Research on Tensile Load Capacity of Self-Cutting Undercut Mechanical Anchors

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Abstract: The self-cutting undercut mechanical anchor is a type of mechanical anchor within post-installed fastening systems, which achieves its anchoring effect based on the mechanical interlock formed between the expanded borehole at the base and the anchor's expansion element. Compared to other mechanical anchors, the self-cutting undercut anchor have superior load-bearing capacity, minimal displacement, and exhibits reduced sensitivity to concrete cracking and borehole diameter variations. This paper introduces a specific self-cutting undercut mechanical anchor and presents experimental investigations on its tensile load capacity under varying concrete crack widths. The experimental results reveal that the ultimate tensile load capacity of this anchor remains nearly unchanged within concrete crack widths ranging from 0 to 1.5 mm, whereas the tensile stiffness (displacement) increases proportionally with the widening of cracks.

Keywords: Self-cutting Undercut Mechanical Anchors; Tensile Load Capacity; Concrete Cracks; Tensile Stiffness; Displacement

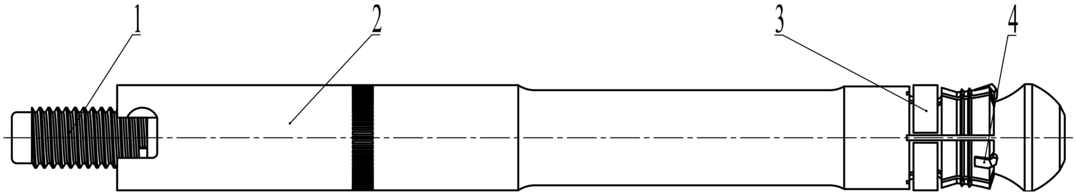
1. Introduction

Mechanical anchors are a prominent category within post-installed fastening techniques, valued for their ease of installation and operational flexibility compared to traditional cast-in-fixing anchoring methods[1,2]. Among these, the self-cutting undercut mechanical anchor stands out for its exceptional overall performance. Its anchoring mechanism involves the anchor's expansion element carving an inverted conical cavity at the base of the concrete borehole, creating a robust mechanical interlock between the expansion element and the newly formed cavity[3,4]. According to the *Chinese Design Code for Strengthening Concrete Structures* (GB 50367-2013), self-cutting undercut mechanical anchors can achieve anchorage effects comparable to those of cast-in headed bolts[5]. However, unlike cast-in headed bolts, the anchorage performance of self-cutting undercut mechanical anchors is influenced by a more complex set of factors, including the anchoring mechanism, installation conditions, and product design and manufacturing requirements[6]. Among these factors, the width of concrete cracks plays a pivotal role. Crack formation in reinforced concrete is inevitable due to variables such as member cross-sectional size, rebar diameter, and reinforcement ratio. Under typical reinforcement conditions, crack widths generally range from 0.3 to 0.8 mm [7-9], while in nuclear power construction, crack widths can reach up to 1.5 mm[10]. This paper introduces a high-performance self-cutting undercut mechanical anchor and investigates its tensile load capacity under varying concrete crack widths. The study aims to systematically examine how different crack widths affect the tensile performance of these anchors, thereby providing valuable insights for their application in cracked concrete environments.

2. Structure of the Self-Cutting Undercut Mechanical Anchor

The self-cutting undercut mechanical anchor comprises several key components: a conical-headed anchor rod, a cutting sleeve, a conical washer, and a nut. The cutting sleeve is equipped with a carbide blade, as illustrated in Figure 1.

The carbide blade is brazed onto the cutting sleeve to ensure a secure connection. During installation, a rotary percussion drill drives the cutting sleeve to rotate within the drilled hole. The carbide blade simultaneously rotates and carves into the bottom of the borehole, while the impact force from the drill hammer causes the expansion element at the front end to progressively expand axially along the conical-headed anchor rod. Eventually, the conical-headed anchor rod and its expansion element embed firmly within the inverted conical cavity created by the carbide blade's cutting action, establishing a mechanical interlock. When the anchor is in operation, the object to be anchored is inserted over the conical-headed anchor rod or cutting sleeve. Subsequently, the conical washer and nut are installed in sequence. The conical washer positioned between the nut and the anchored object serves to compensate for any reduction in pretension force that may arise from minor slip between the anchor and the concrete during service.



1 — Conical-headed anchor rod; 2 — Cutting sleeve; 3 — Non-metallic support ring; 4 — Carbide blade

Figure 1. Schematic Diagram of the Self-Cutting Undercut Mechanical Anchor Structure

3. Tensile Load Capacity Testing and Evaluation Parameters

3.1 Performance Characteristics and Installation Parameters of the Self-Cutting Undercut Mechanical Anchor

The specimens utilized in this study employ M12 self-cutting undercut mechanical anchors. Their performance specifications and installation parameters are detailed in Table 1.

Table 1. Performance and Installation Parameters of the Self-Cutting Undercut Mechanical Anchor

Specification	Grade	Drill Diameter (mm)	Drill Depth (mm)	Effective Embedment Depth (mm)	Installation Torque (N·m)
M12	Anchor Rod Grade 8.8, Nut Grade 8	22	133	125	80

3.2 Test Protocol

Table 2. Test Scheme for Tensile Load Capacity under Varying Concrete Crack Widths

No.	Concrete Strength	Drill Diameter (mm)	Crack Width (mm)	Quantity (pieces)
1	C30	dm (22.3-22.4)	0	5
2	C60	dm (22.3-22.4)	0	5
3	C30	dm (22.3-22.4)	0.3	5
4	C60	dm (22.3-22.4)	0.3	5
5	C30	dm (22.3-22.4)	0.5	5
6	C60	dm (22.3-22.4)	0.5	5
7	C30	dm (22.3-22.4)	0.8	5
8	C60	dm (22.3-22.4)	0.8	5
9	C30	dm (22.3-22.4)	1.5	5

The methodology for evaluating the tensile load capacity of mechanical anchors adheres to the uniform standards set forth by the Chinese JG/T 160-2017 *Mechanical Anchors for Concrete* and the European EAD 330232-01-0601 *Mechanical Fasteners for Use in Concrete*. Both standards stipulate that anchors must be installed on smooth, rebar-free cast concrete specimens, with the concrete strength varying within ±5 MPa. The spacing criteria require the mechanical anchor to be positioned no less than twice the effective embedment depth from the edge of the specimen, and adjacent anchors must be separated by at least four times the effective embedment depth. After the anchor is installed to a self-cutting depth, the fixture is tightened to the installation torque T_{inst}. After a 10-minute dwell, the torque is released, then retightened to $0.5T_{inst}$. Subsequently, within 1 to 3 minutes, a uniformly increasing tensile load is applied axially on the anchor until failure occurs. Load–displacement curves, slip behavior, and failure modes are recorded throughout the process. The detailed test scheme examining the tensile capacity under variable concrete crack widths is summarized in Table 2.

3.3 Evaluation Parameters

The standards JG/T 160-2017 *Mechanical Anchors for Concrete* and EAD 330232-01-0601 *Mechanical Fasteners for Use in Concrete* exhibit certain discrepancies in their criteria for assessing the tensile load capacity of mechanical anchors. According to the Chinese standard JG/T 160-2017, the tensile load capacity is principally evaluated through four indices: the ultimate tensile load capacity N_{Ru}, the coefficient of variation of tensile capacity ν_N, the coefficient of variation of tensile stiffness ν_β, and the slip coefficient γ_{min}. In contrast, the European EAD 330232-01-0601 assesses tensile capacity via four primary parameters: the ultimate tensile load N_{Ru}, the coefficient of variation of tensile capacity CV_F, the slip load N_{sl}, and the coefficient of variation of displacement at 50% of the ultimate load CV_σ. Notably, the slip load N_{sl} is primarily employed for reducing the characteristic tensile capacity value. Both standards evaluate anchor performance based on the ultimate tensile failure load, load variability, uncontrollable slip during tension, and displacement and its variability during tensile loading. The specific distinctions are summarized in Table 3.

Table 3. Comparison of Tensile Load Capacity Evaluation Indices for Mechanical Anchors

Evaluation Aspect	JG/T 160-2017	EAD 330232-01-0601
Ultimate Tensile Load Limit	N_{Ru}	N_{Ru}
Load Variability	ν_N	CV_F
Uncontrollable Slip	Slip coefficient γ_{min}: Ratio of load corresponding to displacement exceeding 10% beyond the maximum load plateau or temporary drops greater than 5% of maximum load to the maximum load, derived from the load–displacement curve.	Slip load N_{sl}: Load at which displacement exceeds 10% beyond the maximum load plateau or temporary drops greater than 5% occur in the load–displacement curve.
Displacement Variability	Coefficient of variation of tensile stiffness ν_β: Variation coefficient of slope of load–displacement curve between 30% and 10% of the maximum load.	CV_σ: Coefficient of variation of displacement at 50% of the ultimate load (elastic deformation stage of the anchor rod).

Both standards employ consistent methods for evaluating ultimate tensile failure loads, load variability, and uncontrollable slip during tension. The principal divergence lies in the assessment of displacement variability: JG/T 160-2017 evaluates this through the coefficient of variation of tensile stiffness based on the axial load–displacement relationship[11] within the initial phase of the tensile test (between 10% and 30% of the ultimate load), whereas EAD 330232-01-0601 directly assesses the coefficient of variation of displacement at 50% of the ultimate load[12], corresponding to the anchor rod's elastic deformation stage.

4. Experimental Results and Analysis

4.1 Experimental Results

4.1.1 C30 concrete strength

The tensile load capacity test results of self-cutting undercut mechanical anchors under C30 concrete strength with varying crack widths are presented in Table 4, while the corresponding load–displacement curves are illustrated in Figure 2.

4.1.2 C60 concrete strength

Table 4. Tensile Load Capacity of Self-Cutting Undercut Mechanical Anchors in C30 Concrete with Different Crack Widths

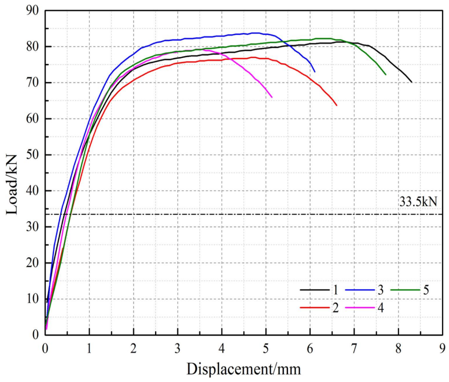
Concrete Crack Width		1#	2#	3#	4#	5#	Average Value
Uncracked Concrete	Ultimate Load N_{ru}/kN	81	76.9	83.6	79.2	82.3	81.0
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.03					/
	Slip Load N_{sl}/kN	81	76.9	83.6	79.2	82.3	81.0
	Slip Coefficient γ_{min}	1	1	1	1	1	1
0.3 mm Cracked Concrete	Ultimate Load N_{ru}/kN	80	80.5	77.6	77.6	82.4	79.6
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.03					/
	Slip Load N_{sl}/kN	80	80.5	77.6	77.6	82.4	79.6
	Slip Coefficient γ_{min}	1	1	1	1	1	1
0.5 mm Cracked Concrete	Ultimate Load N_{ru}/kN	80.8	80.9	83.4	79.1	78.8	80.55
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.008					/
	Slip Load N_{sl}/kN	80.8	80.9	83.4	79.1	78.8	80.55

	Slip Coefficient γ_{min}	1	1	1	1	1	1
0.8 mm Cracked Concrete	Ultimate Load N_{ru}/kN	72	75	72	73	73	72.76
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.02					/
	Slip Load N_{sl}/kN	72	75	72	73	73	72.76
	Slip Coefficient γ_{min}	1	1	1	1	1	1
1.5 mm Cracked Concrete	Ultimate Load N_{ru}/kN	71.9	72.0	70.8	71.4	71.5	71.5
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.1					/
	Slip Load N_{sl}/kN	71.9	72.0	70.8	71.4	71.5	71.5
	Slip Coefficient γ_{min}	1	1	1	1	1	1

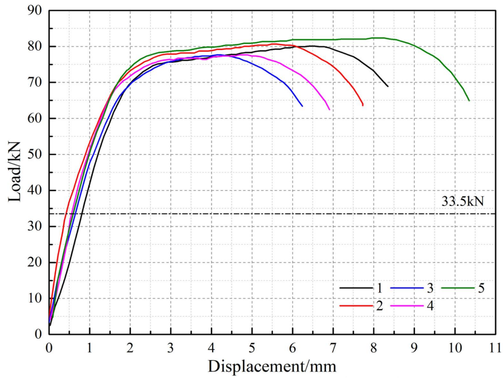
Table 5. Tensile Load Capacity of Self-Cutting Undercut Mechanical Anchors in C60 Concrete with Various Crack Widths

Concrete Crack Width		1#	2#	3#	4#	5#	Average Value
Uncracked Concrete	Ultimate Load N_{ru}/kN	79.4	81.2	79.3	79.9	84.7	80.9
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.03					/
	Slip Load N_{sl}/kN	79.4	81.2	79.3	79.9	84.7	80.9
	Slip Coefficient γ	1	1	1	1	1	1
0.3 mm Cracked Concrete	Ultimate Load N_{ru}/kN	79.4	79.6	81.6	82.9	80.5	80.9
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.02					/
	Slip Load N_{sl}/kN	79.4	79.6	81.6	82.9	80.5	80.9
	Slip Coefficient γ	1	1	1	1	1	1
0.5 mm Cracked Concrete	Ultimate Load N_{ru}/kN	80.9	80.7	81.4	81.1	80.8	81.0
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.003					/
	Slip Load N_{sl}/kN	80.9	80.7	81.4	81.1	80.8	81.0
	Slip Coefficient γ	1	1	1	1	1	1
0.8 mm Cracked Concrete	Ultimate Load N_{ru}/kN	73.9	75.9	73.0	75.2	74.4	72.8
	Failure Mode	Steel failure	Steel failure	Steel failure	Steel failure	Steel failure	/
	Load Variation Coefficient $\nu_N(C_{VF})$	0.02					/
	Slip Load N_{sl}/kN	73.9	75.9	73.0	75.2	74.4	72.8
	Slip Coefficient γ	1	1	1	1	1	1

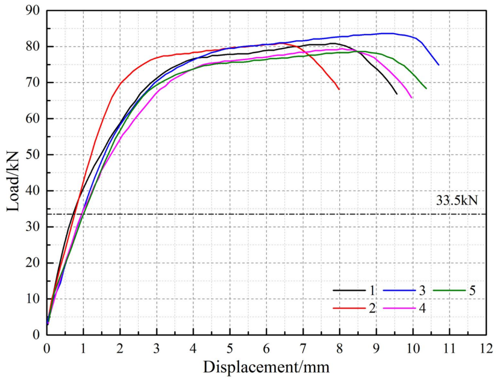
The tensile load capacity test results of self-cutting undercut mechanical anchors under C60 concrete strength with identical crack widths are delineated in Table 5, accompanied by the tensile load–displacement curves exhibited in Figure 3.



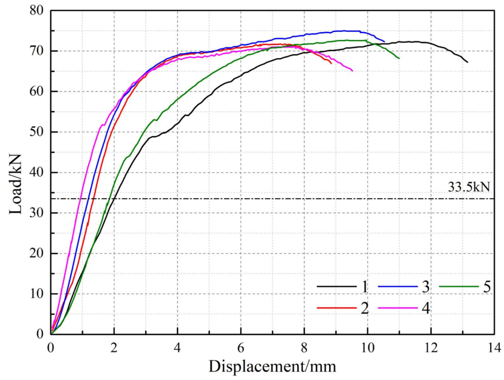
(a) Uncracked Concrete



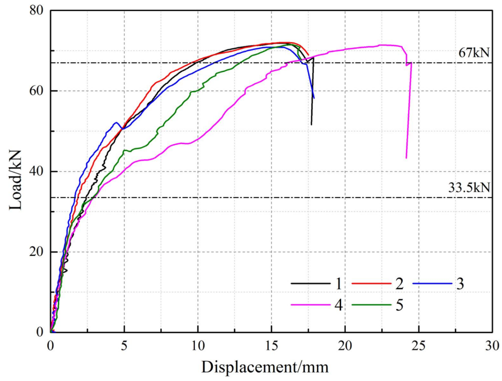
(b) 0.3 mm Cracked Concrete



(c) 0.5 mm Cracked Concrete

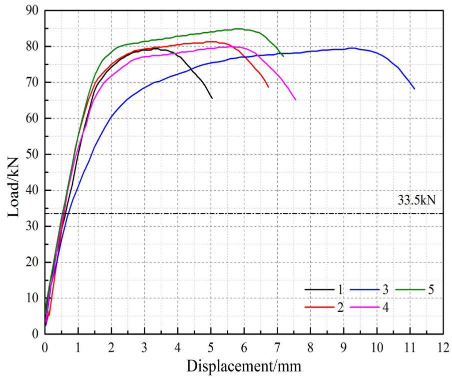


(d) 0.8 mm Cracked Concrete

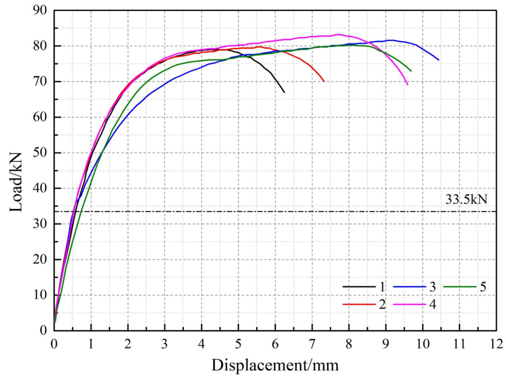


(e) 1.5 mm Cracked Concrete

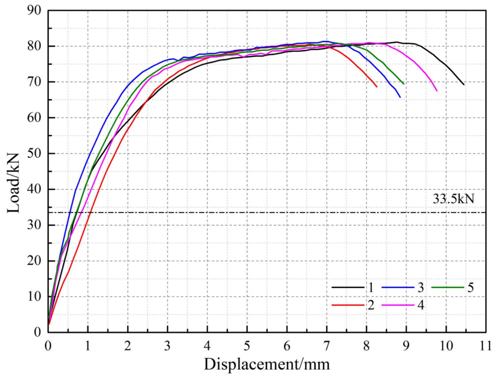
Figure 2. Tensile Load–Displacement Curves of Self-Cutting Undercut Anchors in C30 Concrete with Various Crack Widths.



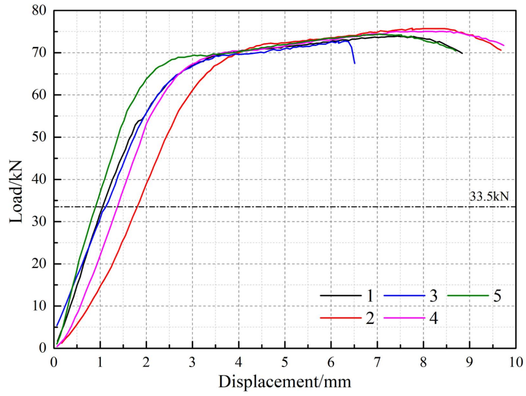
(a) Uncracked Concrete



(b) 0.3 mm Cracked Concrete



(c) 0.5 mm Cracked Concrete



(d) 0.8 mm Cracked Concrete

Figure 3. Tensile Load–Displacement Curves of Self-Cutting Undercut Anchors in C60 Concrete across Various Crack Widths

4.2 Results Analysis

4.2.1 Load Capacity and Its Variability

As evidenced by Table 4, for C30 concrete strength, the self-cutting undercut mechanical anchors exhibited steel failure as the failure mode throughout the tensile load capacity tests across concrete crack widths ranging from 0 mm to 1.5 mm. The average ultimate tensile load capacity spanned from 71.5 kN to 81.0 kN, consistently surpassing the product of the nominal tensile strength and stress cross-sectional area of the anchor rod (67 kN). The coefficient of variation in load capacity ranged narrowly between 0.008 and 0.1. Figure 2 further demonstrates the absence of any uncontrollable slip phenomena. Similarly, Table 5 reveals that under C60 concrete strength, the self-cutting undercut mechanical anchors likewise failed by steel fracture during tensile capacity tests within crack widths from 0 mm to 0.8 mm. The ultimate tensile load capacity varied from 72.8 kN to 81.0 kN, exceeding the nominal tensile strength multiplied by the stress cross-sectional area (67 kN), with a coefficient of variation between 0.003 and 0.03. Figure 3 corroborates the lack of uncontrollable slip occurrences.

Collectively, these findings illustrate the exemplary load-bearing performance of self-cutting undercut mechanical anchors across a spectrum of concrete crack widths. The crack width exerts negligible influence on the ultimate tensile load capacity and its variability, and no evidence of uncontrolled slip is observed. This resilience stems from the robust mechanical interlock formed between the expansion element of the anchor and the inverted conical cavity, which exhibits remarkable adaptability to concrete cracking. The mechanical interlock remains intact despite crack presence, as confirmed through post-tensile test inspection of the anchor's morphology within the concrete matrix. Figure 4 portrays the post-test condition of the self-cutting undercut mechanical anchor embedded in concrete under a crack width scenario of 1.5 mm.

(a) Photograph of anchor steel failure

(b) Post-tensile test morphology of anchor embedded in concrete

Figure 4. Morphological State of the Anchor within Concrete following Tensile Test under 1.5 mm Crack Width Condition

4.2.2 Displacement Variability

According to the provisions of JG/T 160-2017, the average tensile stiffness of self-cutting undercut mechanical anchors and their coefficients of variation under varying concrete crack widths are summarized in Table 6. The results indicate that, irrespective of whether the anchors are embedded in high-strength concrete (C60) or lower-strength concrete (C30), the tensile stiffness diminishes progressively as crack width increases. This signifies that, under an identical tensile load, the displacement of the anchors becomes more pronounced. Specifically, for C30 concrete, when the crack width reaches 0.8 mm, the tensile stiffness decreases by 55.05% compared to uncracked concrete, and this reduction intensifies to 67.82% at a crack width of 1.5 mm. For C60 concrete, at a crack width of 0.8 mm, the tensile stiffness declines by 40.41% relative to the uncracked state. The stiffness variation coefficients remain below 0.4 across all scenarios.

According to EAD 330232-01-0601, the displacement corresponding to 50% of the ultimate load for self-cutting undercut mechanical anchors and its coefficient of variation are presented in Table 7. For statistical convenience, the 50% ultimate load is taken as half of the product of the anchor rod's nominal tensile strength and its stress cross-sectional area, namely 33.5 kN. The results demonstrate that, as the concrete crack width enlarges, the displacement corresponding to 50% of the ultimate load gradually increases; however, the overall displacement augmentation remains modest. Specifically, in C30 concrete, when the crack width is 0.8 mm, the average displacement increases by 0.95 mm relative to uncracked concrete, and at 1.5 mm crack width, this increment rises to 1.87 mm. In C60 concrete, the average displacement increase at a crack width of 0.8 mm is merely 0.67 mm. Across all cases, the coefficients of variation for displacement are below 0.4.

Table 6. Average Tensile Stiffness and Coefficients of Variation of Self-Cutting Undercut Mechanical Anchors under Different Concrete Crack Widths

Concrete Strength	Crack Width	1#	2#	3#	4#	5#	Average Value	Coefficient of Variation	Tensile Stiffness Reduction Rate
C30	Uncracked	61.34	52.74	68.37	68.28	53.03	60.75	0.13	/
	0.3mm	68.97	51.03	49.11	53.01	60.57	56.53	0.15	6.95%
	0.5mm	48.53	39.16	31.56	33.49	30.00	36.55	0.21	39.84%
	0.8mm	23.51	33.26	38.74	19.61	21.43	27.31	0.30	55.05%
	1.5mm	14.38	19.46	20.82	16.04	27.05	19.55	0.25	67.82%

C60	Uncracked	52.01	65.01	47.17	54.74	51.77	54.14	0.12	/
	0.3mm	51.14	50.10	53.47	55.32	45.85	51.18	0.07	7.31%
	0.5mm	43.14	27.96	60.19	46.55	47.33	45.04	0.26	16.81%
	0.8mm	34.29	19.92	27.09	27.29	43.89	30.50	0.30	40.41%

Table 7. Displacement Corresponding to 50% Ultimate Load and Their Coefficients of Variation under Different Concrete Crack Widths

Concrete Strength	Crack Width	1#	2#	3#	4#	5#	Average Value	Coefficient of Variation
C30	Uncracked	0.43	0.58	0.34	0.46	0.57	0.48	0.21
	0.3mm	0.81	0.42	0.64	0.57	0.59	0.61	0.23
	0.5mm	0.71	0.77	0.98	0.95	0.99	0.88	0.15
	0.8mm	1.33	1.15	0.89	1.82	1.97	1.43	0.32
	1.5mm	2.41	1.86	1.66	2.93	2.87	2.35	0.25
C60	Uncracked	0.62	0.56	0.70	0.55	0.54	0.59	0.11
	0.3mm	0.58	0.51	0.50	0.53	0.73	0.57	0.17
	0.5mm	0.73	1.05	0.53	0.83	0.72	0.77	0.25
	0.8mm	1.03	1.78	1.12	1.35	1.00	1.26	0.26

In summary, whether considering the tensile stiffness from JG/T 160-2017 or the displacement at 50% ultimate load as per EAD 330232-01-0601, the self-cutting undercut mechanical anchors exhibit a progressive increase in displacement with widening concrete cracks, albeit with relatively minor overall increments. Combined with the ultimate tensile load capacity test findings, it is evident that the ultimate load capacities remain essentially consistent across varying crack widths; however, the displacement in cracked concrete surpasses that in uncracked concrete. This increase in displacement may lead to a reduction in the preload between the anchorage and the concrete during service in cracked concrete conditions. Therefore, to ensure the reliability of the anchorage under such circumstances, it is recommended to apply a reduction to the ultimate tensile load capacity values of self-cutting undercut mechanical anchors when employed in cracked concrete environments.

5. Conclusions and Recommendations

This study introduced a novel self-cutting undercut mechanical anchor and conducted tensile load capacity tests across varying concrete crack widths. An analytical evaluation based on JG/T 160-2017 and EAD 330232-01-0601 addressed the ultimate tensile load capacity, load variability, uncontrollable slip, and displacement variability, culminating in the following conclusions and recommendations:

(1) The width of concrete cracks exerts negligible influence on both the ultimate tensile load capacity and its variability for self-cutting undercut mechanical anchors.

(2) As the concrete crack width widens, the tensile stiffness of the self-cutting undercut mechanical anchors diminishes gradually, accompanied by an increase in displacement; however, the overall augmentation in displacement remains comparatively minor.

(3) When deploying self-cutting undercut mechanical anchors in cracked concrete, it is advisable to implement a reduction in their tensile load capacity to ensure dependable performance under service conditions.

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