THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Technical Memorandum

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Subject:	P11 TxDOT Project 0-7090: Evaluate the Development of High Strength Reinforcing Steel in Texas
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1. Introduction

This document conveys design recommendations for applying high-strength reinforcing bars in bridge substructure components, specifically deep beams and drilled shaft footings. These recommendations are based on the research findings from Task 3: Example Calculations & Designs, Task 6: Bar Development & Lap Splice, Task 7: Substructures, and Task 11: Numerical Structural Performance Assessment of Project 0-7090, with detailed results documented in the previously submitted previous technical memorandums. The focus of this document is on practical considerations for design application. It begins with a summary of the current design recommendations, followed by proposed design recommendations derived from the research findings. Finally, it provides comparative examples of design drawings.

1.1. Overview

1.1.1. Current Recommendations

The recommendations specified in current design provisions, such as ACI318-19 (2019) and AASHTO LRFD (2020), for designing tension lap splice as listed in Table 1-1. Although both codes allow the use of high-strength steel with a minimum yield strength of up to 100 ksi and bar sizes up to No.11, there is no supporting test data.

Table 1-1. Comparison of provisions of design for lap slice in tension

<table>
<tr><th>Design code</th><th>Tension development length</th><th>Lap splice in tension</th></tr>
<tr><td>AASHTO LRFD 2020</td><td>1) f_y: up to 100 ksi
2) d_b: up to No.11 bar
3) f_c': up to 15 ksi for normal
up to 10 ksi for lightweight
4) Equation
$$l_d = l_{db}\left(\frac{\lambda_{rl}\lambda_{cf}\lambda_{rc}\lambda_{er}}{\lambda}\right)$$
$$l_{db} = 2.4 d_b \frac{f_y}{\sqrt{f_c'}}$$
$$\lambda_{rc} = \frac{d_b}{c_b + k_{tr}},\ k_{tr} = 40\frac{A_{tr}}{sn}$$
shall not be less than 12 in.
where,
l_{db}: basic development length (in.)
λ_{rl}: reinforcement location factor
λ_{cf}: coating factor
λ_{rc}: reinforcement confinement factor
λ_{er}: excess reinforcement factor
λ : concrete density modification factor</td><td>1) f_y: up to 100 ksi
2) d_b: up to No.11 bar
3) f_c': up to 15 ksi for normal
up to 10 ksi for lightweight
4) Class A splice: 1.0 l_d
Class B splice: 1.3 l_d
shall not be less than 12 in.

5) For splices whose specified yield strength is larger than 75 ksi, transverse reinforcement satisfying the requirements shall be provided over the required lap splice length.</td></tr>
</table>

Design code	Tension development length	Lap splice in tension
	f_y: specified minimum yield strength of reinforcement (ksi) d_b: nominal diameter of reinforcing bar or wire (in.) f_c': compressive strength of concrete for use in design (ksi) c_b: the smaller of distance from center of bar or wire being developed to the nearest concrete surface and one-half the center-to-center spacing of the bars or wires being developed (in.) k_{tr}: transverse reinforcement index A_{tr} : total cross-sectional area of all transverse reinforcement that is within the spacing s and that crosses the potential plane of splitting through the reinforcement being developed (in.^{2}) s: maximum center-to-center spacing of transverse reinforcement within l_d (in.) n: number of bars or wires developed along plane of splitting	
ACI 318-19	1) f_y:up to 100 ksi 2) d_b : Not limited, reinforcement size is considered by using ψ_s 3) $\sqrt{f_c'}$: up to 100 psi 4) Equation $$l_d = \frac{3}{40}\frac{f_y}{\lambda\sqrt{f_c'}}\frac{\psi_t\psi_e\psi_s\psi_g}{\left(\frac{c_b + k_{tr}}{d_b}\right)}d_b$$ shall not be less than 12 in. where, l_d : development length in tension of deformed bar (in.) ψ_t: factor used to modify development length for casting location in tension ψ_e factor used to modify development length based on reinforcement coating ψ_s: factor used to modify development length based on reinforcement size ψ_g: factor used to modify development length based on grade of reinforcement d_b : modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normal-weight concrete of the same compressive strength	1) f_y: up to 100 ksi 2) d_b: up to No.11 bar 3) $\sqrt{f_c'}$: up to 100 psi 4) Class A splice: 1.0 l_d Class B splice: 1.3 l_d shall not be less than 12 in. Class A or B is determined considering $A_{s,provided}/A_{s,required}$ over length of splice and maximum percentage of A_s spliced within required lap length.

The design recommendation for reinforcement details in D-regions (disturbed or discontinuity) are summarized in Table 1-2. The required amount of reinforcement provided for ties in a strut-and-tie model is determined by the yield strength of the reinforcement. This implies that using high-strength steel can reduce the quantity of reinforcement while still maintaining a comparable load-carrying capacity of the strut-and-tie model. Additionally, ACI 318-19 and AASHTO LRFD (2020) recommend providing distributed reinforcement, referred to as crack control reinforcement, to redistribute cracks caused by struts of a strut-and-tie model.

Table 1-2. Comparison of provisions of design for D-regions

Design code	Strength of tie	Crack control reinforcement
AASHTO LRFD (2020)	$P_n = f_y A_{st} + A_{ps}[f_{pe} + f_y]$ where, f_y : yield strength of nonprestressed longitudinal reinforcement (ksi) A_{st} : total area of longitudinal nonprestressed reinforcment (in.^{2}) A_{ps}: area of prestressing steel (in.^{2}) f_{pe} : effective stress in prestressing steel after losses (ksi)	$\frac{A_v}{b_w s_v} \geq 0.003 \quad \frac{A_h}{b_w s_h} \geq 0.003$ where, A_v : total area of vertical crack control reinforcement within spacing s_v (in.^{2}) A_h: total area of horizontal crack control reinforcement within spacing s_h (in.^{2}) b_w: width of member's web (in.) s_v, s_h: spacing of vertical and horizontal crack control reinforcement, respectively (in.) *The spacing of the bars in these grids shall not exceed the smaller of d/4 and 12.0 in.
ACI318-19	Strut without longitudinal reinforcement $F_{ns} = f_{ce} A_{cs}$ Strut with longitudinal reinforcement $F_{ns} = f_{ce} A_{cs} + A'_s f'_s$ where, F_{ns}: nominal strength of a strut (lb) f_{ce}: effective compressive strength of the concrete in a strut or a nodal zone (psi) A_{cs}: cross-sectional area at one end of a strut in a strut-and-tie model, taken perpendicular axis the strut (in.^{2}) A'_s : area of compression reinforcement (in.^{2}) f'_s : compressive stress in reinforcement under factored loads, excluding prestressed reinforcement (psi)	Minimum distributed reinforcement ratio shall be provided as follows: (1) Not restrained - Orthogonal grid: 0.0025 in each direction - Reinforcement in one direction crossing strut at angle $\alpha_1 = \frac{0.0025}{sin^2 \alpha_1}$ (2) Restrained - Distributed reinforcement not required * Distributed reinforcement shall satisfy (a) Spacing shall not exceed 12 in., (b) Angle α_1 shall not be less than 40 degrees.

However, both ACI 318-19 (2019) and AASHTO LRFD (2020) impose limitations on the strength of the reinforcing bars in D-regions, as shown in Table 1-3.

Table 1-3. Design limits of rebar strength in D-regions

Design code	Rebar strength limit
AASHTO LRFD (2020)	• Up to 75 ksi

Design code	Rebar strength limit
ACI 318-19	• For longitudinal tie, up to 80 ksi, other is up to 60 ksi.

The internal force flow of drilled shaft footings forms three-dimensional strut-and-tie models. Hence, the crack control reinforcement requirements specified in current provisions are ambiguous when applied to this three-dimensional environment. However, the research findings by Yi et al. (2023) suggest that the side face reinforcement, typically provided for shrinkage and temperature control, can serve a similar function to crack control reinforcement. The amount of reinforcement can be determined using a modified equation derived from the minimum shrinkage and temperature reinforcement requirement specified in AASHTO LRFD (2020) (Article 5.10.6). In accordance with Yi et al. (2023), the side face reinforcement ratio (ρ_s) should be at least 0.18% to enhance the internal strut capacity of drilled shaft footings by redistributing the cracks on the side surfaces adjacent to the interior strut. If this reinforcement ratio is not provided, a minimum nodal efficiency factor ($\nu = 0.45$) should be applied when performing nodal capacity checks to account for the strength degradation due to the premature failure of the strut.

$$\frac{A_s}{s} \geq \rho_s \frac{A_g}{Perimeter} \frac{60}{f_y} \tag{2.1}$$

where,

ρ_s= side face reinforcement ratio in each direction (longitudinal or transverse)

A_g= gross area of the section where the face reinforcement is to be provided perpendicularly [in.^{2}]

A_s= area of side face reinforcement in each direction [in.^{2}]

$Perimeter$= perimeter of the section where the face reinforcement is to be provided perpendicularly [in.]

s = spacing of side face reinforcement in each direction [in.]

f_y= specified yield strength of reinforcement [ksi]

The side face reinforcement also imposes the same strength limitation as that of the AASHTO LRFD (2020), 75 ksi.

Considering the current design recommendations, it is evident that using high-strength rebars can reduce the quantity of reinforcement while maintaining the same load-carrying capacity as conventional reinforcement (Grade 60). However, current provisions do not allow the use of Grade 100 reinforcement for designing reinforcement details in D-regions, which limits the potential to reduce the amount of reinforcement.

1.1.2. Proposed Design Recommendations

The research team conducted large-scale tests and numerical analyses on lap spliced beams, deep beams and drilled shaft footings using high-strength steel (Grade 100). The test results revealed that the current recommendation for determining tension lap splice length is valid for No.11 bar with high-strength steel (Grade 100).

For deep beams, it was found that the deep beam specimens designed with Grade 100 reinforcement for longitudinal ties conservatively achieved shear capacities as estimated using the strut-and-tie method outlined in the current AASHTO LRFD (2020). This indicates that reducing the reinforcing bar quantity for ties in proportion to the reinforcing bar strength can also be applied to Grade 100 reinforcement. Rebar strain measurements during testing confirmed that the deep beam specimens designed with Grade 100 and conventional Grade 60 reinforcement transferred comparable tie forces. Furthermore, the tests and analyses demonstrated that using Grade 100 bars as a crack control reinforcement ratio of 0.3% ratio, which is the minimum ratio suggested by AASHTO LRFD (2020), is adequate to limit maximum diagonal crack widths to 0.016 inches or less under service loads. Therefore, it is recommended that the strength limit for reinforcement details in deep beams designed using the strut-and-tie method be increased to 100 ksi.

For drilled shaft footings, the bottom mat reinforcing bar strain measurements obtained from tests and numerical analyses also showed that Grade 100 bottom mat reinforcement, with a reduced amount in proportion to the yield strength ratio, can carry a comparable tie force to that designed using Grade 60 reinforcing bars. This finding aligns with the results from the deep beam specimens. Therefore, the recommendation to increase the strength limit up to 100 ksi can be applied for designing the bottom mat reinforcement in drilled shaft footings.

However, reducing the amount of side face reinforcement in relation to the yield strength of Grade 100 steel was found ineffective in redistributing cracks on the side surfaces of the footing, which resulted in a reduction in the capacity of the interior strut. Therefore, a minimum side face reinforcement ratio of 0.18% should be maintained in drilled shaft footings, regardless of the rebar grade, to enhance the internal strut capacity by redistributing the side-surface cracks. If this requirement is not fulfilled, the reduced internal strut capacity must be accounted for by applying a minimum nodal efficiency factor (ν) of 0.45.

1.2. Comparison of Design Drawings: Current design with normal-strength steel and proposed design with high-strength steel

The example design drawings of the test specimens are presented to offer comparative examples between the conventional design using normal-strength rebar and the design using high-strength rebar, incorporating the proposed design recommendations. For deep beams, bent cap of IH-610 bus lane provided by TxDOT was used as an example, and drilled shaft footing utilized in design example of the previous research project (0-6953).

The reinforcement can be reduced as summarized in Table 1-4 and Table 1-5.

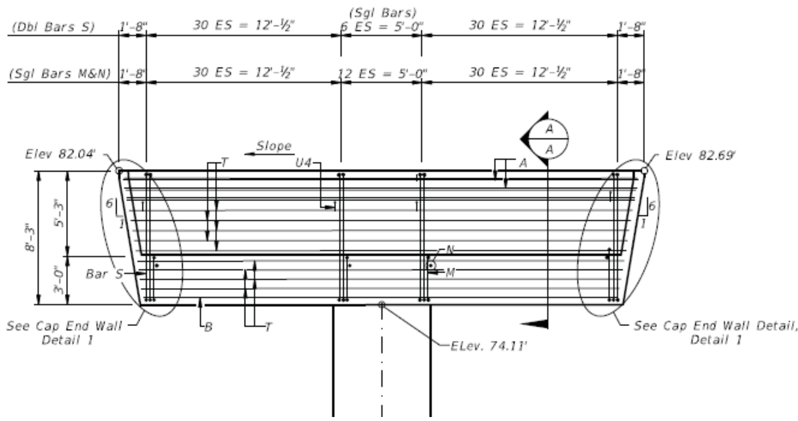
Table 1-4. Rebar quantity of bent cap of IH610 buslane

Type	Size	Grade	No. of rebar	Weight (lb)	Compare
Longitudinal	#11	60	55	9,273	-
		100	34	5,723	38%↓
Skin	#7	60, 100	12	719	Same
Vertical	#6	60	129	4,779	-
		100	81	3,001	37%↓
Ledge	#7	60	73	3,954	-
		100	49	2,654	33%↓
Corbel	#7	60, 100	16	1,006	Same
	#11	60, 100	10	1,558	Same
Total		60	-	21,325	-
		100	-	14,661	31%↓

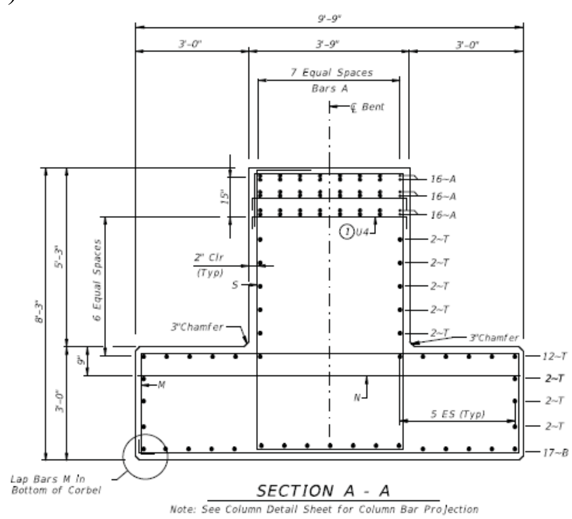
Table 1-5. Rebar quantity of drilled shaft footing

Type	Size	Grade	No. of rebar	Weight (lb)	Compare
Bottom mat	#11	60	76	9,334	-
		100	48	5,895	37%↓
Total		60	-		-
		100	-		37%↓

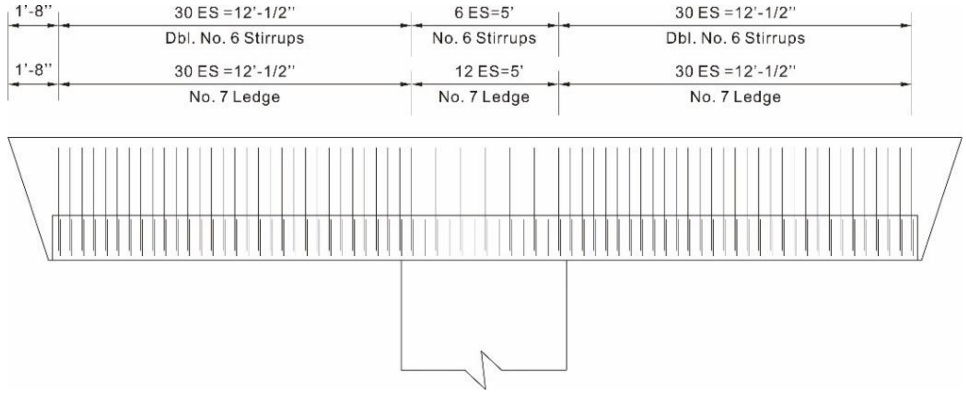
1.2.1. Deep Beam



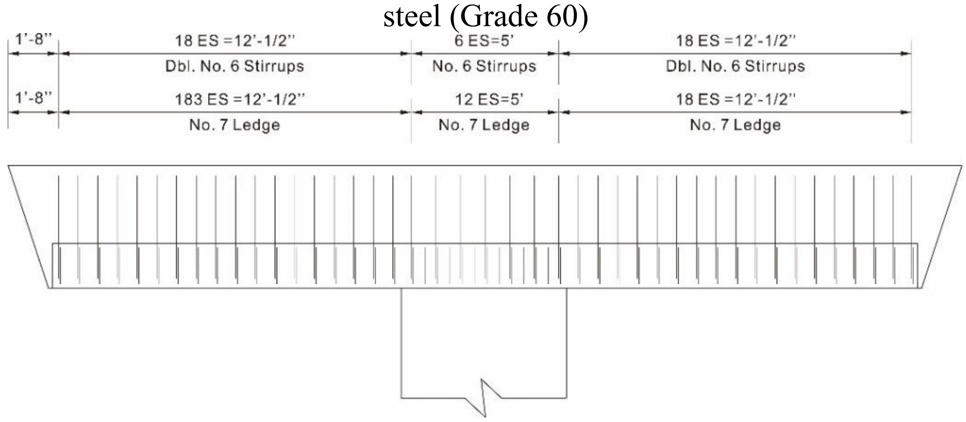
(a) Details of Bent 5 of IH610 buslane: Elevation



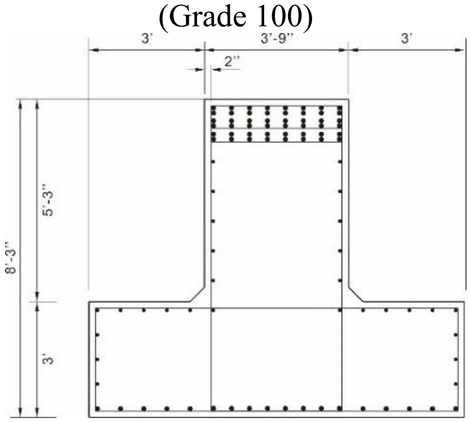
(b) Details of Bent 5 of IH610 buslane: Cross-section



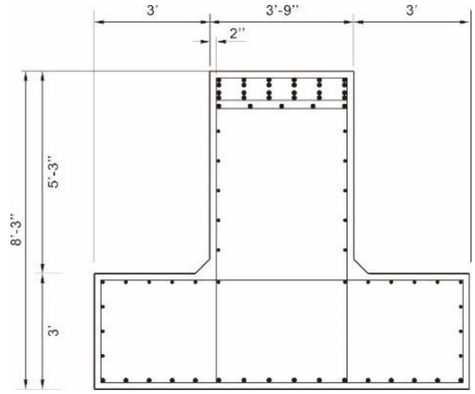
(c) Rebar layout of Bent 5 of IH 610 buslane by STM with normal-strength steel (Grade 60)



(d) Rebar layout of Bent 5 of IH 610 buslane by STM with high-strength steel (Grade 100)



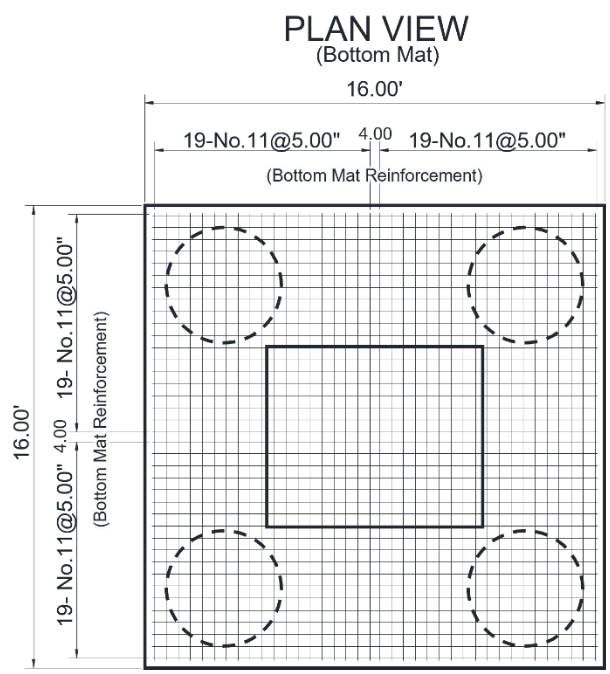
(e) Cross-section of Bent 5 of IH 610 buslane by STM with normal-strength steel (Grade 60)



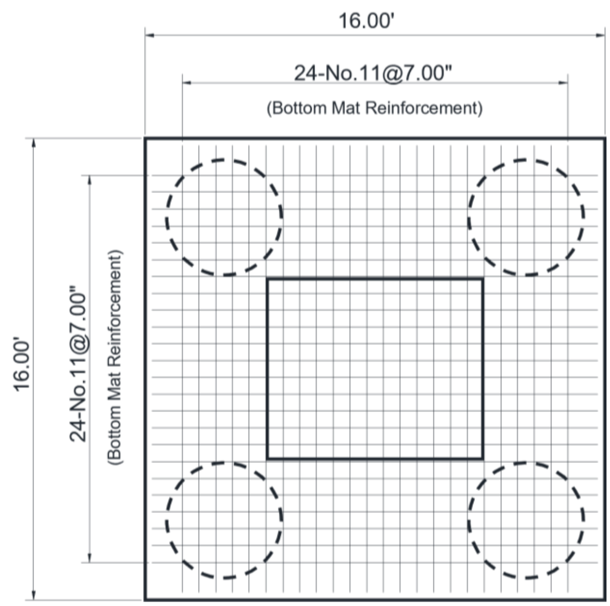
(f) Cross-section of Bent 5 of IH 610 buslane by STM with high-strength steel (Grade 100)

Figure 1-1. Example design drawing of deep beams (Bent of IH610 buslane)

1.2.2. Drilled Shaft Footing



(a) Grade 60 bars



(b) Grade 100 bars

Figure 1-2. Example design drawing of drilled shaft footing

Reference

AASHTO LRFD Bridge Design Specifications, 9th edition, American Association of State Highway and Transportation Officials, Washington, D.C, 2020.

ACI Committee 318, ACI 318-19/ACI 318R-19 Building Code Requirements for Reinforced Concrete and Commentary, American Concrete Institute, Farmington Hills, MI, 2019.

Yi Y, Kim H., Boehm RA., Webb ZD., Choi J., Wang HC., Murcia-Delso J., Hrynyk TD., and Bayrak O., 3D Strut-and-Tie Modeling for Design of Drilled Shaft Footings, Report No. FHWA/TX-21/0-6953-1, Center for Transportation Research, University of Texas at Austin, Austin, Texas, 2022.