Design of Steel Headed Stud Anchors in Concrete-Filled Steel Composite Deck

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ABSTRACT

This paper reports common failure mechanisms of steel headed stud anchors (shear studs) in concrete-filled steel composite decks found in the literature comprised through an extensive database of push-out tests representing multiple shear stud configurations used in composite construction around the world. Monotonically and cyclically loaded push-out test specimens perpendicular or parallel steel deck, or in solid slabs, are included in the evaluation. Comparisons to experimental strengths are made with the steel headed stud anchor strength prediction methods from various international codes and standards along with other mechanics-based design provisions proposed in the literature. Results indicate that shear stud strength predictions for concrete failure modes are often overestimated, meaning the predicted shear stud strength is higher compared to the experimental shear stud strength based on push-out tests, especially for deck perpendicular configurations. To better address concrete-related failures, two alternative design equations are presented within the context of the AISC *Specification* framework and are validated through comparisons with both push-out tests and composite beam tests documented in the literature.

Keywords: composite construction, composite beam, composite diaphragm, steel headed stud anchor, shear connector, steel deck.

INTRODUCTION

Background

Concrete-filled steel composite decks are one of the most prevalent diaphragm assemblies used in building construction (Ahmed and Tsavdaridis, 2019). Composite action allows the assembly to act as one, thereby increasing the flexural stiffness of the entire deck system and allowing for a reduction in steel beam depth and weight. Steel headed stud anchors (shear studs) are the most widely used shear connectors to induce composite action between the steel members and concrete slab. A channeled steel deck, commonly oriented perpendicular or parallel to the span of the steel beam, is used as permanent formwork for the concrete-fill and stiffens the entire assembly with the steel headed stud anchors located in the troughs of the deck.

The push-out test, developed in Switzerland in the 1930s for spiral shear connectors (Davies, 1967), has become the prevailing method to estimate the shear strength of shear connectors. Steel headed stud anchors first appeared as shear connectors in the 1950s, initially studied without the influence of a steel deck (Ollgaard et al., 1971; Slutter and Driscoll, 1963; Viest, 1956). The total assemblage is weakened due to edge-like conditions introduced by a trapezoidal troughs when placed transverse to the span of the beam (Easterling et al., 1993). Several researchers have proposed strength reduction factors to account for this reduced strength (Fisher, 1970; Grant et al., 1977; Lawson, 1992; Mottram and Johnson, 1990). The 1978 AISC *Specification* (AISC, 1978) adopted the strength reduction factor of Grant et al. (1977), which has since been removed.

Baseline limitations to the composite assembly have been set through extensive testing in the literature. Work from Goble (1968) found that flange pull-out failure occurs when the diameter-to-flange thickness ratio is above 2.7. The 2022 AISC *Specification for Structural Steel Buildings* (2022b), hereafter referred to as the 2022 AISC *Specification*, proposes a ratio of 2.5, unless the steel headed stud anchor is located directly over the web of the beam. Slutter and Driscoll (1963) proposed that the total height-to-diameter ratio for shear studs embedded in normal-weight concrete should be equal to or larger than 4.2 to achieve full shear transfer. Fisher (1970) found smaller diameter studs to be more efficient shear connectors compared to larger diameter studs and recommended the stud diameter to be

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limited to 0.75 in. (19 mm) or less. The 2022 AISC *Specification* requires 0.75 in. (19 mm) or less diameter studs for slabs with steel deck ribs and 1 in. (25.4 mm) or less diameter studs for solid slabs. Fisher also concluded that the number of studs per rib does not increase the shear strength of the rib by the same proportion. Smith and Couchman (2010) found that the perpendicular spacing of the studs has little effect on the resistance and groups of more than two offer little additional strength. The 2022 AISC *Specification* applies an R_g factor to account for stud grouping and will be discussed in detail in the following sections. Ollgaard et al. (1971) observed a reduction in stud strength as the longitudinal stud spacing decreased and approached 6 times the stud diameter for studs in lightweight concrete slabs. The 2022 AISC *Specification* requires a minimum center-to-center stud spacing of 4 times the stud diameter in any direction. Additionally, Fisher (1970) noted a loss of strength in concrete-filled steel composite deck with lightweight (LW) concrete.

The majority of steel decks used today possess a stiffener that is located in the middle of the deck rib to increase the strength of the deck. Due to the geometric interference, studs must be welded on one side of the stiffener. The stud can be placed on either side that offers more or less concrete cover in the direction of loading, known as the strong and weak positions, respectively. Lawson (1992) was the first to account for stud position due to stiffeners with a strength reduction factor. Shear stud behavior is heavily dependent on their location in the deck rib (Easterling et al., 1993; Lyons et al., 1994; Sublett et al., 1992).

A small number of prior studies have been dedicated to investigating cyclic loading on steel headed stud anchors in composite deck construction (Pallarés and Hajjar, 2010; Zhai et al., 2018). The 2022 AISC *Seismic Provisions* (2022a) specify a 25% reduction to the 2022 AISC *Specification* stud strength equation with a limitation to 0.75 in. diameter studs. Recent research shows this reduction to be adequate and conservative (Pallarés and Hajjar, 2010).

Objectives

This work reevaluates the design procedures for the calculation of shear strength of steel headed stud anchors in concrete-filled steel composite deck, specifically addressing concrete-related failures. Although many researchers have studied the effects of concrete limit states, previously proposed strength prediction models for steel headed stud anchors have either not been fully implemented or have been adopted with modifications that do not adequately account for all failure mechanisms, potentially leading to an unconservative strength prediction model.

An extensive database of push-out tests from the literature has been compiled, focusing on common shear stud configurations, particularly those with 0.75 in. (19 mm) or less diameter studs in perpendicular concrete-filled steel composite deck under monotonic loading. The study also includes push-out tests with parallel deck, solid slabs, and cyclic loading. Experimental results are compared with strength prediction models from the following: 2022 AISC *Specification*, Canadian Standards Association S16:19 (CSA, 2019), Eurocode 4 (CEN, 2004), and Rambo-Roddenberry et al. (2002a, 2002b) with additional validation from composite beam tests.

This paper primarily focuses on strength limit-state design, specifically evaluating the shear strength of steel headed stud anchors in concrete-filled steel composite decks used in building construction, where partial composite action is assumed. Partial composite action is typical in buildings due to shorter spans, lower live-to-dead load ratios, and the use of fewer shear connectors to simplify construction and reduce costs. The study excludes fatigue limit states, which are more relevant in bridge applications.

Two new strength prediction models are presented, specifically to address the limit state of concrete failure, including concrete-pull out and rib shear failure described herein. These models, developed with push-out tests and validated with composite beam tests, modify the 2022 AISC *Specification*, utilizing common factors that are familiar to the specification.

EXPERIMENTAL DATABASES AND STRENGTH MODELS

A significant amount of prior research has been dedicated to understanding the behavior of steel headed stud anchors, especially subjected to monotonic loading. Push-out tests and composite beam test results were gathered from the literature to comprehensively cover numerous configurations of shear studs in concrete-filled steel composite deck. Test specimens from the literature were not considered if failure resulted from experimental test procedures. Both lightweight (LW) and normal weight (NW) concrete test specimens were included. When measured material properties were unavailable, nominal properties were used as noted (see asterisk in Table 1 and Table 4). Concrete strengths originally reported as cube strength (Johnson and Yuan, 1998b; Lloyd and Wright, 1990; Smith and Couchman, 2010) were converted to equivalent cylinder strength; a conversion factor of 0.80 was applied where a cylinder strength was not reported directly. Specific testing details for each test specimen are presented in Bond et al. (2022).

Push-Out Test Database

Specimens with Perpendicular Steel Deck, Monotonically Loaded

A total of 240 push-out test specimens with a steel deck oriented perpendicular to the support beam have been gathered from 18 studies (Briggs et al., 2022; Cashell and Baddoo, 2014; Ernst, 2006; Hawkins and Mitchell, 1984; Hicks, 2009; Jayas and Hosain, 1988; Johnson and Yuan, 1998b; Lawson et al., 2017; Lim et al., 2020; Lloyd and Wright, 1990; Lyons et al., 1994; Nellinger, 2015; Rambo-Roddenberry et al., 2002a, 2002b; Robinson, 1988; Russell et al., 2021; Smith and Couchman, 2010; Sublett et al., 1992; Vigneri et al., 2022). All tests utilize 0.75 in. (19 mm) studs with deck heights ranging from 1.5 in. (38 mm) to 3 in. (76 mm). All specimens have a steel headed stud anchor diameter-to-flange thickness ratio of greater than 2.5 corresponding to the limit set in the 2022 AISC *Specification*. For consistency in the data analysis, only specimens with through-deck welding were considered. Possible steel headed stud anchor configurations included in the database, shown in Figure 1, include strong (S), weak (W), middle (M) or two strong (2S); two weak (2W), two middle (2M); along with staggered (STAG); and two in line (2L) or alternating (Alt.). A "strong stud" is welded on the side of the deck rib with the most concrete available for shear transfer, typically near the end of the span. A "weak stud" is placed on the side with less concrete, usually near the point of maximum bending moment, resulting in lower shear resistance due to potential concrete-related failure. The "middle" designation refers to studs placed at the center of the deck rib without a raised stiffener. Other stud configurations in Figure 1 include various groupings of strong and weak studs. For these configurations, the distance (e_{mid}) from the center of the stud anchor to the steel deck web, measured at the mid-height of the deck rib, is used to classify the stud position as either strong or weak for further calculations.

Additional testing features are varied between authors in the database and should be considered in the evaluation of the results. For example, features like the weld collar dimension, applied normal force, and use of welded wire mesh and its placement have been found to have varying influence on the ultimate strength of a push-out test specimen (Oehlers and Johnson, 1981; Rambo-Roddenberry et al., 2002b; Smith and Couchman, 2010). These features are not always reported for each study and could contribute to the scatter in the test-to-predicted plots.

Specimens with Parallel Steel Deck, Monotonically Loaded

A total of 30 push-out test specimen with steel deck oriented parallel to the support beam have been gathered from four studies (Briggs et al., 2022; Johnson and Yuan, 1997; Lloyd and Wright, 1990; Zandonini and Bursi, 2000). Each test consists of 0.75 in. (19 mm) or less studs with deck heights ranging from 1.5 in. (38 mm) to 3 in. (76 mm). Only specimens with through-deck welding were considered, and all specimens have a steel headed stud anchor diameter-to-flange thickness ratio of greater than 2.5. Failure modes were noted as either a concrete failure, steel failure, or a combination of the two.

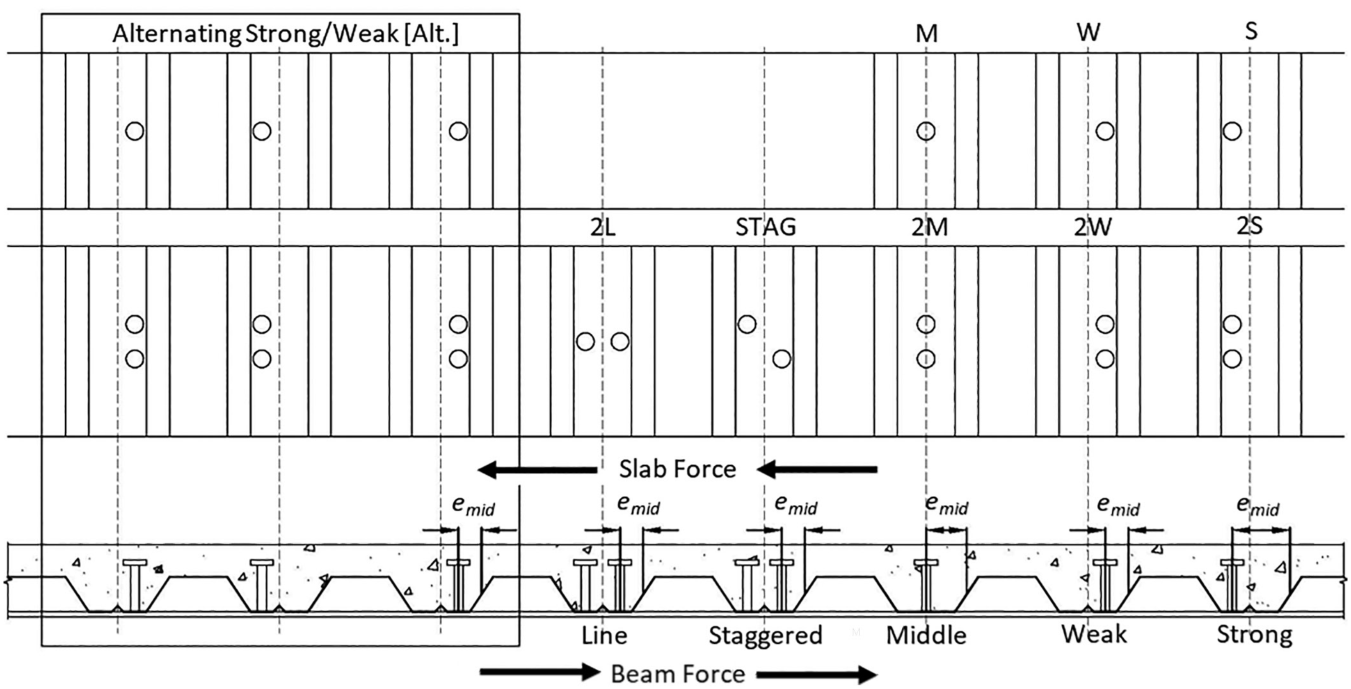


Fig. 1. Stud configurations in deck perpendicular push-out test database.

Cyclically Loaded Specimens

Few studies have been dedicated to the cyclic behavior of steel headed stud anchors in push-out tests. For cyclically loaded specimens, a total of 33 push-out test specimens with steel deck oriented perpendicular or parallel to the support beam have been gathered from three studies (Briggs et al., 2022; Bursi and Gramola, 1999; Hawkins and Mitchell, 1984). All tests utilize 0.75 in. (19 mm) studs with deck heights ranging from 1.5 in. (38 mm) to 3 in. (76 mm). Only specimens with through deck welding were considered and all specimens have a steel headed stud anchor diameter-to-flange thickness ratio of greater than 2.5. Failure modes were noted as either a concrete failure, steel failure, or a combination of the two.

Solid Slab Specimens

Push-out tests with solid slabs were also considered for comparison of the strength prediction models presented in this work; solid slabs refer to cast-in-place concrete slabs without profiled steel decking. The solid slab database is comprised of 165 monotonic test specimens from 15 different studies (An and Cederwall, 1996; Baldwin et al., 1965; Buttry, 1965; Chapman and Balakrishnan, 1964; Chinn, 1965; Dallam, 1968; Hawkins, 1971; Jayas and Hosain, 1988; Mainstone and Menzies, 1967; Menzies, 1971; Ollgaard et al., 1971; Shim et al., 2004; Shoup and Singleton, 1963; Steele, 1967; Viest, 1956), expanding on work by Pallarés and Hajjar (2010). All tests utilize steel headed stud anchor diameters ranging from 0.625 in. (15.9 mm) to 1 in. (25.4 mm) and stud heights ranging from 2 in. (50.8 mm) to 9 in. (227 mm). All specimens have a steel headed stud anchor diameter-to-flange thickness ratio of greater than 2.5. Failure modes have been specified by Pallarés and Hajjar as either stud failure, concrete failure, mixed failure, or not reported (NR).

Composite Beam Tests

A database of composite beam tests from the literature has been compiled and used for analysis from work done by Rambo-Roddenberry et al. (2002b, 2002a). Composite beam tests involve full-scale specimens composed of a steel beam and a concrete slab connected with shear studs and are used to evaluate the integrated behavior and strength of the composite system. The tests used from this database comprise 47 composite beams tests from 12 different sources (Rambo-Roddenberry et al., 2002b, 2002a). All tests utilize 0.75 in. (19 mm) studs with deck heights ranging from 1.5 in. (38 mm) to 3 in. (76 mm) with perpendicular decking and monotonic loading. Steel headed stud anchor heights ranged from 3 in. (76 mm) to 7 in. (177.8 mm). Composite beam tests are used to validate the presented design equations.

REVIEW OF EXISTING STUD STRENGTH MODELS AND FAILURE MODES

Steel Headed Stud Anchor Failure Modes

The ultimate behavior of steel headed stud anchors in perpendicular concrete-filled steel composite deck can be divided up into four failure modes, largely dependent on the location of the stud in the deck rib. Common failure modes are described in this section.

Stud shearing (SS), sometimes referred to as shank shearing, is common for strong-position steel headed stud anchors in perpendicular steel deck. This failure mode consists of a plastic zone directly above the weld collar, followed by fracture of the steel headed stud anchor shank. A shear type failure occurs in the plastic zone in the shank, with minor cracking to the surrounding concrete (Johnson and Yuan, 1998a). This limit state is associated with the upper bound, or cap, of the 2022 AISC *Specification* strength prediction equation.

Rib punching (RP) occurs in weak-position steel headed stud anchors as a localized ductile failure in perpendicular steel deck and is characterized by the crushing of a small portion of concrete in front of the stud, causing the steel deck to bulge and tear (Johnson and Yuan, 1998a). Specimens failing in RP with weak position studs generally exhibit a quick decrease in initial stiffness compared to other failure modes (Briggs et al., 2022). After ultimate strength is reached, a slow decline in strength is shown correlating to the crushing of concrete and tearing of the deck (Briggs et al., 2022). The ultimate strength of weak-position studs is lower compared to strong-position studs, but they exhibit greater ductility.

Rib shear (RS) is a concrete shear failure on the plane on the top of the deck rib, normally seen close to the edge of a specimen. Descriptions of RS and prevention methods for this failure mode are discussed by Ernst (2006). Due to a lack of test data, RS is not discussed further in this paper but is an important topic for future research.

Concrete pull-out (CP) failure is of specific consideration in this paper due to the nature of the representation of this limit state in design strength prediction models. Anchors cast in concrete subject to tension form a concrete failure cone (Shaikh and Yi, 1985). The failure cone develops as the steel headed stud anchor is put into tension due to pry-out action in shear (ACI, 2019). In composite construction, the most likely concrete failure mode is pry-out failure, rather than breakout failure (ACI, 2019; Pallarés and Hajjar, 2010). In perpendicular deck configurations, the failure cone is interrupted by the influence of the deck ribs, with a similar effect of a free edge. CP is most common in strong-position studs, where a larger concrete failure cone can be developed compared to weak-position studs, which fail prematurely due to RP typically at lower strengths. Experiments show steel headed stud anchors to maintain high initial stiffness for CP, until ultimate strength is reached. Strength drops significantly thereafter when a cone of concrete is torn away from the deck (Briggs et al., 2022).

Many strength prediction models utilize an approach based on prediction of failure modes for assessing the strength of steel headed stud anchors (Pallarés and Hajjar, 2010; Zhai et al., 2018; CSA, 2019). The evolution of the CP failure mode specifically is notable. Shaikh and Yi (1985) observed the influence of edge effects and groups of studs on the concrete failure cone formed for tensile loaded steel headed stud anchors cast in concrete. Hawkins and Mitchell (1984) created equations to model the failure surface area of the failure cone when influenced by steel deck. These failure surface areas were utilized in the strength prediction model of Jayas and Hosain (1988), which have since been adopted by CSA S16:19 (CSA, 2019). Revisions to the prior assumptions of a symmetric failure surface area were made in the work of Lloyd and Wright (1990), which derived wedge-like failure surfaces. Furthermore, Johnson and Yuan (1997) utilize equations for CP based on the torsional strength of the concrete rib.

Some researchers found failures relating to weld quality (Ernst, 2006; Lyons et al., 1994; Rambo-Roddenberry et al., 2002b; Sublett et al., 1992). Additionally, a "rib cracking" failure mode was noted by Lyons et al. and Rambo-Roddenberry et al., consisting of disfigurement of the rib accompanied by deck debonding and a "bowing" of the slab away from the loading beam. These failure modes were considered a result of construction or test configurations, and the specimen associated with these failure modes were excluded from the present work.

Strength Prediction Models

Rambo-Roddenberry et al. (2002a, 2002b)

The strength prediction model of Rambo-Roddenberry et al. (2002b) was derived on the basis of 202 push-out tests conducted by Rambo-Roddenberry and colleagues, combined with push-out tests from Lyons et al. (1994), Sublett et al. (1992), and Diaz et al. (Rambo-Roddenberry et al., 2002b). A grouping factor (R_{g_rod}), placement factor (R_{p_rod}), and deck thickness factor (R_{d_rod}) were empirically derived from the stated tests and validated with push-out tests from various authors (Jayas and Hosain, 1989; Johnson and Yuan, 1997; Lloyd and Wright, 1990; Mottram and Johnson, 1990; Robinson, 1988). The strength prediction model of Rambo-Roddenberry et al. (2002b) is summarized in Equation 1.

For studs in 2 in. and 3 in. decks where $d/t \leq 2.7$:

$$Q_{ROD} = 0.5A_s\sqrt{f_c'E_c} \leq R_{p\_rod}R_{g\_rod}R_{d\_rod}A_sF_u \tag{1}$$

R_{p_rod} = 0.68 for $e_{mid} \geq 2.2$ in. (strong position studs)
= 0.48 for $e_{mid} < 2.2$ in. (weak position studs)
= 0.52 for staggered position studs

R_{g_rod} = 1.00 for one stud per rib or staggered position studs
= 0.85 for two studs per rib

R_{d_rod} = 1.00 for all strong position studs
= 0.88 for 22-gauge deck (weak studs)
= 1.00 for 20-gauge deck (weak studs)
= 1.05 for 18-gauge deck (weak studs)
= 1.11 for 16-gauge deck (weak studs)

where d is the diameter of the steel headed stud anchor, t is the thickness of the base metal, A_s is the nominal area of the shear stud, f_c' is the compressive strength of the concrete in ksi, E_c is the Young's modulus of elasticity for concrete in ksi, and F_u is the tensile strength of the shear stud.

CSA S16:19

The 2019 CSA *Design of Steel Structures* (CSA, 2019) strength equation for studs in solid slabs is similar to the 2022 AISC *Specification* strength shown in Equation 1 without the R_p or R_g factors. Perpendicular and parallel deck are accounted for with additional equations. The concrete pull-out area, A_p, is described in work by Jayas and Hosain (Jayas and Hosain, 1988) as a square pyramidal concrete failure cone that radiates down from the top center of the stud head. Equations for this area are based on assumptions from Al-Majhdowi (1975), which only consider a stud placed in the middle of the deck rib. Equations for the concrete pull-out area for varied stud positions are not provided. For studs in solid slabs:

$$Q_{CSA\_SS} = 0.5\phi_{sc}A_s\sqrt{f_c'E_c} \leq A_sF_u \tag{2}$$

where the resistance factor, ϕ_{sc}, is 0.80. For comparison to other models, the test-to-predicted ratios are presented without the 0.80 resistance factor. For studs in slabs with steel deck with ribs perpendicular to the beam:

$$Q_{CSA} = C_dA_p\rho\sqrt{f_c'} \leq Q_{CSA\_SS} \tag{3}$$

where C_d = 0.35 for a 3 in. (75 mm) high deck, C_d = 0.61 for a 1.5 in. (38 mm) high deck, and ρ is the concrete density. For deck heights between 3 in. and 1.5 in., a linear interpolation was taken for the coefficient C_d. For example, C_d = 0.52 for a 2 in. high deck.

Eurocode 4

The strength equation presented in *Design of Composite Steel and Concrete Structures* (CEN, 2004) is similar to the 2022 AISC *Specification* strength with lower coefficients and the inclusion of a partial safety factor, γ_v. An additional factor, k_t, accounts for reduction in strength due to the presence and orientation of the deck.

$$Q_{EN4} = \min\left(\frac{k_t 0.8 F_u \pi d^2}{4\gamma_v}, \frac{k_t 0.29 \alpha d^2 \sqrt{f_c' E_c}}{\gamma_v}\right) \tag{4}$$

where $\alpha = 0.2\left(\frac{H}{d}+1\right)$ for $3 \le \frac{H}{d} \le 4$ or $\alpha = 1$ for $\frac{H}{d} > 4$. For parallel decking:

$$k_t = 0.6\frac{w_r}{h_r}\left(\frac{H}{H-h_r}-1\right) \le 1.0 \tag{5}$$

where w_r is the average rib width, h_r is the height of the rib, and H is the height of the stud. For perpendicular decking:

$$k_t = \frac{0.7}{\sqrt{n_r}}\frac{w_r}{(H-h_r)}\left(\frac{H}{H-h_r}-1\right) \tag{6}$$

where n_r is the number of studs per rib. See EN 1994-1-1, Table 6.2, for restrictions on k_t (CEN, 2004).

AISC Specification

The steel headed stud anchor strength equation presented in the 2022 AISC *Specification* originated from work by Ollgaard et al. (1971). Empirical equations were adopted to predict the shear strength of a single stud embedded in LW or NW concrete (e.g., Equation 7). The original upper bound (e.g., cap), A_sF_u, proposed by Ollgaard et al. has since been adjusted to include considerations of stud position in the trough and the number or grouping of studs. The grouping factor, R_{g_rod}, and placement factor, R_{p_rod}, were empirically derived from research done by Rambo-Roddenberry et al. (2002b). AISC adopted the R_p factor, modifying R_{p_rod} (e.g., an increase from 0.68 to 0.75 for strong position studs and 0.48 to 0.60 for weak position studs) and the deck gauge reduction, R_{d_rod}, was left out.

$$Q_{AISC} = 0.5A_s\sqrt{f_c' E_c} \le R_g R_p A_s F_u \tag{7}$$

where Q_{AISC} is in psi units.

RESULTS AND DISCUSSION

Perpendicular Deck Database Comparison to Rambo-Roddenberry et al., CSA S16:19, Eurocode 4, and the 2022 AISC *Specification*

Figure 2 compares the experimental strength of each push-out test, Q_E, described in the Methods section, to the predicted strength of four models for the shear resistance of steel headed stud anchors [Rambo-Roddenberry et al. (2002b) (Q_{ROD}); CSA S16:19 (CSA, 2019) (Q_{CSA}); Eurocode 4 (CEN, 2004) (Q_{EN4}); and the 2022 AISC *Specification* (Q_{AISC}) predicted strength]. To balance comparisons, the partial safety factor and resistance factor (safety factor) of the Eurocode 4 and CSA S16:19 strength prediction models, respectively, were both set to 1.00. The red x above or below for each specimen in Figure 2(d) signifies the controlling side of the strength prediction equation. For example, if the cap strength (i.e., $R_pR_gA_sF_u$) controlled, a red x would appear above the marker at the top of the graph, otherwise the lower bound of the strength prediction controlled and the red x appears below the marker, Equation 7. LW and NW concrete are delineated with a hollow or shaded symbol, respectively. Table 1 includes the test series number, identifying which tests belong to which study and if the nominal steel headed stud anchor strength, F_u, was used in calculations.

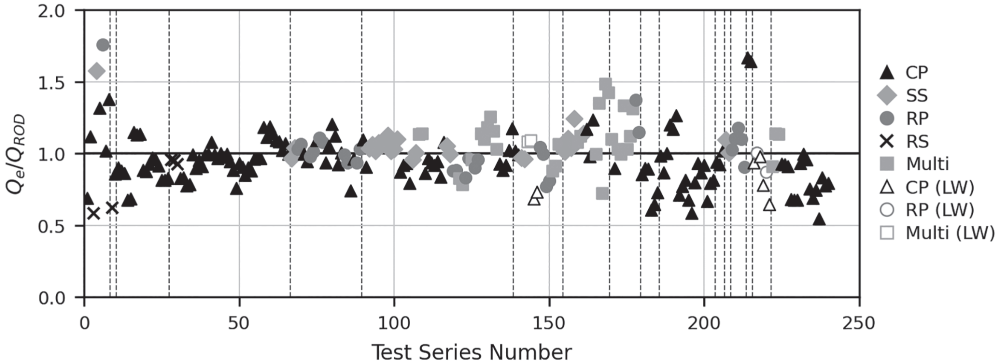
Table 2 shows a summary of the test-to-predicted ratios for the considered strength prediction model's average, minimum, maximum, standard deviation (StDev), and coefficient of variance (CoV). Rambo-Rodenberry's (2002b) model was found to accurately predict steel headed stud anchor strength and was partially adopted by AISC with modifications to the coefficients. In the CSA S16:19 model, the concrete pull-out area is calculated with an assumption the stud lies in the center of the deck trough, even for studs in the strong and weak positions. For these reasons, the model was found to be somewhat unconservative for studs in perpendicular concrete-filled steel composite deck.

In the 2022 AISC *Specification* equation, all but thirteen of the tests are controlled by the cap. The lower bound of Equation 7, $0.5A_s\sqrt{f_c' E_c}$, is applied to all studs, including those in a perpendicular deck, but was developed using only studs in solid slabs (Ollgaard et al., 1971). Specimens with perpendicular steel deck have been observed to have lower strengths compared to similar specimens with a solid slab (Hawkins and Mitchell, 1984; Jayas and Hosain, 1988; Rambo-Roddenberry et al., 2002b; Sublett et al., 1992). Therefore, an alteration to the lower bound of the strength prediction equation, for a stud in perpendicular deck, is desired to account for the decrease in available strength.

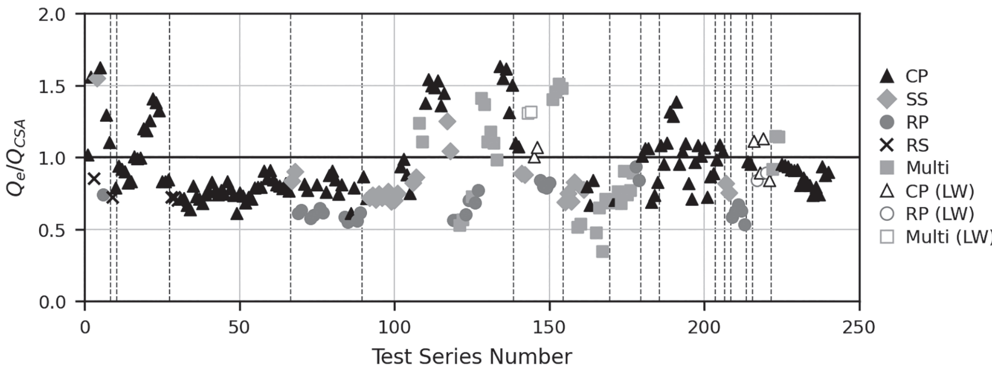
Reassessment of Steel Headed Stud Anchors in the 2022 AISC *Specification*

Perpendicular Deck

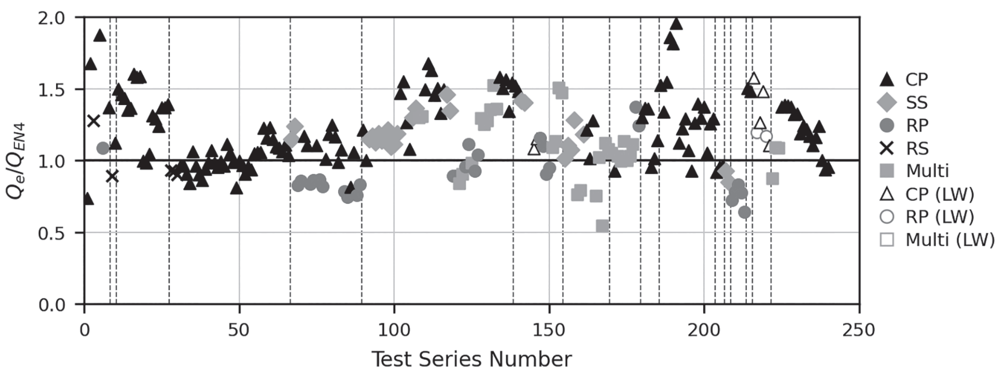
Two new strength prediction models adapted from the 2022 AISC *Specification* are presented herein. The first design strength formula is termed the R_pR_g adjusted AISC strength prediction model and is shown in Equation 8. The R_p and R_g factors account for the reduction in strength due to the position in the trough and the grouping of the steel headed stud anchors. Similarly, this approach adjusts the predicted



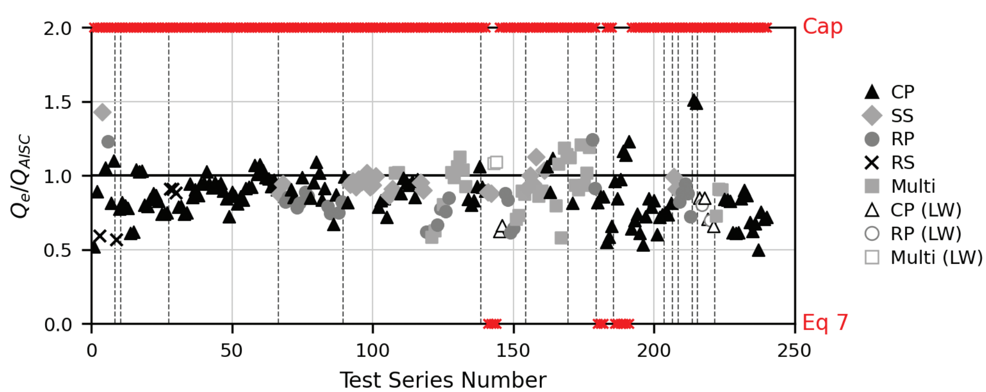
(a) Rambo-Roddenberry et al. (2002)



(b) CSA S16:19 (2019)



(c) Eurocode 4 (CEN, 2004)



(d) 2022 AISC Specification

Fig. 2. Test-to-predicted ratios for shear strength of steel headed stud anchors.

Table 1. Reference and Test Series Number—Perpendicular Decking		
Reference	**First Test Series Number**	**Last Test Series Number**
Hawkins and Mitchell (1984)	1	8
Jayas and Hosain (1988)*	9	10
Robinson (1988)	11	27
Lloyd and Wright (1990)*	28	66
Sublett et al. (1992)*	67	89
Lyons et al. (1994)	90	138
Johnson and Yuan (1998b)	139	154
Rambo-Roddenberry et al. (2002a)	155	169
Ernst (2006)	170	179
Hicks (2009)	180	185
Smith and Couchman (2010)	186	203
Cashell and Baddoo (2014)	204	206
Nellinger (2015)	207	208
Lawson et al. (2017)	209	213
Lim et al. (2020)	214	215
Briggs et al. (2022)	216	221
Vigneri (2021)	222	224
Russell et al. (2021)	225	240
* Nominal steel headed stud anchor strength, F_u, used in calculations		

Table 2. Test-to-Predicted Ratio per Each Strength Prediction Model				
	Q_E/Q_{AISC}	Q_E/Q_{ROD}	Q_E/Q_{CSA}	Q_E/Q_{EN4}
Average	0.873	0.978	0.901	1.175
Max	1.513	1.760	1.634	2.197
Min	0.497	0.548	0.347	0.547
StDev	0.162	0.183	0.258	0.274
CoV	0.185	0.187	0.286	0.233

strength to address concrete failures in steel deck by applying the 2022 AISC *Specification* R_p and R_g factors to the lower bound of the stud strength equation, $0.5A_s\sqrt{f_c'E_c}$. The R_pR_g adjusted AISC strength prediction model is:

$$Q_{R_pR_g} = R_pR_g\left(0.5A_s\sqrt{f_c'E_c}\right) \le R_pR_gA_sF_u \tag{8}$$

The second strength prediction method is the result of a regression analysis performed on specimens that failed in concrete pull-out, similar to the derivation of the original R_p and R_g values (Rambo-Roddenberry et al., 2002b, 2002a). The linear regression compared the existing lower bound of the stud strength equation, $0.5A_s\sqrt{f_c'E_c}$, with the experimental specimen strengths from the perpendicular deck database. The slope of the regression line with a *y*-intercept of zero is then taken as the concrete failure regression coefficient, R_r, to adjust the lower bound of the AISC strength prediction model. The development of the R_r coefficient is presented for all deck configurations in the following sections and summarized in Equation 9. This method is labeled as the LB-regression adjusted AISC strength prediction model and is shown in Equation 9. The regression analysis for perpendicular deck is shown in Figure 3. The LB-regression adjusted AISC strength prediction is:

$$Q_{LB} = R_r\left(0.5A_s\sqrt{f_c'E_c}\right) \le R_pR_gA_sF_u \tag{9}$$

For ¾-in.-diameter studs:
$R_r = 0.65$ (for perpendicular deck)
$R_r = 0.75$ (for parallel deck)

For studs with diameters between ¾ in. and 1.0 in.:

$R_r = 0.80$ (for solid slabs)

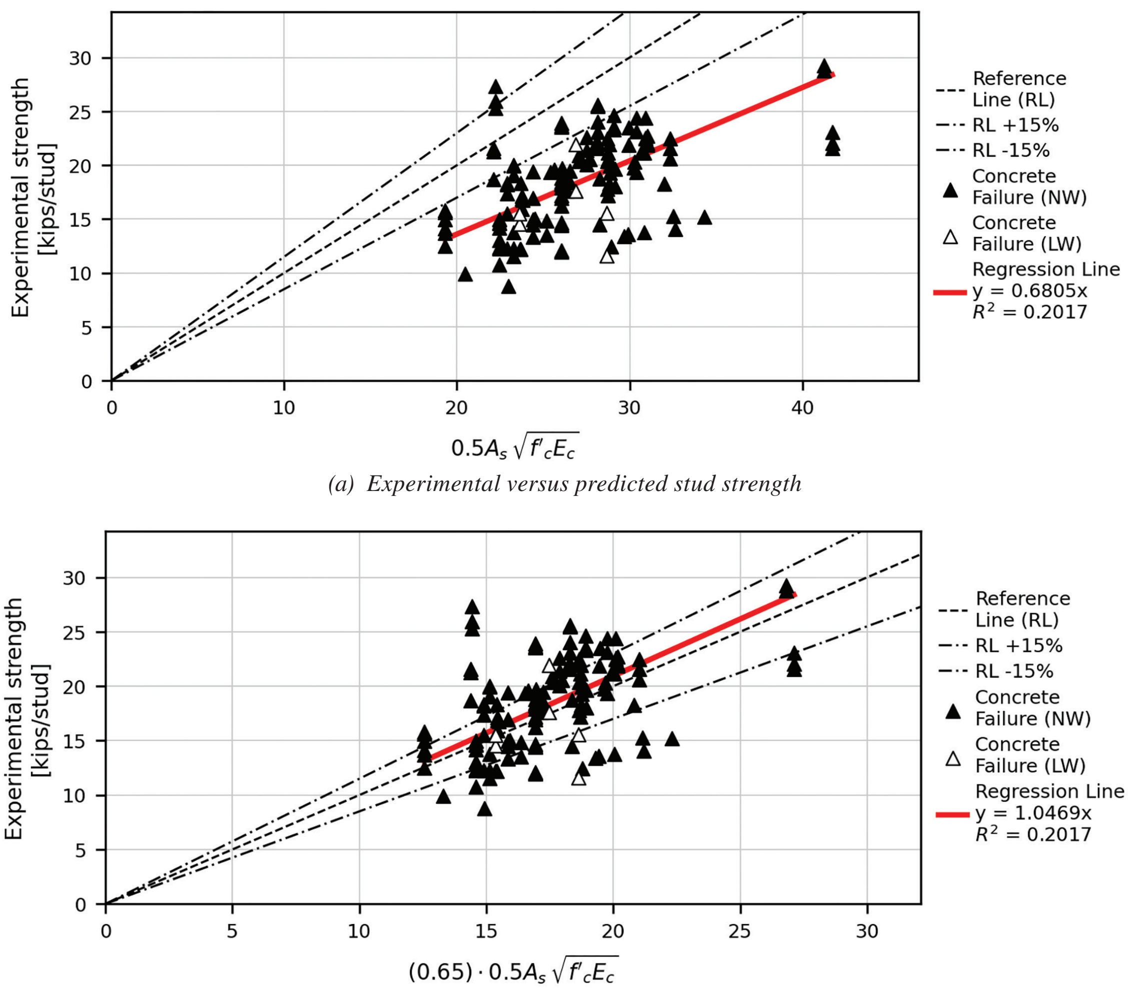
Test-to-predicted graphs for each method are presented in Figure 4 for tests with deck perpendicular. Test series numbers are provided in Table 1 for perpendicular decking along with an indication of nominal vs. measured stud strength property usage for different studies. Similar to Figure 2, the red x above or below the symbol for each specimen signifies which portion of the respective strength prediction equation controlled.

Descriptive statistics of the test-to-predicted ratios are shown in Table 3 for the two proposed strength models. The R_pR_g adjusted AISC strength prediction model, Equation 7, uses factors that are already familiar to the designer and does not require a prediction of the limit state in design. The LB-regression adjusted AISC strength prediction model has been found to adequately predict stud strength for the perpendicular push-out test specimen. Both methods account for the metal deck in the lower bound of the strength prediction equation and result in a test-to-predicted ratio closer to 1.0.

While the proposed equations improve the accuracy of the test-to-predicted ratios, the CoV for the LB-regression adjusted AISC model increases slightly compared to the existing model, whereas the R_pR_g adjusted AISC model achieves a marginally lower CoV. The increase in variability for the LB-regression model may be attributed to the more complex adjustments introduced by that equation. Despite this, both proposed models offer more accurate predictions in terms of the test-to-predicted ratios. Further experimental data and refinements are recommended to address this variability and to improve the consistency of the predictions.

Parallel Deck

The new strength prediction models were also considered for monotonically loaded push-out tests with parallel deck. Details from the parallel deck push-out test database were



(a) Experimental versus predicted stud strength

(b) Regression line defining the LB-regression coefficient

Fig. 3. Linear regression analysis for perpendicular deck specimens with concrete pull-out failure.

Table 3. Perpendicular Test-to-Predicted Ratio per Each Presented Strength Prediction Model for Perpendicular Steel Deck			
	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}
Average	0.873	1.009	1.050
Max	1.513	1.639	1.892
Min	0.497	0.579	0.579
Stdev	0.162	0.184	0.216
CoV	0.185	0.183	0.206
Note: R_r = 0.65 for perpendicular deck remains unchanged in Equation 9.			

presented earlier. Figure 5 shows the results from the linear regression comparing the existing lower bound of the stud strength equation, $0.5A_s\sqrt{f_c'E_c}$, with the experimental strength of concrete failures in the parallel deck database. From the slope of the regression line, the LB regression coefficient is taken as $R_r = 0.75$ for the parallel deck case.

The R_pR_g adjusted AISC strength prediction model and LB-regression adjusted AISC strength prediction model are analyzed using the experimental strengths of the parallel deck database and compared with the 2022 AISC *Specification* strength prediction in Figure 6. Table 4 matches the test series number with its corresponding reference. Descriptive statistics of the test-to-predicted ratios for each strength prediction model are shown in Table 5. The two new strength prediction models increase the average test-to-predicted ratio by about 0.05. Thus, the 2022 AISC *Specification* equations give adequate predictions of the strengths of steel headed stud anchors in parallel deck.

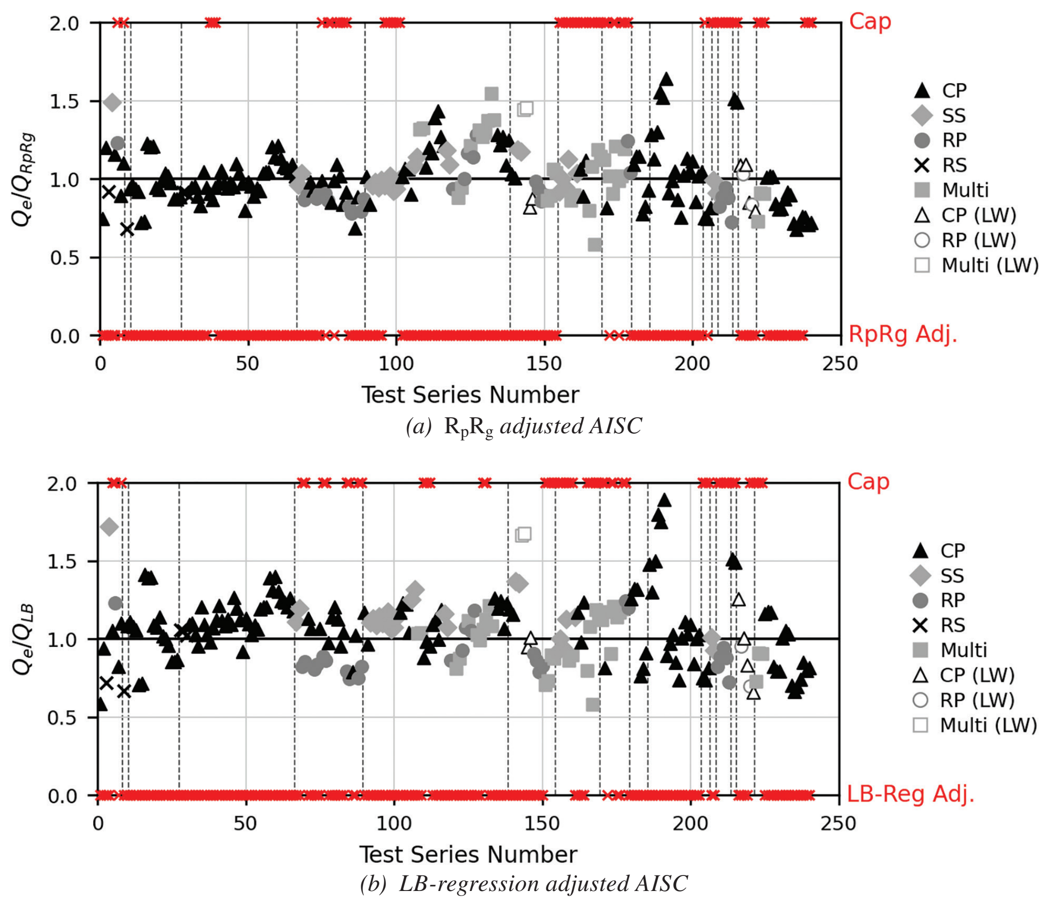


Fig. 4. Perpendicular deck test-to-predicted strengths for steel headed stud anchors.

Table 4. Reference and Test Series Number—Parallel Deck		
Reference	**First Test Series Number**	**Last Test Series Number**
Lloyd and Wright (1990)*	1	3
Johnson and Yuan (1997)	4	21
Bursi and Gramola (1999)	22	27
Briggs et al. (2022)	28	30

* Nominal steel headed stud anchor strength (F_u) used in calculations

Table 5. Parallel Deck Test-to-Predicted Ratio per Each Presented Strength Prediction Model

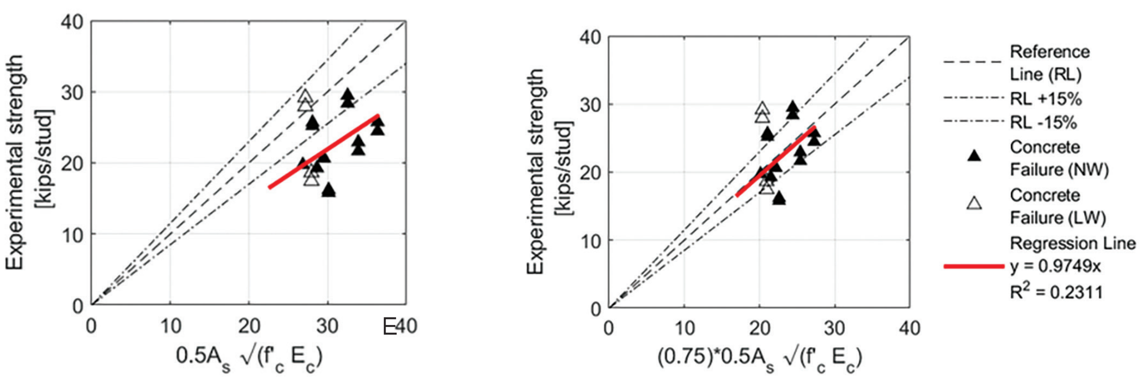
	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}
Average	1.011	1.061	1.057
Max	1.391	1.432	1.432
Min	0.677	0.700	0.700
StDev	0.180	0.183	0.183
CoV	0.178	0.172	0.173

Cyclic Loading

The cyclically loaded push-out test database with perpendicular and parallel deck configurations is presented in the Methods section. The LB regression coefficient, R_r, is adopted from the monotonically loaded perpendicular and parallel specimens for each case.

The R_pR_g adjusted AISC strength prediction model and LB-regression adjusted AISC strength prediction model are evaluated against the experimental strengths of the cyclic push-out test database and their results are compared with the existing AISC strength prediction in Figure 7. Table 6 provides the test series number with its corresponding reference, while Table 7 shows the descriptive statistics for these comparisons. Consistent with the findings of Pallarés and Hajjar (2010) for solid slabs, the 2022 AISC *Specification* stud strength prediction is generally conservative for cyclically loaded specimens with parallel deck orientation. However, for cyclically loaded specimens with perpendicular decking, the 2022 AISC *Specification* stud strength prediction tends to be unconservative, even when applying the 0.75 strength reduction factor for cyclically loaded steel headed stud anchors. This unconservativeness is partly due to the baseline monotonic strengths also being underestimated.

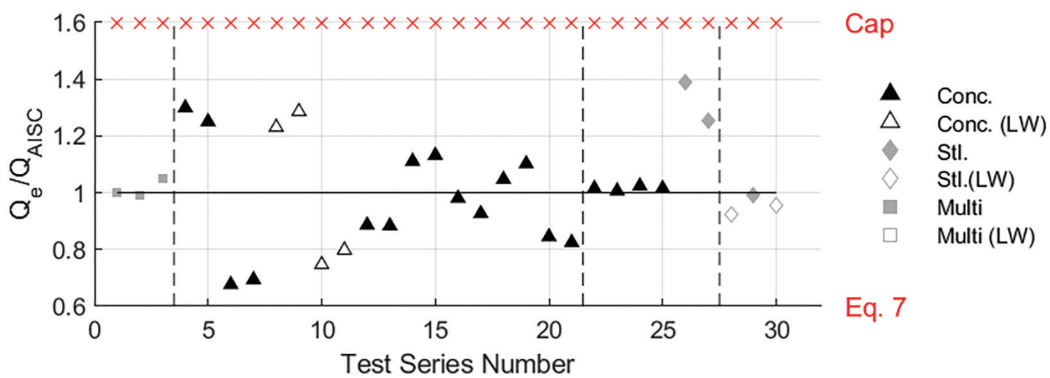
To further understand this relationship, the ratio of the experimental cyclic strength, Q_{E_C}, to monotonic strength,



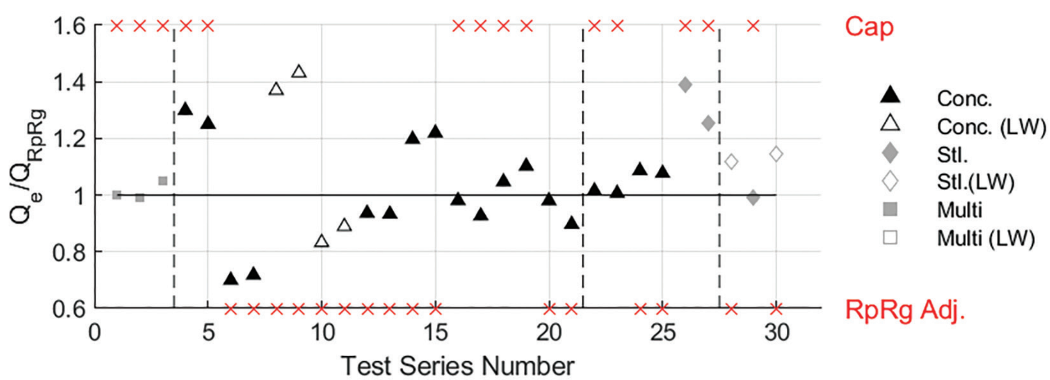
(a) *Without LB-regression coefficient* (b) *With LB-regression coefficient*

Fig. 5. Linear regression analysis for parallel deck specimen with concrete failure.

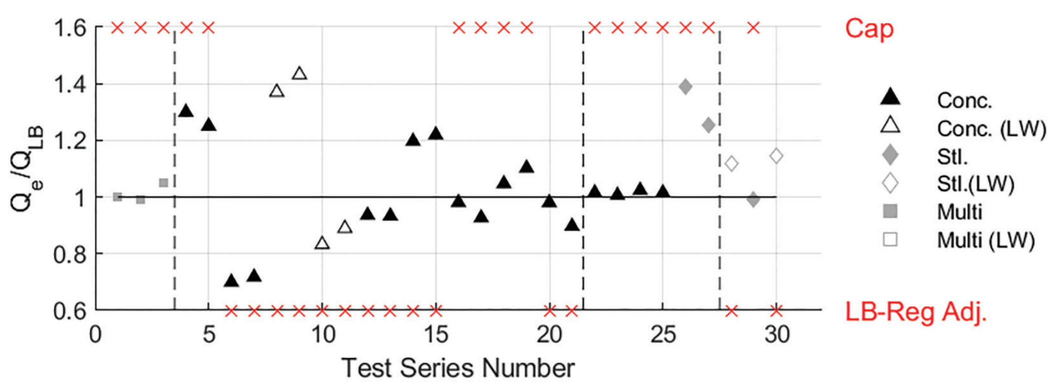
Q_{E_M}, was calculated for identical perpendicular deck push-out test specimens from (Briggs et al., 2022). This dataset, although limited to four specimens, shows an average cyclic-to-monotonic strength ratio of 0.901 with a standard deviation of 0.101, as shown in Table 7. These findings suggest that if the monotonic strength prediction is adjusted, the cyclic strength prediction may also become more accurate. Additional cyclic test data, especially for composite steel decks with perpendicular decking, would help refine these predictions.



(a) *2022 AISC* Specification

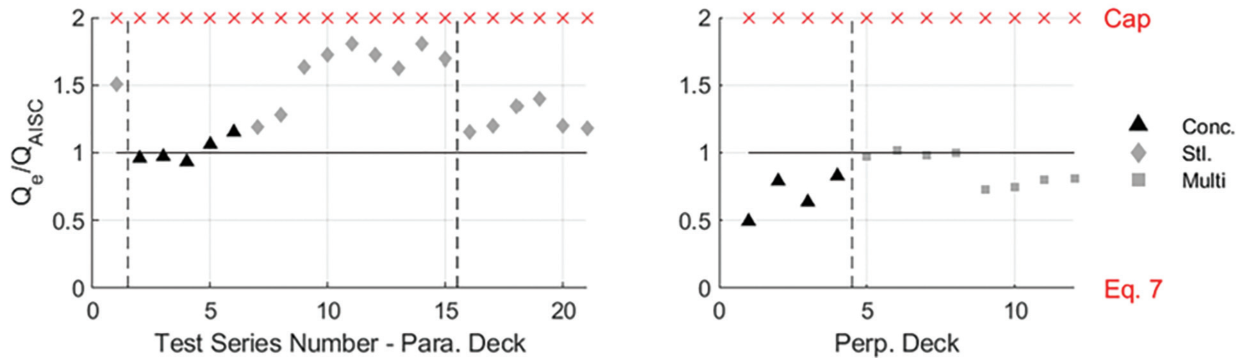


(b) R_pR_g *adjusted AISC*

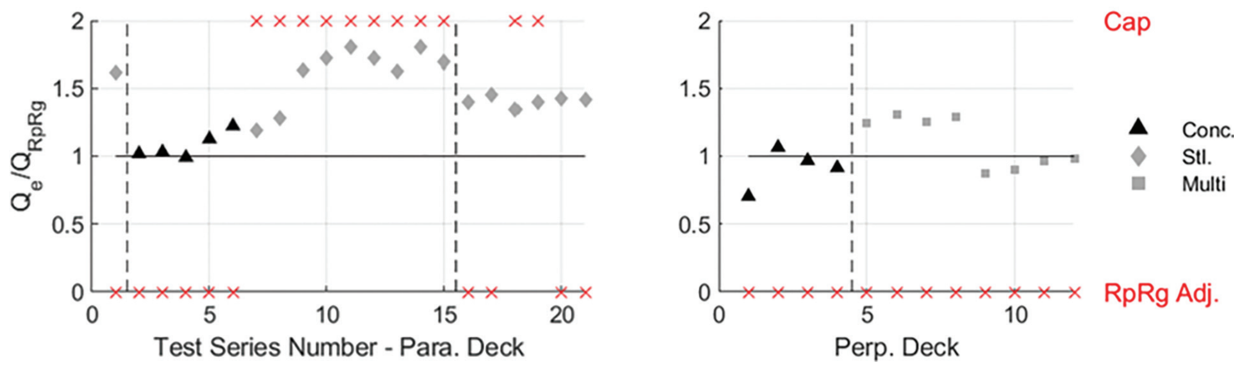


(c) LB-regression adjusted AISC

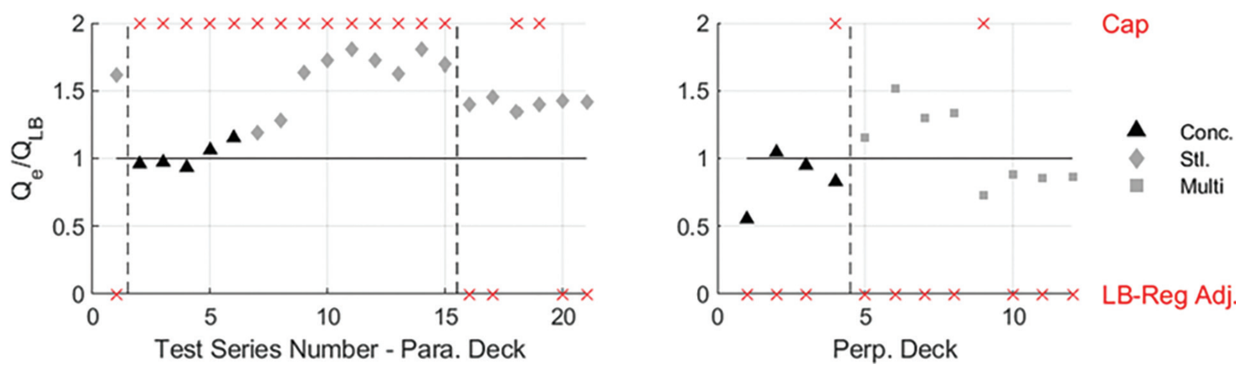
Fig. 6. Parallel deck test-to-predicted graphs for steel headed stud anchors.



(a) 2022 AISC Specification



(b) R_pR_g *adjusted AISC*



(c) LB-regression adjusted AISC

Fig. 7. Cyclically loaded test-to-predicted graphs for steel headed stud anchors.

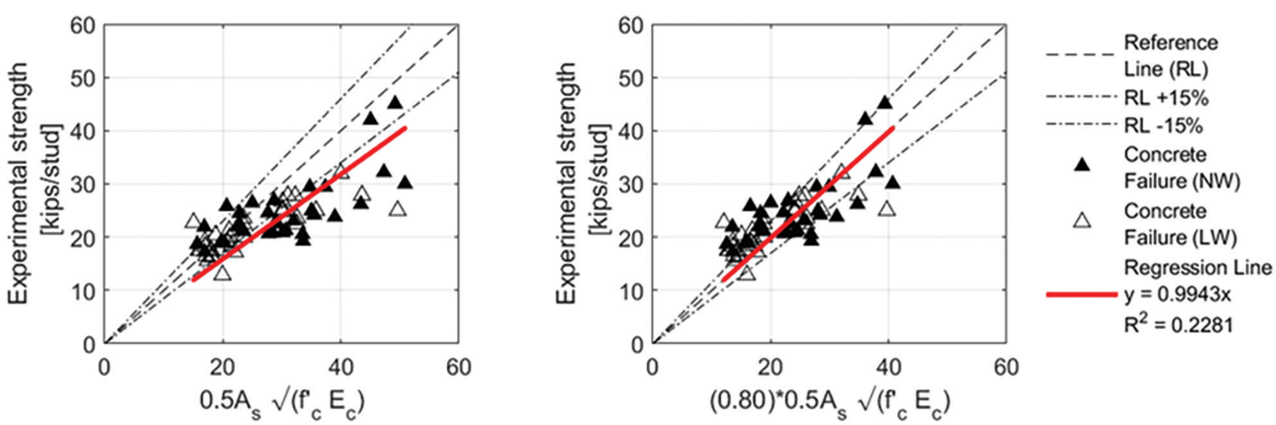
Table 6. Reference and Test Series Number—Cyclically Loaded					
Perpendicular Decking			Parallel Decking		
Reference	First Test Series Number	Last Test Series Number	Reference	First Test Series Number	Last Test Series Number
Hawkins and Mitchell (1984)	1	4	Hawkins and Mitchell (1984)	1	1
Briggs et al. (2022)	5	12	Bursi and Gramola (1999)	2	15
			Briggs et al. (2022)	15	21

Table 7. Cyclically Loaded Test-to-Predicted Ratio per Each Presented Strength Prediction Model							
	Perpendicular Decking			Parallel Decking			
	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}	Q_{E_C}/Q_{E_M}
Average	0.818	1.039	1.000	1.359	1.424	1.410	0.901
Max	1.021	1.311	1.512	1.806	1.806	1.806	1.037
Min	0.493	0.705	0.553	0.934	0.991	0.934	0.781
StDev	0.159	0.194	0.278	0.293	0.263	0.283	0.101
CoV	0.194	0.186	0.278	0.216	0.184	0.201	0.112

Solid Slabs

Details of the solid slab push-out test database are presented in the Methods section. From work by Pallarés and Hajjar (2010), a reduction factor of 0.65 was presented for solid slabs applied to A_sF_u. The 2022 AISC *Specification* adopted a 0.75 reduction factor for solid slabs, in the form of the R_p factor. However, both of these methods rely on an adjustment of the steel cap. The presented strength prediction models present an adjustment to the lower bound to account for concrete related failures in solid slabs.

Solid slab push-out tests with concrete failures exhibit different behavior and properties compared to comparable members with steel deck. Thus, a linear regression coefficient, R_r = 0.80, for the LB-regression adjusted AISC strength prediction model with solid slabs was developed utilizing push-out specimen from the solid slab database failing with concrete related failures, as shown in Figure 8.



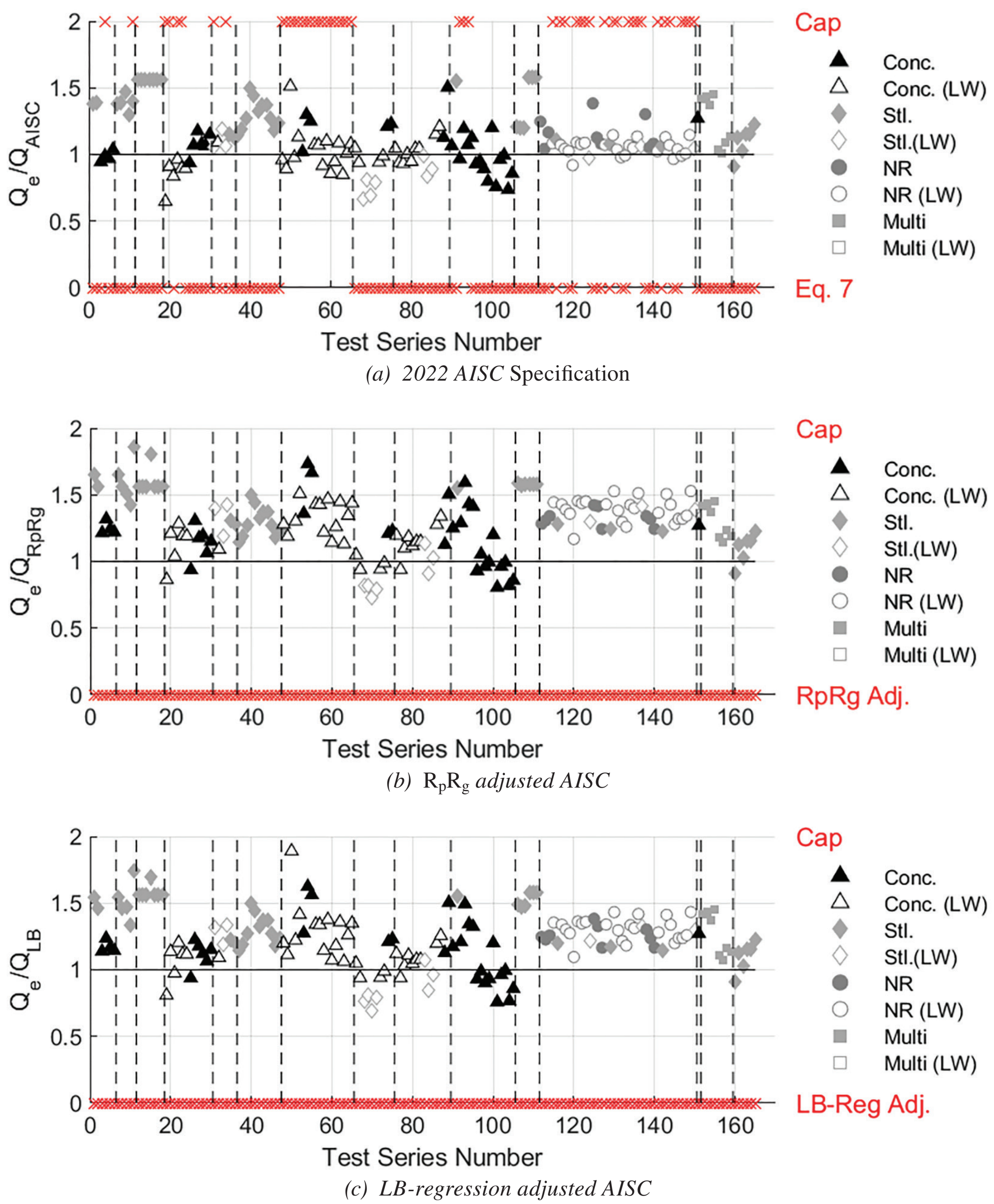
(a) *Without LB-regression coefficient*   (b) *With LB-regression coefficient*

Fig. 8. Linear regression analysis for solid slab specimen with concrete failure.

The R_pR_g adjusted and LB-regression adjusted models are analyzed using the experimental strengths of the solid slab database and compared with the existing 2022 AISC *Specification* strength prediction in Figure 9. Table 8 matches the test series number with its corresponding reference. A summary of the average, minimum, maximum, StDev, and CoV of the test-to-predicted ratios for each strength prediction model is shown in Table 9.

Lightweight vs. Normal Weight Concrete

Descriptive statistics of the test-to-predicted ratios, disaggregated by LW and NW concrete specimen, for push-out tests with a perpendicular deck and a parallel deck are shown in Tables 10 and 11, respectively. For a perpendicular deck, the LW concrete specimen (10 total specimens) generally failed with a more unconservative ratio compared



(a) 2022 AISC Specification

(b) R_pR_g *adjusted AISC*

(c) LB-regression adjusted AISC

Fig. 9. Solid slab test-to-predicted graphs.

Table 8. Reference and Test Series Number—Solid Slab		
Reference	**First Test Series Number**	**Last Test Series Number**
Viest (1956)	1	6
Shoup and Singleton (1963)	7	11
Chapman and Balakrishnan (1964)	12	18
Buttry (1965)	19	30
Chinn (1965)	31	36
Mainstone & Menzies (1967)	37	47
Steele (1967)	48	65
Dallam (1968)	66	75
Baldwin et al. (1965)	76	89
Hawkins (1971)	90	105
Menzies (1971)	106	111
Ollgaard et al. (1971)	112	150
Jayas and Hosain (1989)	151	151
An and Cederwall (1996)	152	159
Shim et al. (2004)	160	165

Table 9. Solid Slab Test-to-Predicted Ratio per Each Presented Strength Prediction Model			
	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}
Average	1.118	1.291	1.237
Max	1.575	2.016	1.890
Min	0.647	0.728	0.691
StDev	0.206	0.223	0.211
CoV	0.184	0.172	0.170

Table 10. Perpendicular Deck Test-to-Predicted Ratio Disaggregated by LW and NW Concrete						
	NW Concrete (230 Specimens)			LW Concrete (10 Specimens)		
	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}
Average	0.876	1.008	1.049	0.802	1.028	1.070
Max	1.513	1.639	1.892	1.090	1.454	1.677
Min	0.497	0.579	0.579	0.623	0.791	0.658
StDev	0.161	0.182	0.209	0.161	0.235	0.340
CoV	0.184	0.180	0.199	0.200	0.228	0.318

Table 11. Parallel Deck Test-to-Predicted Ratio Disaggregated by LW and NW Concrete						
	NW Concrete (24 Specimens)			LW Concrete (6 Specimens)		
	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}	Q_E/Q_{AISC}	Q_E/Q_{RpRg}	Q_E/Q_{LB}
Average	1.02	1.04	1.04	0.99	1.13	1.13
Max	1.39	1.39	1.39	1.29	1.43	1.43
Min	0.68	0.70	0.70	0.75	0.83	0.83
StDev	0.17	0.17	0.17	0.22	0.24	0.24
CoV	0.17	0.16	0.16	0.22	0.21	0.21

to the NW concrete specimen (230 total specimens). The parallel deck specimens exhibited a similar result for the 2022 AISC *Specification* prediction with a much smaller margin between LW and NW specimens. However, in general, more data is preferred to determine the effects of LW vs. NW concrete in push-out tests.

Composite Beam Test

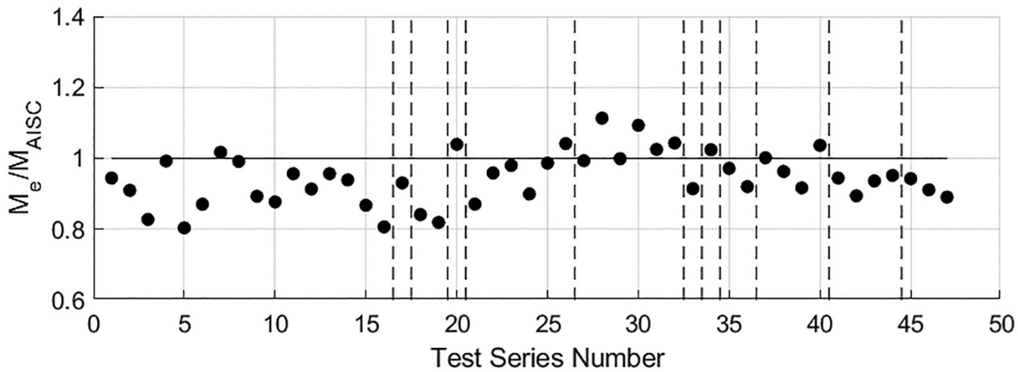
Two new strength prediction methods were developed in the Results and Discussion section from a database of push-out tests with steel deck and solid slabs. Full-scale beam tests can offer insight to steel headed stud anchor behavior in composite beams subject to flexure. This section will validate the proposed strength prediction models with experimental composite beams tests with perpendicular slabs from the literature. Partially composite beam tests were compiled from work done by Rambo-Roddenberry et al. (2002b, 2002a), which include tests summarized by Grant et al. (1977), Robinson (1988), Jayas and Hosain (1989), and others. All calculations utilized measured properties. The AISC predicted percent composite and experimental percent composite for each test is shown in Bond et al. (2022).

The maximum experimental moment, M_e, is compared to strengths calculated using the AISC flexural strength for composite beams, M_{AISC}, and the flexural strengths utilizing the proposed stud strengths, M_{RpRg} and M_{LB}, shown in Figure 10. Table 12 matches the test series number with its corresponding reference. A summary of the statistical parameters for the test-to-predicted ratios for each strength prediction model is shown in Table 13. These ratios demonstrate that the 2022 AISC *Specification* is slightly unconservative for predicting flexural strength and the proposed equations bring the average test-to-predicted ratio closer to 1.0 without increasing the CoV.

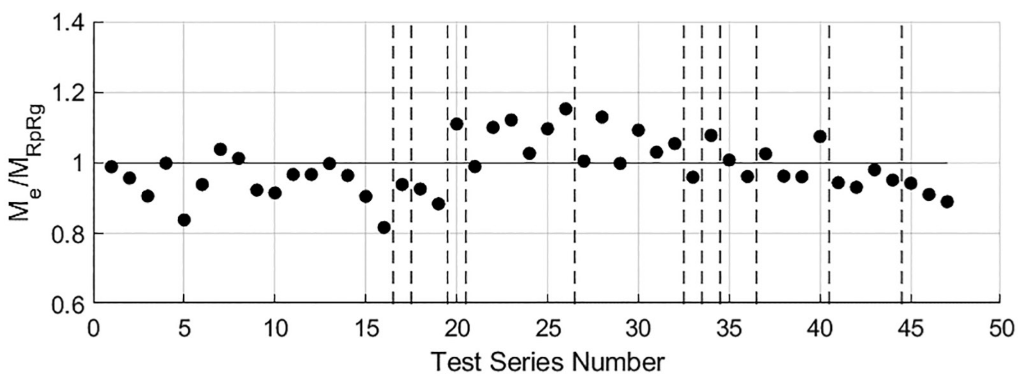
Future Work

Future work could explore a simplified approach to stud strength prediction based on failure modes. For example, this study shows that the current 2022 AISC *Specification* formula effectively addresses the SS failure mode. For the RP failure mode, existing prediction equations are accurate but complex, highlighting a need for simplification (Johnson and Yuan, 1997). Additional experimental data is required to better understand the RS failure, particularly regarding edge effects and detailing, such as pour stops. Finally, the CP failure mode is the primary focus in this work. A failure mode-based strength prediction model could estimate shear connection strength for each failure mode (e.g., Q_{CP}, Q_{ss}, Q_{DP}, Q_{RS}), with the minimum value determining the expected failure mode and design shear strength.

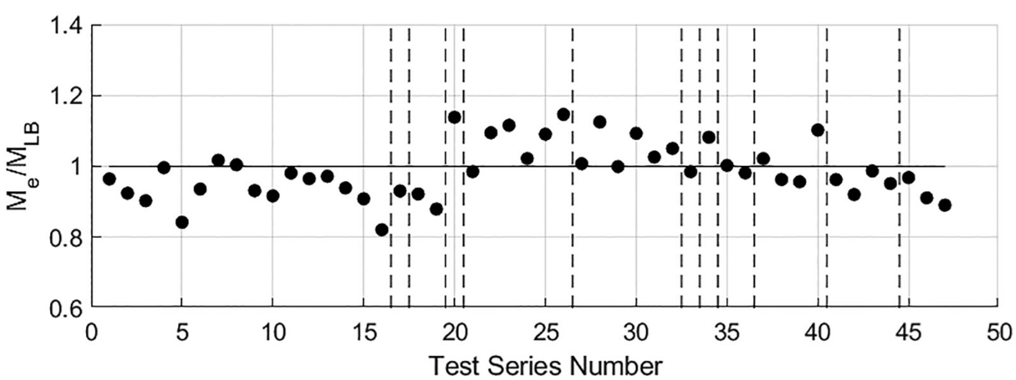
Variability in the test-to-predicted results stems from differences in traditional push-out test setups, material properties, and uneven resistance distribution among multiple studs. To address this, new push-out test setups have been introduced to better assess shear stud strength (Briggs et al., 2022; Sanden, 1996). Updating previous databases with



(a) 2022 AISC Specification



(b) R_pR_g *adjusted AISC*



(c) LB-regression adjusted AISC

Fig. 10. Composite beam test, test-to-predicted graphs.

Table 12. Reference and Test Series Number—Composite Beam Tests		
Reference	**First Test Series Number**	**Last Test Series Number**
Grant et al. (1977)	1	16
Robinson and Wallace (1971)	17	17
Fisher et al. (1967)	18	19
Seek et al. (1970)	20	20
Furlong and Henderson (1975)	21	26
Allan et al. (1976)	27	32
Jones (1975)	33	33
Lacap (1975)	34	34
Robinson (1988)	35	36
Jayas and Hosain (1989)	37	40
Gibbings et al. (1993)	41	44
Rambo-Roddenberry et al. (2002a)	45	47

Table 13. Test-to-Predicted Ratio Composite Beam Tests per Each Strength Prediction Model			
	M_E/M_{AISC}	M_E/M_{RpRg}	M_E/M_{LB}
Avg.	0.95	0.99	0.99
Max	1.11	1.15	1.15
Min	0.80	0.82	0.82
StDev	0.07	0.08	0.08
CoV	0.08	0.08	0.08

recent test data would help validate current methods and improve understanding of shear stud behavior.

It is recommended that future work include design strength formulas that address rib shear and rib punching failure. Additionally, steel headed stud anchors in perpendicular deck near the edge of slab may result in a rib shear failure mode and should be examined further with more tests and research (Hawkins and Mitchell, 1984). Specifically, the effect of pour stops and other unique detailing near the edge of slab should be considered where there is a large gap in the literature addressing these conditions.

CONCLUSION

In this work, failure modes in the shear strength prediction of steel-headed studs in concrete-filled steel composite deck and solid slabs is assessed with 468 push-out tests from the literature. The experimental stud strengths have been compared to the stud strength prediction models from Rambo-Roddenberry et al. (2002b, 2002a), CSA S16:19 (2019), Eurocode 4 (CEN, 2004), and the 2022 AISC *Specification*. Test-to-predicted plots of the push-out tests are disaggregated failure mode to demonstrate somewhat unconservative strength predictions for concrete-related failures.

This research highlights potential adjustments to the 2022 AISC *Specification* stud strength equation that will enable a more accurate assessment of strength while retaining the general form of the equation. Test-to-predicted ratios are presented for each test specimen for two new proposed strength prediction methods. The following conclusions are made from this research:

1. Failure modes for steel headed stud anchors in concrete filled steel composite deck can be described as stud shearing, concrete pull-out, rib punching, and rib shear, or a combination of these failure modes. The 2022 AISC *Specification* formula for predicting stud strength is adequate for steel stud failures but produces somewhat unconservative estimates for the concrete pull-out and rib punching failure modes.

2. The stud strength prediction equations from work by Rambo-Roddenberry et al. (2002b) was found to have an acceptable correlation for stud strength. However, the 2022 AISC *Specification* and earlier editions of the *Specification* adopted moderately increased R_p and R_g factors, leading to the somewhat unconservative strength prediction for concrete related failures. For instance, the average test-to-predicted stud strength ratio for the AISC *Specification* is 0.873, compared to 0.978 for the equations by Rambo-Roddenberry et al.

3. To improve the prediction of the concrete pull-out failure mode, new equations are presented for the shear strength prediction of steel headed stud anchors with steel deck. The new models increase the accuracy for the test-to-predicted ratios for a perpendicular deck specimen from 0.87 for the 2022 AISC *Specification* equation to 1.01 for the R_pR_g adjusted strength prediction and 1.05 for the LB regression strength prediction model. Similarly, the models slightly increase the accuracy for the test-to-predicted ratios of flexural strengths for deck perpendicular composite beam tests from 0.95 for the 2022 AISC *Specification* to 0.99 for both the R_pR_g adjusted strength prediction and for the LB regression strength prediction. The authors suggest adopting these models for design applications involving perpendicular decks, as they provide more accurate predictions of stud strength, particularly for concrete-related failure modes.

4. The presented equations (R_pR_g adjusted and LB-regression adjusted strength predictions) were also applied to concrete failure modes for parallel deck and solid slab configurations. Although more data is preferred for parallel deck push-out tests, results here show parallel deck and solid slab configurations to be sufficiently represented by the existing 2022 AISC *Specification* stud strength equation.

5. For the data available, the experimental cyclic strength and monotonic strength of corresponding tests indicates that if the monotonic strength prediction is adjusted, the existing 25% reduction for steel headed stud anchors subjected to cyclic loads is likely to be adequate. In addition, more data is desirable for cyclically loaded concrete-filled steel composite deck with deck perpendicular.

In addition, adapting the proposed approach for calculating the nominal design strength of headed stud steel anchors is primarily justified by its improved ability to predict stud failure modes and its more conservative prediction of the strength for configurations with perpendicular steel decking.

SYMBOLS

A_p Concrete pull-out area defined in CSA S16:19, in.^{2} (mm^2)

A_s Area of the steel headed stud anchor shank, in.^{2} (mm^2)

C_d Deck height coefficient for CSA S16:19 strength prediction method

E_c Young's modulus of elasticity for concrete, ksi (MPa)

F_u Tensile strength of steel headed stud anchor, ksi (MPa)

H Steel headed stud anchor height, in. (mm)

Q_{AISC} 2022 AISC *Specification* predicted strength of a single steel headed stud anchor, kips (kN)

Q_{ROD} Rambo-Roddenberry predicted strength of a single steel headed stud anchor, kips (kN)

Q_{CSA} CSA S16:19 predicted strength of a single steel headed stud anchor, kips (kN)

Q_{RpRg} R_pR_g predicted strength of a single steel headed stud anchor, kips (kN)

Q_{LB} Lower-bound predicted strength of a single steel headed stud anchor, kips (kN)

R_{d_rod} Deck gauge factor for Rambo-Roddenberry et al. strength prediction model

R_{g_rod} Grouping factor for Rambo-Roddenberry et al. strength prediction model

R_{p_rod} Placement factor for Rambo-Roddenberry et al. strength prediction model

R_g Grouping factor for 2022 AISC *Specification* strength prediction model

R_p Placement factor for 2022 AISC *Specification* strength prediction model

R_r LB-regression coefficient

d Diameter of steel headed stud anchor shank, in. (mm)

e_{mid} Distance from center of the steel headed stud anchor to the steel deck web, measured at mid-height of the deck rib, in. (mm)

f'_c Concrete cylinder compressive strength, ksi (MPa)

h_r Height of deck rib, in. (mm)

k_t CSA reduction factor accounting for deck orientation

n_r Number of studs per rib

t Thickness of the base metal, in. (mm)

w_r Average rib width, in. (mm)

ϕ_v Resistance factor for shear strength

γ_v CSA partial safety factor

ρ Concrete density, kip/ft³ (kg/m³)

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