Article

Push-Out Tests on Various Steel Anchors with Partial-Length Welding in Steel–Concrete Composite Members

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Featured Application: Steel–Concrete Composite Structures.

Abstract: To investigate the behavior of various steel anchors, push-out tests were performed for 13 test specimens. Test parameters included the geometry of beams (wide-flange beams and composite beams) and the type of steel anchors (stud anchors and Z- and C-channel anchors with full- or partial-length welding). Test results showed that the performance of test specimens strongly depends on the types of steel anchors rather than the geometry of steel beams. The specimens with C-channel anchors showed the highest load-carrying capacity but the most drastic load reduction after the peak load. The specimens with Z-channel anchors showed a similar behavior to those with C-channel anchors but the load reduction occurred at a slightly slower rate. The load-carrying capacity was increased with the length of the Z- and C-channel anchors. The specimens with stud anchors reached the peak load at a slow rate and showed the most ductile behavior. The test results were compared with predictions by various design equations for steel anchors available in the literature, and the existing design equations for channel anchors with partial-length welding were considered applicable to design.

Keywords: composite structure; steel anchor; channel anchor; partial-welding; push-out test

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1. Introduction

Steel–concrete composite members show high load-carrying capacity, high local stability, and high stiffness due to the composite action of steel and concrete [1,2]. To achieve the desired composite action or to transfer longitudinal shear between steel and concrete, steel anchors or shear connectors should be provided at the interface between the steel and concrete [1,3]. For this purpose, steel-headed stud anchors (hereafter, stud anchors) have been most widely used, but recently steel shape anchors such as C-, L-, T- and Z-channels (hereafter, channel anchors collectively) have also gained popularity since conventional welding equipment can be used and the required performance can be obtained with a smaller number of connectors [3,4].

In general, channel anchors are welded to the base steel sections along the full length of the anchors. However, in some cases of composite members using U-shaped or built-up sections [4–6], only both ends of the channel anchors are welded to base steel sections. In those cases, the partially welded channel anchors can function as (1) steel anchors as intended, (2) battens to form a closed or built-up section, and (3) walk-plates or steps during construction. Figure 1 shows an example that utilizes partially welded Z-channel anchors to a composite beam: an H-beam (or wide-flange beam) with a concrete-filled U-shaped flange (hereafter, UH-beam). As shown in the figure, the partially welded channel anchors can be used as an alternative to the combined conventional stud anchors and battens.

Figure 1. Application of steel anchors to UH-beams: (a) UH-beam with Z-channel anchors; (b) UH-beam with conventional stud anchors.

For the performance and design of channel anchors, numerous studies have been conducted. Viest et al. [7] carried out tests for push-out and beam specimens (consisting of steel beams and concrete slabs) using C-channel anchors and found that the strength of the concrete and the web thickness, flange thickness, and length of the channel anchor affected the load-carrying capacity of the test specimens, but the height and orientation of the channel anchor had negligible effects. They provided a theoretical analysis model, assuming that the channel anchor acts as a dowel. Slutter and Driscoll [8] also carried out push-out and beam tests, and proposed a design equation for the strength of C-channel anchors. The design equation of Slutter and Driscoll [8] is adopted in ANSI/AISC 360-16 [9] and KDS 41 31 00 [10] with a modification, and CSA S16-09 [11] also specifies a similar form of design equation. It is noteworthy that slip between the steel beam and concrete slab is inevitable [7], but the slip is not an important factor of the ultimate load of test specimens if a sufficient number of steel anchors are provided [8]. Yokota and Kiyomiya [12] carried out push-out tests using L-, C-, and T-channel anchors and found that the test specimens failed by the tensile fracture of steel anchors, crushing of concrete, or shear failure of concrete, and the failure modes were affected by the shape and direction of the steel anchors and the strength of concrete. Maleki and Mahoutian [13] performed experimental and analytical studies for C-channel anchors embedded in unconfined (without stirrups) normal or polypropylene concrete slabs and found that the specimens without stirrups failed in a more brittle way and show much lower strength than a specimen with stirrups. Pashan and Hosain [14] carried out push-out tests with test parameters of the concrete strength and the length and web thickness of C-channel anchors, and suggested a design equation, which was simplified from their previous study. Ros [15] developed a type of sandwich beam test method and proposed equations for the design of L-channel anchors as a function of strut angle and also for the shear force–relative displacement relationship. Baran and Topkaya [3] formulated a design equation for C-channel anchors based on the typical failure mechanism in push-out tests and plastic analysis principles. Tahmasbi et al. [16] performed finite element simulations for L- and inversed L-channel anchors (where “inversed” indicates that the angle is in a sitting position or has no top flange) embedded in a concrete slab, and suggested a design equation based on the parametric study results. JSCE [17] provides design equations for stud anchors and L-channel anchors, and Qiu et al. [18] modified the JSCE’s design equation for the design of L- and T-channel anchors based on their push-out test results with unreinforced concrete slabs (to simulate composite sandwich structures). It is noted that the current version of Eurocode 4-04 [19] provides a design equation only for stud anchors.

Each of these previous studies provides a valuable insight into the design of steel anchors but the majority of the previous studies, including the current design codes, are for channel anchors with full-length welding. Considering the fact that steel anchors with partial-length welding are also widely used in practice with the increasing application of U-shaped or built-up sections, more experimental studies are required for partially welded channel anchors, and the applicability of design equations to the partially welded channel anchors needs to be examined.

In the present study, to investigate the behavior of various steel anchors, push-out tests were performed for 13 test specimens. Test parameters included the geometry of steel beams (H-beams and UH-beams) and the type of steel anchors (stud anchors, and Z- and C-channel anchors with full- or partial-length welding). Test results were compared with predictions by existing design equations for steel anchors, and the applicability of the equations to the partially welded channel anchors was discussed.

2. Test Program

2.1. Test Specimens

Figure 2 shows the push-out test specimens. A total of 13 specimens were prepared, and the test parameters included the geometry of the steel beams and the type of steel anchors. Table 1 summarizes the test parameters. The configuration and dimensions of the test specimens were determined in accordance with the standard test of shear connectors specified in Eurocode 4–04 [19], but some dimensions were minorly adjusted to accommodate the details of the test parameters: the test specimens were 600×600 mm in section and 700 mm in height.

Figure 2. Test specimens (units in mm): (a) typical section; (b) typical elevation; (c) details of the steel beam and steel anchor.

Table 1. Test parameters.

Group	Specimen ¹	Steel Beam ²	Steel Anchors ² (Length)	Concrete Slabs
S	HS	H—300 × 250 × 10 × 10 mm	S— ϕ 19 × 90 mm	150 × 600 mm
	UI-S	UI—100 × 250 × 8 × 75 mm	S— ϕ 19 × 90 mm	
	UO75-S	UO—75 × 180 × 8 × 100 mm	S— ϕ 19 × 90 mm	
	UO100-S	UO—100 × 180 × 8 × 100 mm	S— ϕ 19 × 90 mm	
Z	H-Z130	H—300 × 250 × 10 × 10 mm	Z—80 × 50 × 6 × 6 mm (130 mm)	
	H-Z230	H—300 × 250 × 10 × 10 mm	Z—80 × 50 × 6 × 6 mm (130 mm)	
	UI-Z130	UI—100 × 250 × 8 × 75 mm	Z—80 × 50 × 6 × 6 mm (130 mm)	
	UO75-Z230	UO—75 × 180 × 8 × 100 mm	Z—80 × 50 × 6 × 6 mm (130 mm)	
C	UO100-Z230	UO—100 × 180 × 8 × 100 mm	Z—80 × 50 × 6 × 6 mm (130 mm)	
	H-C130	H—300 × 250 × 10 × 10 mm	C—80 × 50 × 6 × 6 mm (130 mm)	
	H-C230	H—300 × 250 × 10 × 10 mm	C—80 × 50 × 6 × 6 mm (130 mm)	
	UI-C130	UI—100 × 250 × 8 × 75 mm	C—80 × 50 × 6 × 6 mm (130 mm)	
	UO100-C230	UO—100 × 180 × 8 × 100 mm	C—80 × 50 × 6 × 6 mm (130 mm)	

¹ Designation: geometry of steel beam—type of steel anchor; ² Dimensions of steel shapes: wide-flange section: H—height × width × web thickness × flange thickness; U-channel with inward/outward bent lips: UI/UO—height × bottom width × thickness × top lip width; headed stud anchor: S— ϕ shank diameter × length; Z-channel anchor: Z—height × flange width × web thickness × flange thickness; and C-channel anchor: C—height × width × web thickness × flange thickness.

Steel beams varied in geometry, namely conventional H-beams and UH-beams. For the H-beams, welded built-up wide-flange sections of 300 × 250 × 10 × 10 mm (H—height × width × web thickness × flange thickness) were used. On the other hand, for the U-shaped flange of the UH-beams, lip channels (or U-channels with inward bent lips: UI) of 100 × 250 × 8 × 75 mm and hat channels (or U-channels with outward bent lips: UO) of 100 × 180 × 8 × 100 mm or 75 × 180 × 8 × 100 mm (UI/UO—height × bottom width × thickness × top lip width) were used. Two symmetric U-shaped flanges were connected by a 10-mm-thick web plate for double-sided push-out testing, and all steel beams were identical in total section height.

For steel anchors, stud anchors of 2— ϕ 19 × 90 mm (two rows of S— ϕ shank diameter × length), Z-channels of 80 × 50 × 6 × 6 mm (Z—height × flange width × web thickness × flange thickness), and C-channels of 80 × 50 × 6 × 6 mm (C—height × width × web thickness × flange thickness) were used. The Z- and C-channel anchors varied in length (130 mm and 230 mm) to accommodate the spacing between the two top lips bent inward or outward, and all steel anchors were spaced at 200 mm and placed symmetrically in both concrete slabs. The welded length of all channel anchors used in UH-beams was 15 mm measured at one end, while in H-beams, channel anchors were welded to the beam flange along the full length of the anchors.

Two symmetric concrete slabs of 150 mm thickness were connected to the flanges of a steel beam through steel anchors. Each of the concrete slabs was cast in the horizontal position, and greasing was provided on the flanges of the steel beam to prevent bonding at the interface between the flanges and concrete slabs [19]. For reinforcement, vertical bars of D13 (nominal diameter = 12.7 mm [20]) were placed at a spacing of 175 mm and horizontal bars of D10 (nominal diameter = 9.53 mm [20]) were placed at a spacing of 160 mm.

In each test specimen, test parameters (geometry of steel beams and type of steel anchor) were combined and each test specimen was referred to by a designation which includes these two test parameters: in the designation, the numerals after UO refer to the depth of the concrete-filled U-shaped flange, and the numerals after Z and C refer to the length of the Z- and C-channel anchors.

2.2. Material Properties

For steel beams and Z- and C-channel anchors, SM355 steel plates were used (specified minimum yield stress = 355 MPa and specified minimum tensile strength = 490 MPa [10]), while for stud anchors, HS1 studs were used (specified minimum yield stress = 235 MPa

and specified minimum tensile strength = 400 MPa [21]). For concrete, C24 was used (specified compressive strength = 24 MPa).

For steel coupons sampled from the steel beams and steel anchors, tension tests were carried out according to KS B 0802 [22]. Before the tension tests, actual dimensions such as the thickness of plates and the shank diameter of studs were also measured. For each concrete mix, four concrete cylinders were prepared and cured alongside the test specimens [19]. On the day of testing, compression tests were carried out for the concrete cylinders according to KS F 2405 [23].

The measured material properties such as the mean yield strength and tensile strength of steel and the mean compressive strength (f'_c) of concrete are summarized in Table 2. It is noted that since the last four specimens (No. 10–13 in Table 1) were additionally tested after testing the first nine specimens (No. 1–9 in Table 1), SM355-10T, SM355-8T, SM355-6T, and C24 had two different material properties.

Table 2. Measured material properties.

Structural Component	Material ¹	Thickness (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)	Remarks
Steel Beam	SM355-10T	10.1	404.7	551.9	23.6	No. 1–9
	(H-beam and web of UH-beam)	10.0	385.0	522.7	24.7	No. 10–13
	SM355-8T	8.1	446.3	541.5	23.0	No. 1–9
	(flange of UH-beam)	7.8	304.7	473.0	27.3	No. 10–13
Steel Anchors	HS1- ϕ 19	19.0	413.8	478.7	17.3	
	(stud anchor)					
	SM355-6T	6.0	406.8	524.4	32.7	
	(Z-channel anchor)					
Slab	SM355-6T	5.8	533.3	606.3	18.7	
	(C-channel anchor)					
	C24		$f'_c = 28.0$ MPa at the day of testing (No. 1–9)			
	(Concrete)		$f'_c = 30.3$ MPa at the day of testing (No. 10–13)			

¹ Since the C-group was additionally tested after testing the S- and Z-groups, SM355-10T, SM355-8T, SM355-6T, and C24 had two different material properties.

2.3. Test Setup and Instrumentation

Figure 3 shows the test setup for push-out testing. Considering the longitudinal slip between the concrete slabs and steel beam, the steel beam protruded 80 mm from the top of concrete slabs. A loading plate (PL-330 × 380 × 10) was provided on the top of the steel beam, and through a 10 MN universal testing machine (UTM), monotonic loading was applied to the loading plate under displacement control (1.8 mm/min). To prevent eccentric loading, test specimens were carefully aligned to the center of loading and the testing was terminated when the load dropped to 80% of the peak load [24].

Figure 3. Test setup.

To measure displacement, 7 linear variable displacement transducers (LVDTs) were installed around the test specimen: one beneath the loading plate, two under the steel beam, two on the inner surfaces of the concrete slabs, and two for transverse separation of the concrete slabs from the steel beam. To measure strain, strain gauges were also placed on steel anchors.

3. Test Results

3.1. Failure Modes

Figure 4 shows the test specimens at the end of push-out testing. The overall behavior and failure mode varied with the type of steel anchor.

Figure 4. Failure Modes: (a) H-S; (b) UI-S; (c) UO75-S; (d) UO100-S; (e) H-Z130; (f) H-Z230; (g) UI-Z130; (h) UO75-Z230; (i) UO100-Z230; (j) H-C130; (k) H-C230; (l) UI-C130; (m) UO100-C230.

In the case of the S-group (H-S, UI-S, UO75-S, and UO100-S using stud anchors; Figure 4a–d), the test specimens failed by fracture of the studs at the bottom of the studs. Crushing and cracking of concrete occurred first around the root of studs. The bottom and sides of the concrete slabs also showed crushing and minor longitudinal cracking. Under further loading, splitting of concrete occurred on the exterior surfaces of the concrete slabs (but the splitting was limited) and the load increment was gradually decreased. The peak load was reached by fracture of the studs, and then the load was suddenly dropped and concrete slabs were separated (about 1–2 mm) from the steel beam.

In the case of the Z-group (H-Z130, H-Z230, UI-Z130, UO75-Z230, and UO100-Z230 using Z-channel anchors; Figure 4e–i), the test specimens failed by splitting of the concrete. The splitting of concrete was initiated at the locations of the steel anchors and propagated to the outside. Compared with the S-group, the peak load was reached earlier, and the splitting on the exterior surfaces of concrete slabs and the crushing of concrete around the interface between the steel beam and concrete slabs were more prominent. However, the degradation in load after the peak was less drastic. The test specimens of C-group (H-C130, H-C230, UI-C130, and UO100-C230 using C-channel anchors; Figure 4j–m) were also failed by splitting of concrete as in Z-group. In Z- and C-groups, the separation of concrete slabs from the steel beam was about 6–15 mm after the test.

The failure mode was not clearly distinguished by the geometry of steel beams, but in the case of using the U-channel with outward bent lips (UO) for the steel beam, the longitudinal slip between the steel beam and concrete slabs was most prominent.

3.2. Shear Force—Slip Relationship

Figure 5 shows the shear force—slip relationship. To quantify the effects of test parameters, the maximum strength, initial stiffness, and slip capacity were evaluated from the test results. The maximum strength (V_m) was taken as the peak load. The initial stiffness (K_i) was taken as the secant stiffness at the point where steel anchors reached the yield strain, and the yielding of steel anchors was determined by the measurement as shown in Figure 6. The slip capacity (μ) was taken as the ratio of yield slip-to-ultimate slip (δ_y / δ_u), in which the yield slip δ_y was defined as the slip measured at the yielding of steel anchors and the ultimate slip was defined as the slip corresponding to $0.8V_m$ after the peak load [24]. The performance points of δ_y , V_m , and δ_u are marked with a circle, triangle, and cross on each plot of Figure 5, respectively, and the test results are summarized in Table 3.

Figure 5. Shear Force—Slip Relationship: (a) H-S; (b) UI-S; (c) UO75-S; (d) UO100-S; (e) H-Z130; (f) H-Z230; (g) UI-Z130; (h) UO75-Z230; (i) UO100-Z230; (j) H-C130; (k) H-C230; (l) UI-C130; (m) UO100-C230; (n) Definitions of Performance Points.

Figure 6. Shear Force—Strain Relationship of Steel Anchors: (a) S-group; (b) Z-group; (c) C-group.

To clarify the effect of each test parameter, the shear force—slip behavior was compared in terms of steel anchors in Figure 7a, and in terms of steel beams in Figure 7b.

The figure reconfirms the higher effect of steel anchors than steel beams on structural behavior: similar behavior in Figure 7a for same steel anchors with different steel beams; but large difference in behavior in Figure 7b for same steel beams with different steel anchors. In general, the geometry of steel beams and the depth of the concrete-filled U-shaped flange (UO75 and UO100) had no significant effect. A similar observation can be found in a previous study [18]: for most shear connectors in push-out tests, the effect of the thickness of the connected plate could be ignored. On the other hand, the type of steel anchors had a distinct effect. The specimens with C-channel anchors showed highest load-carrying capacity, but the load reduction after the peak load was most drastic. The specimens with Z-channel anchors showed a similar behavior to those with C-channel

anchors, but the load reduction occurred in a slightly slower rate. As the length of channel anchors increased (Z130 and Z230 or C130 and C230 with the same welded length), the load-carrying capacity was increased. Although there was also a sudden drop after reaching the peak load even in the case of using stud anchors, the specimens with stud anchors reached the peak load in a slow rate and showed most ductile behavior.

Table 3. Test Results.

Specimen	Yielding of Steel Anchors			Maximum Strength	Ultimate Slip	
	V_y (kN)	δ_y (mm)	$K_i = V_y/\delta_y$ (kN/mm)	V_m (kN)	δ_u (mm)	$\mu = \delta_u/\delta_y$
H-S	640.0	3.4	190.9	1024.6	22.5	6.7
UI-S	901.5	3.2	284.2	1262.5	21.6	6.8
UO75-S	718.6	3.7	195.4	900.0	27.5	7.5
UO100-S	584.0	3.1	189.7	834.1	26.3	8.5
H-Z130	566.3	2.2	260.3	861.2	17.8	8.2
H-Z230	1008.3	2.6	389.9	1246.5	9.7	3.8
UI-Z130	876.8	2.6	335.1	963.5	6.9	2.6
UO75-Z230	1411.2	3.9	363.0	1473.3	8.4	2.1
UO100-Z230	1362.7	4.6	297.9	1401.2	10.0	2.2
H-C130	857.7	2.2	392.4	1077.0	10.9	5.0
H-C230	1191.0	2.2	553.9	1541.8	8.4	3.9
UI-C130	1025.3	2.7	384.0	1409.8	10.4	3.9
UO100-C230	1340.5	2.9	456.2	1740.9	11.7	4.0

Figure 7. Comparisons of Behavior: (a) in terms of Steel Anchors; (b) in terms of Steel Beams.

4. Discussions

4.1. Existing Design Equations for Stud Anchors and Fully-Welded Channel Anchors

For the nominal shear strength Q_n of a steel anchor (stud anchors and fully-welded channel anchors) embedded in a solid concrete slab, current design codes such as ANSI/AISC 360–16 [9] provide design equations. Table 4 summarizes existing design equations including current code equations and the other design equations available in the literature [3,9–18]. It is noted that for direct comparisons among those design equations, some of symbols were modified from the original expressions and the design factors such as strength reduction factors and partial factors were not included in the equations.

Table 4. Existing Design Equations for Stud Anchors and Channel Anchors with Full-length Welding.

Design Code or Authors	Design Equation, Q_n [N] ¹
ANSI/AISC 360-16 [9] & KDS 41 31 00 [10]	$0.5A_{sa}\sqrt{f'_c E_c} \leq R_g R_p A_{sa} F_u$ for stud anchor where $R_g = 1.0$ and $R_p = 0.75$ throughout the present study
CSA S16-09 [11]	$0.3(t_f + 0.5t_w)L_{ca}\sqrt{f'_c E_c}$ for C-channel anchor $0.5A_{sa}\sqrt{f'_c E_c} \leq A_{sa}F_u$ for stud anchor
Eurocode 4-04 [19]	$45(t_f + 0.5t_w)L_{ca}\sqrt{f'_c}$ for C-channel anchor $\min\{0.8F_u A_{sa}; 0.29\alpha d_{sa}^2 \sqrt{f'_c E_c}\}$ for stud anchor where $\alpha = 0.2(h_{sa}/d_{sa} + 1)$ for $3 \leq h_{sa}/d_{sa} \leq 4$ or 1 for $h_{sa}/d_{sa} > 4$
Yokota and Kiyomiya [12]	$88\sqrt{t_w}L_{ca}\sqrt{f'_c}$ for C-channel anchor $65\sqrt{t_w}L_{ca}\sqrt{f'_c}$ for L-channel anchor
Maleki and Mahoutian [13]	$27.2(t_f + 0.5t_w)L_{ca}\sqrt{f'_c}$ for C-channel anchor
Pashan and Hosain [14] Ros [15]	$(336t_w^2 + 5.24L_{ca}h_{ca})\sqrt{f'_c}$ for C-channel anchor $(63\frac{t_w}{h_{ca}} + 1.6)\sqrt{f'_c}L_{ca}h_{ca}$ for L-channel anchor
Baran and Topkaya [3] Tahmasbi et al. [16]	$0.25(7.2 - 0.023L_{ca})(1.5 - 0.005h_{ca})f'_c L_{ca}h_{ca} + \frac{2t_w^2 L_{ca}}{h_{ca}}F_u$ for C-channel anchor $0.213L_{ca}\sqrt{t_w f'_c} \times 10^3$ for L-channel anchor $\min\{31A_{sa}\sqrt{(h_{sa}/d_{sa})f'_c} + 10000; A_{sa}F_u\}$ for stud anchor
JSCE [17]	$\min\{0.0056h_{ca}L_{ca}\sqrt{f'_c}k_1k_2k_3; 0.001t_{sc}L_{ca}F_u/\sqrt{3}\}$ for L-channel anchor where $k_1 = 2.2(t_{sc}/h_{ca})^{2/3} \leq 1.0$, $k_2 = 0.4\sqrt{t_p/t_{sc}} + 0.43 \leq 1.0$, $k_3 = \sqrt{s_{ca}/10} \times h_{ca} \leq 1.0$
Qiu et al. [18]	$k_h k_2 k_3 195.894(t_w)^{0.425}(f'_c)^{0.383} \times L_{ca}$ for L-channel anchor where, $k_h = \exp(-1.918t_w/h_{ca})$

¹, d_{sa} , h_{sa} = cross-sectional area, diameter, and height of stud anchor; t_f , t_w , h_{ca} , L_{ca} , s_{ca} = flange thickness, web thickness, height, length, and spacing of channel anchor, and t_{sc} = lesser of thickness of channel anchor considering welded part and thickness of channel anchor itself; F_u = tensile strength of steel anchor; f'_c , E_c = compressive strength and elastic modulus of concrete; and t_p = thickness of base steel plate (steel beam flange).

Although the design equations for channel anchors in Table 4 are for a specific shape with full-length welding, all of those equations were applied to the test specimens of the present study to verify their applicability. The elastic modulus of concrete was calculated as $E_c = 4700\sqrt{f'_c}$ [25] in all equations for direct comparison, and the contribution V_{nc} of the concrete inside the UH-beam, which was cast monolithically with concrete slabs, was taken into account in the calculation of the design shear strength V_n as follows.

$$V_n = \Sigma Q_n + V_{nc} \quad (1)$$

$$V_{nc} = 0.66 \times \min\left\{\sqrt{2/(1 + 0.004d_c)}; 1\right\} \times (\rho_w)^{1/3} \sqrt{f'_c} b_c d_c \times 2 \quad (2)$$

where, V_{nc} = nominal shear strength provided by the concrete, which was calculated in accordance with ACI 318–19 [25] (for the case of normal-weight concrete, non-prestressed members, not providing the minimum amount of shear reinforcement, and having no axial load); ρ_w = longitudinal reinforcement ratio; and b_c , d_c = width and depth of concrete measured at the interface between the monolithically cast beam and slab (b_c = clear distance between top flanges of U-section, d_c = net length excluding the width b_{ca} of channel anchors). The factor of 2 in Equation (2) is for double-sided push-out testing, and the vertical reinforcement in the concrete slab (4-D13) was considered as longitudinal tension reinforcement [26] in the calculation of ρ_w .

Figure 8 shows the comparison (in this figure, each design equation is identified by an abbreviated name of the design code or authors, and C or L behind the abbreviated name indicates C- or L-channel anchor). As shown in Figure 8a, for stud anchors, the current design codes provided quite good predictions (the ratio $V_{pred}/V_{test} = V_n/V_m$ of prediction-to-test was close to 1 for all codes). On the other hand, as shown in Figure 8b,c for channel anchors, V_{pred}/V_{test} was scattered widely, but unexpectedly, each equation

showed a similar tendency for both fully-welded channel anchors and partially-welded channel anchors. Among the predictions, the combination of the equation of Maleki and Mahoutian [13] and Equations (1) and (2) best matched with the test results (mean and standard deviation of V_{pred}/V_{test} was $m \pm \sigma = 0.80 \pm 0.13$ for fully-welded channel anchors or 0.77 ± 0.15 for partially-welded channel anchors). It is noted that the overall average of the calculated concrete contribution V_{nc} by Equation (2) was 6.6% of V_n (V_{nc}/V_n was in the range of 3.0–12.1% for all cases).

Figure 8. Comparison of Predictions to Tests: (a) Stud Anchors; (b) Fully-welded Channel Anchors (H-beams); (c) Partially-welded Channel Anchors (UH-beams).

Although some of the equations showed relatively good and conservative predictions suitable for design purpose, this is limited only to the test results of the present study. Fundamentally, it is not appropriate to apply the existing design equations for fully-welded channel anchors to the design of partially-welded channel anchors, because the failure mode and shear strength are strongly affected by the shape and welding condition of steel anchors [4,5,12].

4.2. Comparison to Existing Design Equations for Channel Anchors with Partial-Length Welding

As mentioned above, it is not suitable to apply the existing design equations for fully-welded channel anchors to the design of partially-welded channel anchors. For this reason, as given in Equation (3), AC495 [27] provides the design equation for L-channel anchors welded to U-shaped cold-formed steel beams, which is similar to the equation of ANSI-AISC 360-16 [9].

$$Q_n = \frac{0.6 \times 100^{3/2} (t_f + 0.5t_w) \sqrt{f'_c E_c}}{\sqrt{L_{bw}}} \quad (3)$$

where, L_{bw} = web-to-web clear distance of the U-shaped cold-formed steel beam.

Meanwhile, Keo et al. [4] also proposed a design equation for inversed L-channel anchors with partial-length welding based on their push-out tests and parametric study of finite element simulations.

$$Q_n = 2(A_{ca1} + A_{ca2}) \frac{F_u}{\sqrt{3}} + 2 \left(19 - 38.1 \frac{b_{ca}}{d_{slab}} \right) A_{cb} f'_c \quad (4)$$

where, A_{ca1} , A_{ca2} , A_{cb} = shear plane areas, and bearing area of channel anchors, respectively. Those definitions are illustrated in the literature [4], but approximately $A_{ca1} = t_w L_{ca,w}$, $A_{ca2} = t_f b_{ca}$, and $A_{cb} = t_f L_{ca,w}$ were used in the present study. b_{ca} = width of channel anchor; $L_{ca,w}$ = welded length of channel anchor measured at one end; and d_{slab} = depth of concrete slab.

Those two equations were applied to the test results for comparison. It is noted that unlike the design equations in Table 4, in Equations (3) and (4), the contribution V_{nc} of concrete was taken into account implicitly. Thus, the design shear strength was calculated as $V_n = \Sigma Q_n$. To compare over a wider range of design parameters such as the type of steel anchors, the other test results available in the literatures [4–6] were also included. Some of information that was not clearly specified in the literature was assumed based on the figures in the literature, and the test parameters are summarized in Appendix A.

Figure 9 and Table 5 show the comparison. In overall, the equation of Keo et al. [4] ($m \pm \sigma$ of $V_{pred}/V_{test} = 0.94 \pm 0.28$) gave the better prediction on average, but it scattered wider compared to the equation of AC495 [27] (1.32 ± 0.23): to be more specific, 1.07 ± 0.11 for C-channel anchors, 1.42 ± 0.09 for L-channel anchors, 1.34 ± 0.24 for inversed L-channel anchors, and 1.19 ± 0.24 for Z-channel anchors in the case of the equation of AC495 [27], while 0.87 ± 0.02 for C-channel anchors, 0.52 ± 0.04 for L-channel anchors, 1.01 ± 0.26 for inversed L-channel anchors, and 1.06 ± 0.14 for Z-channel anchors in the case of the equation of Keo et al. [4]. The equation of Keo et al. [4] was derived for inversed L-channel anchors having no top flange, but it showed relatively good agreement for all anchor shapes because the uplift of concrete slabs was prevented by hoop reinforcement in their study.

Figure 9. Comparison of Predictions to Tests: (a) C-channel Anchors; (b) L-channel Anchors; (c) Inversed L-channel Anchors; (d) Z-channel Anchors.

Although the number of samples used in the comparison was limited, both equations were considered applicable to design, considering the fact that the design factors such as strength reduction factors and partial factors are used in actual design. For safer and more economic design, further experimental studies with various parameters are required.

Table 5. Comparison of Test Results with Predictions by Existing Design Equations for Channel Anchor with Partial-length Welding (units in kN).

Authors	Specimen	Anchor Shape	V_{test}	V_{pred} by Equation (3)	V_{pred} by Equation (4)
Present Study	UI-Z130	Z	963.5	1071.6	1178.3
	UO75-Z230	Z	1473.3	1117.6	1407.5
	UO100-Z230	Z	1401.2	1117.6	1407.5
	UI-C130	C	1409.8	1229.6	1250.2
	UO100-C230	C	1740.9	1281.5	1493.4
Keo et al. [4]	PO-L40	Inv-L	637.1	604.6	516.3
	PO-L50a	Inv-L	932.1	924.2	521.0
	PO-L50b	Inv-L	916.5	935.8	540.5
	PO-L50c	Inv-L	975.9	951.9	567.3
Kim et al. [5]	EA-30-20-200	Inv-L	404.0	447.4	463.7
	EA-30-30-200	Inv-L	488.0	583.5	463.7
	EA-30-40-200	Inv-L	488.0	719.7	463.7
	EA-30-20-300	Inv-L	324.0	335.5	347.7
	EA-30-30-300	Inv-L	339.0	437.6	347.7
	EA-30-40-300	Inv-L	390.0	539.8	347.7
	EA-40-20-200	Inv-L	476.0	833.4	772.8
	EA-40-30-200	Inv-L	720.0	1039.5	772.8
	EA-40-40-200	Inv-L	744.0	1245.6	772.8
	EA-40-20-300	Inv-L	393.0	625.1	579.6
	EA-40-30-300	Inv-L	573.0	779.6	579.6
	EA-40-40-300	Inv-L	567.0	934.2	579.6
	EA-50-20-200	Inv-L	732.0	1053.1	927.3
	EA-50-30-200	Inv-L	924.0	1265.1	927.3
	EA-50-40-200	Inv-L	940.0	1477.1	927.3
	EA-50-20-300	Inv-L	555.0	789.8	695.5
	EA-50-30-300	Inv-L	693.0	948.8	695.5
	EA-50-40-300	Inv-L	789.0	1107.8	695.5
Lee et al. [6]	AN-160-60-4.5	L	1561.6	2185.5	800.1
	AN-160-60-6	L	1877.5	2866.1	1066.8
	AN-160-80-4.5	L	1670.6	2185.5	800.1
	AN-160-80-6	L	1996.4	2866.1	1066.8
Accuracy of Prediction: $m \pm \sigma$ of V_{pred}/V_{test}				1.32 ± 0.23	0.94 ± 0.28

5. Conclusions

To investigate the behavior of various steel anchors, push-out tests were performed on the test parameters including the geometry of steel beams (H-beams and UH-beams) and the type of steel anchors (stud anchors, and Z- and C-channel anchors with full- or partial-length welding), and the test results were compared with predictions by various design equations for steel anchors available in the literature. The research findings are summarized as follows.

- (1) Although channel anchors with partial-length welding are widely used in current composite construction, the majority of current design codes and previous studies are for channel anchors with full-length welding.
- (2) Push-out test results showed that the performance of test specimens strongly depends on the types of steel anchors rather than the geometry of steel beams. The specimens with C-channel anchors showed highest load-carrying capacity but most drastic load reduction after the peak load. The specimens with Z-channel anchors showed a similar behavior to those with C-channel anchors, but the load reduction occurred in a slightly slower rate. The load-carrying capacity was increased with the length of Z- and C-channel anchors. The specimens with stud anchors reached the peak load in a slow rate and showed most ductile behavior.
- (3) Some of existing design equations for fully-welded channel anchors showed relatively good and conservative predictions after considering the contribution of the concrete

inside the UH-beam cast monolithically with concrete slabs, but, fundamentally, it is not appropriate to apply the existing design equations for fully-welded channel anchors to the design of partially-welded channel anchors, because the failure mode and shear strength are strongly affected by the shape and welding condition of steel anchors.

- (4) Existing two design equations for partially-welded channel anchors were compared with the present and previous test results. The comparison showed that both equations are considered applicable to design, considering the fact that the design factors such as strength reduction factors and partial factors are used in actual design.

It is noted that the verification of the existing design equations was made only for limited number of samples. For safer and more economic design, further experimental studies with various design parameters are required, especially for beam specimens which are more realistic in practice.

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Notations

A_{ca1}	shear plane area 1 of channel anchor
A_{ca2}	shear plane area 2 of channel anchor
A_{cb}	bearing area of channel anchor
A_{sa}	cross-sectional area of stud anchor
b_c	width of concrete measured at the interface between monolithically cast beam and slab
b_{ca}	width of channel anchor
d_c	depth of concrete measured at the interface between monolithically cast beam and slab
d_{sa}	shank diameter of stud anchor
d_{slab}	depth of concrete slab
E_c	elastic modulus of concrete
f_c'	compressive strength of concrete
F_u	tensile strength of steel
F_y	yield strength of steel
h_{ca}	height of channel anchor
h_{sa}	height of stud anchor
K_i	initial stiffness or secant stiffness at the point where steel anchors reach yield strain
L_{bw}	web-to-web clear distance of U-shaped cold-formed steel beam
L_{ca}	length of channel anchor
$L_{ca,w}$	welded length of channel anchor measured at one end
Q_n	nominal shear strength of a steel anchor
s_{ca}	spacing of channel anchor
t_f	flange thickness of channel anchor
t_p	thickness of plate

t_{sc}	lesser of thickness of channel anchor considering welded part and thickness of channel anchor itself
t_w	web thickness of channel anchor
V_m	maximum shear strength or peak load
V_n	nominal shear strength of test specimen
V_{nc}	nominal shear strength of concrete inside UH-beam cast monolithically with concrete slab
δ_u	ultimate slip
δ_y	yield slip
μ	slip capacity or ratio of yield slip-to-ultimate slip
ρ_w	longitudinal reinforcement ratio

Appendix A

Table A1. Test Parameters of Previous Studies for Channel Anchor with Partial-length Welding (units in mm, MPa).

Authors	Specimen	Channel Anchor	Concrete Slab	Steel Beam
		$h_{sa} \times b_{sa} \times t_w \times t_f, F_u, L_{sa,w}$	f'_c, d_{slab}	L_{bw}
Keo et al. [4]	PO-L40	Inv-L40 $\times$ 40 $\times$ 4 $\times$ 4, 550, 20	27.0, 200	288
	PO-L50a	Inv-L50 $\times$ 50 $\times$ 5 $\times$ 5, 445, 40	20.3, 200	288
	PO-L50b	Inv-L50 $\times$ 50 $\times$ 5 $\times$ 5, 445, 40	21.3, 200	288
	PO-L50c	Inv-L50 $\times$ 50 $\times$ 5 $\times$ 5, 445, 40	22.7, 200	288
Kim et al. [5]	EA-30-20-200	Inv-L30 $\times$ 30 $\times$ 3 $\times$ 3, 421, 20	28.5, 150	388
	EA-30-30-200	Inv-L30 $\times$ 30 $\times$ 3 $\times$ 3, 421, 30	28.5, 150	388
	EA-30-40-200	Inv-L30 $\times$ 30 $\times$ 3 $\times$ 3, 421, 40	28.5, 150	388
	EA-30-20-300	Inv-L30 $\times$ 30 $\times$ 3 $\times$ 3, 421, 20	28.5, 150	388
	EA-30-30-300	Inv-L30 $\times$ 30 $\times$ 3 $\times$ 3, 421, 30	28.5, 150	388
	EA-30-40-300	Inv-L30 $\times$ 30 $\times$ 3 $\times$ 3, 421, 40	28.5, 150	388
	EA-40-20-200	Inv-L40 $\times$ 40 $\times$ 5 $\times$ 5, 456, 20	28.5, 150	388
	EA-40-30-200	Inv-L40 $\times$ 40 $\times$ 5 $\times$ 5, 456, 30	28.5, 150	388
	EA-40-40-200	Inv-L40 $\times$ 40 $\times$ 5 $\times$ 5, 456, 40	28.5, 150	388
	EA-40-20-300	Inv-L40 $\times$ 40 $\times$ 5 $\times$ 5, 456, 20	28.5, 150	388
	EA-40-30-300	Inv-L40 $\times$ 40 $\times$ 5 $\times$ 5, 456, 30	28.5, 150	388
	EA-40-40-300	Inv-L40 $\times$ 40 $\times$ 5 $\times$ 5, 456, 40	28.5, 150	388
	EA-50-20-200	Inv-L50 $\times$ 50 $\times$ 6 $\times$ 6, 454, 20	28.5, 150	388
	EA-50-30-200	Inv-L50 $\times$ 50 $\times$ 6 $\times$ 6, 454, 30	28.5, 150	388
	EA-50-40-200	Inv-L50 $\times$ 50 $\times$ 6 $\times$ 6, 454, 40	28.5, 150	388
	EA-50-20-300	Inv-L50 $\times$ 50 $\times$ 6 $\times$ 6, 454, 20	28.5, 150	388
	EA-50-30-300	Inv-L50 $\times$ 50 $\times$ 6 $\times$ 6, 454, 30	28.5, 150	388
	EA-50-40-300	Inv-L50 $\times$ 50 $\times$ 6 $\times$ 6, 454, 40	28.5, 150	388
Lee et al. [6]	AN-160-60-4.5	L60 $\times$ 40 $\times$ 4.5 $\times$ 4.5, 493, 80	29.2, 200	304
	AN-160-60-6	L60 $\times$ 40 $\times$ 6 $\times$ 6, 478, 80	29.2, 200	304
	AN-160-80-4.5	L80 $\times$ 40 $\times$ 4.5 $\times$ 4.5, 493, 80	29.2, 200	304
	AN-160-80-6	L80 $\times$ 40 $\times$ 6 $\times$ 6, 478, 80	29.2, 200	304

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