullout test (DPT) [18][19], and direct tension pullout test (DTPT) [20][21] have led to diverse and often conflicting results.

Therefore, a comprehensive investigation is needed to determine the most suitable testing method for accurately and reliably determining the bond strength. This research aims to address this issue by systematically evaluating the various pullout test setups to identify the appropriate method for determining the bond strength of the MBT mechanical coupler.

METHODS

Pullout testing is a fundamental method for evaluating the bond behavior between the concrete and steel reinforcement. This test provides crucial insight into the structural integrity of the reinforced concrete member. The effectiveness of the pullout test method depends on its simplicity, cost-effectiveness, and ability to systematically control and vary the parameters, making it able to assess coupler connection effectiveness and bond strength under tensile stress [22].

Pull-Out Test Method

A comprehensive evaluation was conducted utilizing three different pull-out test configurations, which are: uniform pullout test (UPT), direct pullout test (DPT), and direct tension pullout test (DTPT). The UPT was represented as Method 1 (M1), DPT was Method 2 (M2), and DTPT was Method 3 (M3). The upper adjustable crosshead of the Universal Testing Machine (UTM-1000) was used to securely clamp the upper end of the reinforcement bar, and the lower crosshead firmly held the upper portion of the coupler for the setup M1 test. The pulling force was applied through the upper crosshead, as illustrated in Figure 1.

Method 1 was clamping the top reinforcement bar using the upper movable crosshead of the Universal Testing Machine (UTM), while the lower crosshead secured the top head of the coupler using a steel plate. This configuration subjected the coupler to a uniform tensile force, simulating a situation where the load is primarily transferred through the upper coupler connection. The clamp point for method 1 was located at a distance of $8d_b$ (diameter bar) from the top head of the coupler. The requirement was suggested based on American Society for Testing and Materials (ASTM) E8 [23].

Then, for the M2 test setup, the upper movable crosshead clamped the upper reinforcement bar at $2d_b$ (diameter bar) length. The bottom of the MBT coupler is grasped by the lower movable crosshead, as shown in Figure 2.

Method 2 introduced a loading condition by clamping the top reinforcement bar at $2d_b$ and clamping the bottom of the coupler. This method simulates the short region condition by transferring the tensile force at the rigid region of the mechanical coupler [24].

Meanwhile, for the M3 test setup configuration, the UTM grips clamped both ends of the reinforcement bar at $2d_b$ from both coupler ends. The pulling force will be applied to the upper grip as shown in Figure 3. This configuration subjected the coupler to the purely tensile load, potentially influencing the failure mode and the ultimate load resistance of the mechanical coupler connection [25].

Details of the specimen

A comparative pullout test for the Moment Bolted Coupler (MBT) was carried out on three different configuration setups. The schematic diagram of the MBT is shown in Figure 4, and the detailed specimen of the pullout test is shown in Table 1.

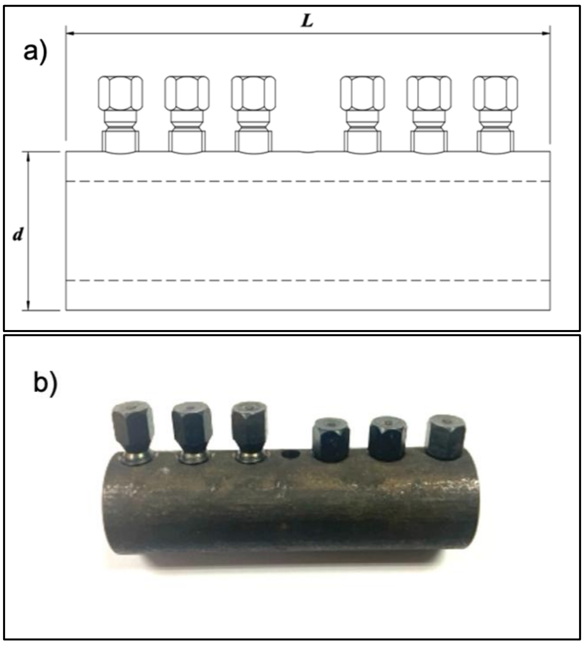


Figure 4. (a) configuration of the Moment Bolted Coupler (MBT); (b) Actual MBT

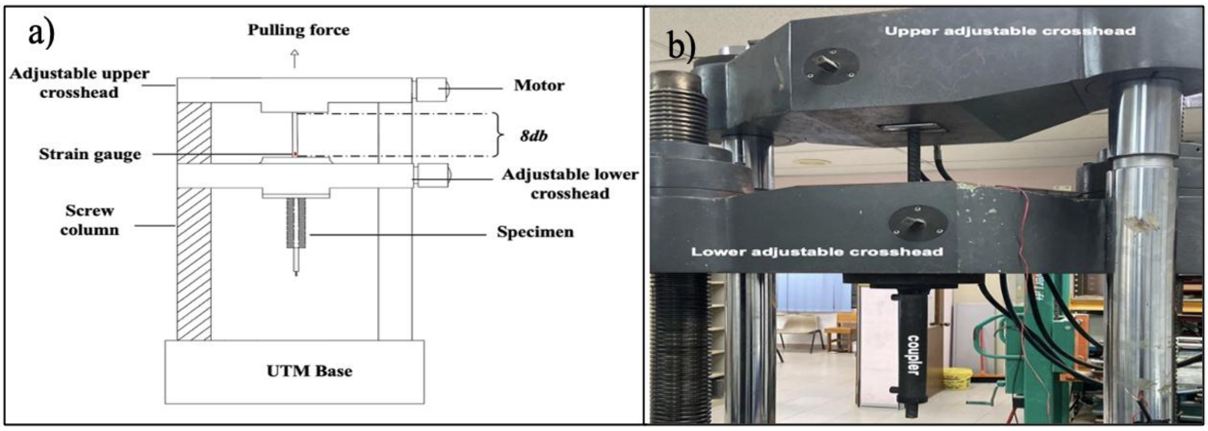


Figure 1. M1 setup (a) Schematic drawing; (b) Experimental testing

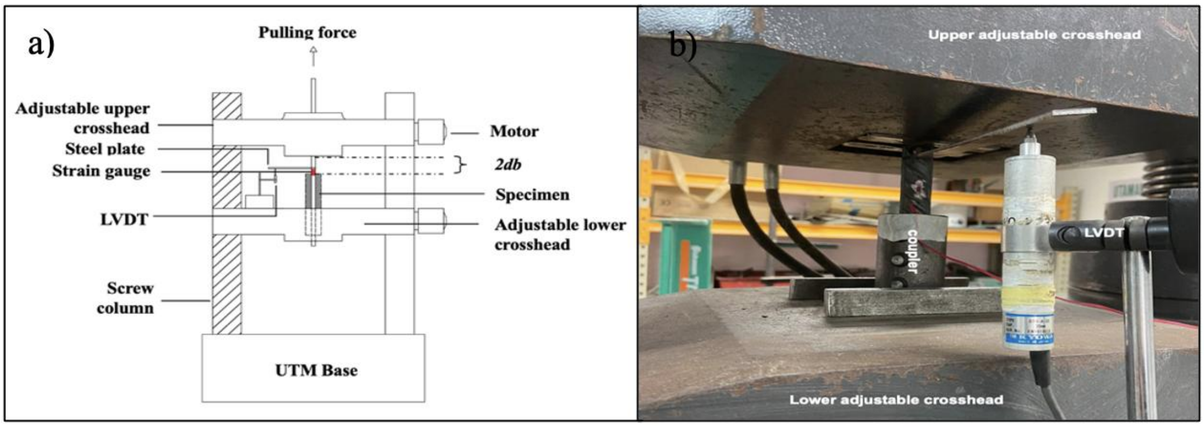


Figure 2. M2 setup (a) Schematic drawing; (b) Experimental testing

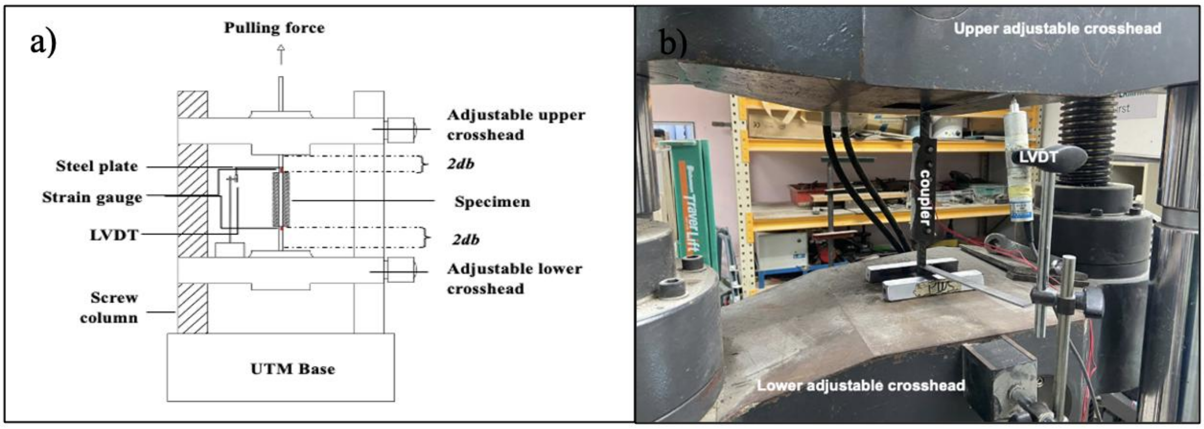


Figure 3. M3 setup (a) Schematic drawing; (b) Experimental testing

In this research, pullout test specimens were prepared based on two different parameters, which are bar diameters (12 mm, 16 mm, and 20 mm) and pull-out setup configuration (Method 1, Method 2, and Method 3). The specimens were named as M1-MBT12 (as depicted in Figure 5), where M1 indicates a type of pull-out method; MBT12 indicates a diameter bar. A total of nine specimens for all tests were prepared. The specimen dimensions in this study are measured as 600 mm in length for the upper reinforcement, and the bottom reinforcement measures 300 mm in length, as shown in Figure 6. In compliance with ASTM E8, a pullout force was applied to each specimen at a loading rate of 0.5 mm/min [26]. A linear variable differential transformer (LVDT) was used to measure the specimen displacement during the pullout test. According to the configuration setup, the LVDTs were positioned at the end of the steel plate that was fastened to the upper reinforcement. Two strain gauges were affixed longitudinally along the bar deformation, as depicted in Figure 6.

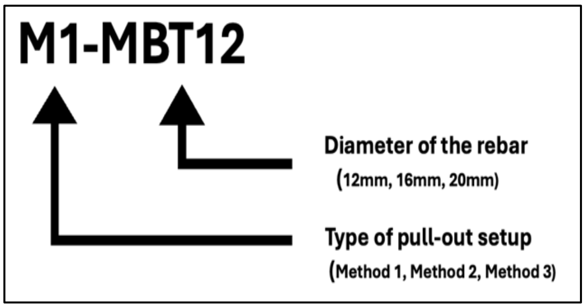


Figure 5. Notation type of specimen

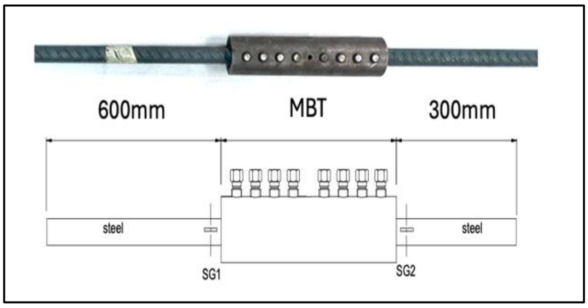


Figure 6. Pull-out specimen dimension

Table 1. Details of the pullout specification

Specimen	Rebar (mm)	Pull-out test method	Coupler length, *L* (mm)	External diameter, *d* (mm)	No. of Bolts	Clamp zone (d_b)
M1-MBT12	12	M1	140	33	6	8
M2-MBT12	12	M2	140	33	6	2
M3-MBT12	12	M3	140	33	6	2
M1-MBT16	16	M1	160	42	6	8
M2-MBT16	16	M2	160	42	6	2
M3-MBT16	16	M3	160	42	6	2
M1-MBT20	20	M1	204	48	8	8
M2-MBT20	20	M2	204	48	8	2
M3-MBT20	20	M3	204	48	8	2

RESULTS AND DISCUSSION

Based on this study, the bond strength is the force required to pull a steel bar out of the coupler sleeve. The bond strength (τ) was determined by calculating the ultimate axial tensile force (F) in kN, the nominal bar diameter(d_b), and the embedded length (L_e). The embedded length refers to the insertion of steel for each coupler in mechanical couplers. Table 2 shows the value of the bond strength for the testing specimen. The bond strength (τ) is calculated using (1) [27]:

$$\tau = F/(\pi d_b\ L_e) \quad (1)$$

The bond strength-displacement curve shows the relationships of MBT to the three different pullout test configurations (M1, M2, and M3). Figure 7 shows the bond strength-displacement curve for all specimens. The pullout testing method significantly affects the behavior of the bond strength-displacement curve. The M2 setup shows the highest bond strength, which is 30.14MPa for 12 mm, 32.48MPa for 16mm, and 37.27MPa for 20 mm. This suggested that the load transfer within a short region in M2 increases the bond strength compared to direct tension on M1. The curves for M2 and M3 are more gradual, replicating steel stress-strain behavior, indicating the ductile failure mode, which is steel rupture. The M1 curve shows the rapid drop, suggesting brittle failure, which is steel slippage. M2 and M3 setups typically fail at higher displacement compared to the M1, which indicates that M2 and M3 are more ductile compared to M1.

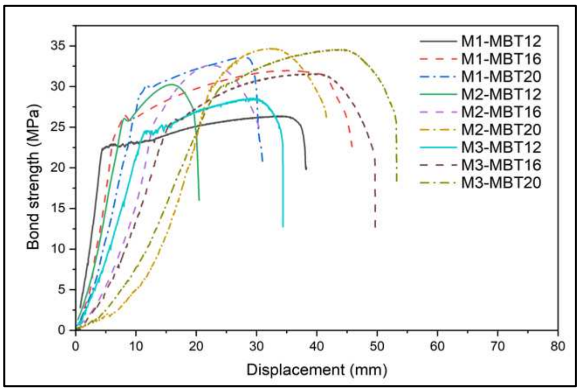
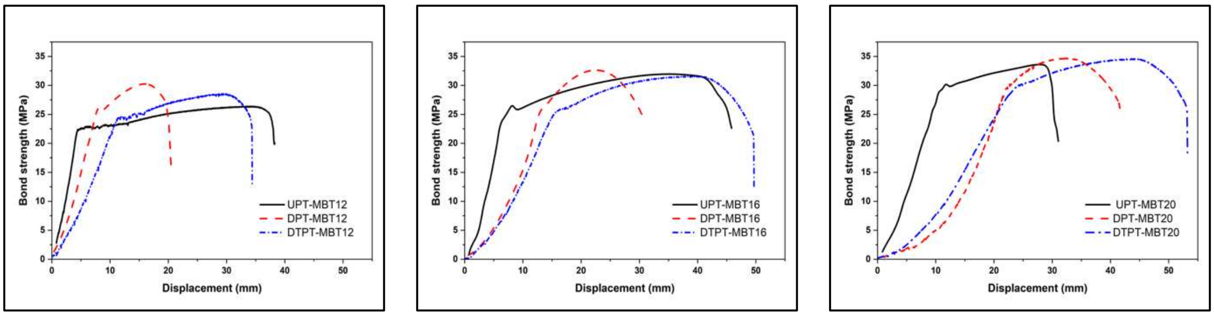


Figure 7. Bond strength – displacement curve

Table 2. Bond strength of the specimens

Specimen	Embedded length, L_e (mm)	Ultimate Tensile Force, *F* (kN)	Ultimate Bond Strength (MPa)	Maximum displacement (mm)
M1-MBT12	70	69.67	26.40	38.27
M2-MBT12	70	79.54	30.14	20.48
M3-MBT12	70	75.92	28.77	34.39
M1-MBT16	80	127.56	31.72	45.84
M2-MBT16	80	130.39	32.48	30.53
M3-MBT16	80	127.02	31.58	49.67
M1-MBT20	102	214.03	33.46	31.03
M2-MBT20	102	222.41	37.27	41.60
M3-MBT20	102	221.56	34.57	53.23



(a) (b) (c)

Figure 8. Bond strength-displacement relationships on different diameters.
a) 12mm; b) 16mm; c) 20mm

Initially, Figure 8 shows that all methods exhibit a linear increase in bond strength with increasing displacement, indicative of an elastic phase where the material deforms reversibly. Beyond this elastic limit, the specimens diverge in behaviour based on the setup. For M1-MBT12, M2-MBT12, and M3-MBT12, the failure mode is steel fracture. The plastic limit bond strength ranges from 22.18 MPa to 24.47 MPa, the plastic limit displacement varies between 4.55 mm and 11.45 mm, the rupture bond strength falls within 12.73 MPa to 20.04 MPa, and the break point displacement spans 34.39 mm to 38.27 mm. The ultimate displacement and bond strength for this group are 29.45 mm to 35.62 mm and 26.40 MPa to 28.77 MPa, respectively.

Similarly, M1-MBT16, M2-MBT16, and M3-MBT16 also exhibit steel fracture. Their plastic limit bond strength varies from 25.80 MPa to 26.46 MPa, plastic limit displacement ranges from 8.18 mm to 16.68 mm, rupture bond strength is between 12.23 MPa and 22.61 MPa, and break point displacement falls within 30.53 mm to 49.67 mm. The ultimate displacement and bond strength for this group are 22.11 mm to 41.54 mm and 31.58 MPa to 32.48 MPa, respectively.

In the case of M1-MBT20, the failure mode is slippage, whereas M2-MBT20 and M3-MBT20 experience steel fracture. The plastic limit bond strength for M1-MBT20 is 30.16 MPa, the plastic limit displacement is 11.78 mm, the rupture bond strength is 20.43 MPa, and the break point displacement is 31.03 mm. The ultimate displacement and bond strength for M1-MBT20 are 28.61 mm and 33.46 MPa, respectively.

For M2-MBT20 and M3-MBT20, the plastic limit bond strength ranges from 29.44 MPa to 30.05 MPa, the plastic limit displacement is between 22.07 mm and 24.28 mm, rupture bond strength varies from 18.37 MPa to 26.06 MPa, and break point displacement falls within 41.60 mm to 53.23 mm. Their ultimate displacement and bond strength are 31.91 mm to 45.36 mm and 34.57 MPa to 37.27 MPa, respectively.

Effect of the bar diameter

The relationship between the bond strength and bar diameter in pull-out is illustrated in Figure 9. Based on the results, the diameter bar has a significant effect on increasing the bond strength when the diameter of the rebar increases for all method setups Thus, it influences the ductility and load-carrying capacity of the mechanical coupler. The M2 pull-out method

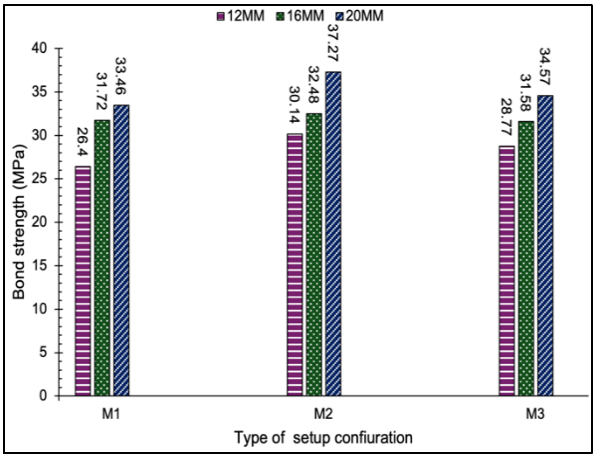


Figure 9. Influences of bar diameter on bond strength

shows the highest bond strength, 30.14MPa, 32.48MPa and 37.27MPa for all different diameters when compared to M1 and M3.The percentage difference was 12.40% for M1, 2.34% for M2, and 10.22% for M3 for diameters 12, 16 and 20 mm, respectively.

It can be seen in Figure 9 that M3 exhibit higher bond strength when compared to M1 for diameters 12 mm and 20 mm. However, the bond strength for M1 diameter 16 mm is slightly higher, with 0.45% compared to M3 diameter 16 mm. Based on three different setup methods, it shows that the M2 setup emerges as the most significant configuration for maximizing bond strength across different bar diameters. However, the bond strength relationship between the pull-out setup method can be concluded as a dependent relationship

Failure mode

Table 3 shows the failure mode of the MBT during the pull-out test. Steel bar rupture failure is the most notable observation for the failure mode that appears for all setup methods. However, only steel bar slippage failure occurs on specimen M1-MBT20.

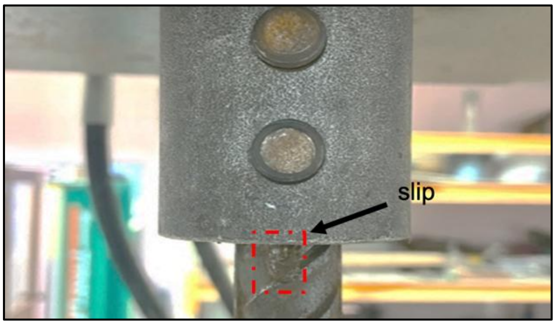


Figure 10. Steel bar slippage failure

Figure 10 shows the steel bar slippage occurring on the M1-MBT20 due to the rupture of the bolts. Each bolt was designed to carry a portion of the tensile force to the coupler connection. When one of the bolts breaks or ruptures (as shown in Figure 11), the load previously carried by the failed bolt is immediately transferred to the remaining bolt. This sudden increase in the load exceeded their design capacity, leading to the steel bar's slippage failure.

Steel rupture failure occurs when the applied load exceeds the yield strength of the reinforcing steel bars, causing the steel to rupture, as illustrated in Figure 12. This indicates that the MBT coupler has functioned appropriately, thus reinforcing bars achieved the maximum strength capacity. Previous researchers [29-31] have also observed that most failure modes are steel bar ruptures that occur when the applied load exceed the tensile strength of the steel.

According to Alharbi et al. (2020) [30], steel bar slippage occurs when the load transfer between the shear screw coupler and the rebar has deteriorated. According to Khedmatgozar (2021) [31], steel bar slippage occurs when the load transfer between the shear screw coupler and the rebar has deteriorated.

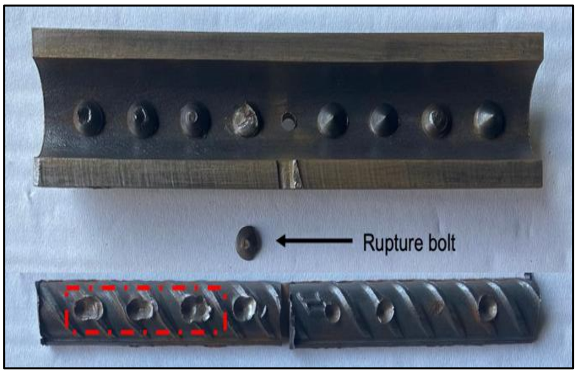


Figure 11. Rupture bolt for M1-MBT29

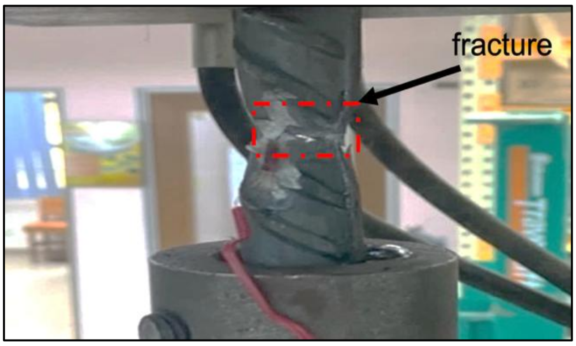


Figure 12. Rupture of the steel bar

Shear screw couplers rely on a combination of screw penetration and shear friction to transfer load effectively. Rupture of the screw coupler leads to the degradation of the load transfer. As a result, the reinforcement bar was slip from the bottom sleeve of the mechanical coupler.

CONCLUSION

This research provides a comprehensive evaluation of three different pull-out test configuration methods (M1, M2, M3) for assessing the bond strength of MBT. The conclusion can be based on the results analysis. The results demonstrate that the M2 method, characterized by direct tensile loading and a standard clamp zone, consistently yields the highest bond strength values across various bar diameters.

This method's simplicity, reliability, and adherence to standardized procedures make it the most suitable choice for determining the maximum bond capacity of MBT. While M1 and M3 offer valuable insights into coupler behavior under eccentric loading and varying clamp zone positions, they exhibit lower bond strength values compared to M2. Based on the findings, it is recommended that the M2 pull-out test method be adopted as the primary method for evaluating the bond strength of MBT in practical applications.

Table 3. Failure mode of the specimen

Specimen	Failure mode	Ultimate Stress, σ (kPa)	Rupture bond strength, τ (MPa)	Break point (mm)
M1-MBT12	Steel fracture	616.07	20.04	38.27
M2-MBT12	Steel fracture	703.29	15.98	20.48
M3-MBT12	Steel fracture	679.65	12.73	34.39
M1-MBT16	Steel fracture	634.45	22.61	45.84
M2-MBT16	Steel fracture	649.54	24.75	30.53
M3-MBT16	Steel fracture	631.98	12.23	49.67
M1-MBT20	Slippage	682.49	20.43	31.03
M2-MBT20	Steel fracture	707.94	26.06	41.60
M3-MBT20	Steel fracture	699.67	18.37	53.23

While increasing bar diameter generally enhances bond strength, the specific pull-out setup and clamp zone can significantly modulate this relationship. This method's consistency and ease of implementation make it a reliable tool for quality control and assurance in construction projects.

Limitation

This study acknowledges certain limitations that should be considered when interpreting the results. The sample size, while sufficient for drawing preliminary conclusions, could be expanded in future research to enhance the statistical significance of the findings. Additionally, the study focused on a specific type of mechanical coupler (MBT). Further research could investigate the bond behavior of other coupler types to generalize the findings

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