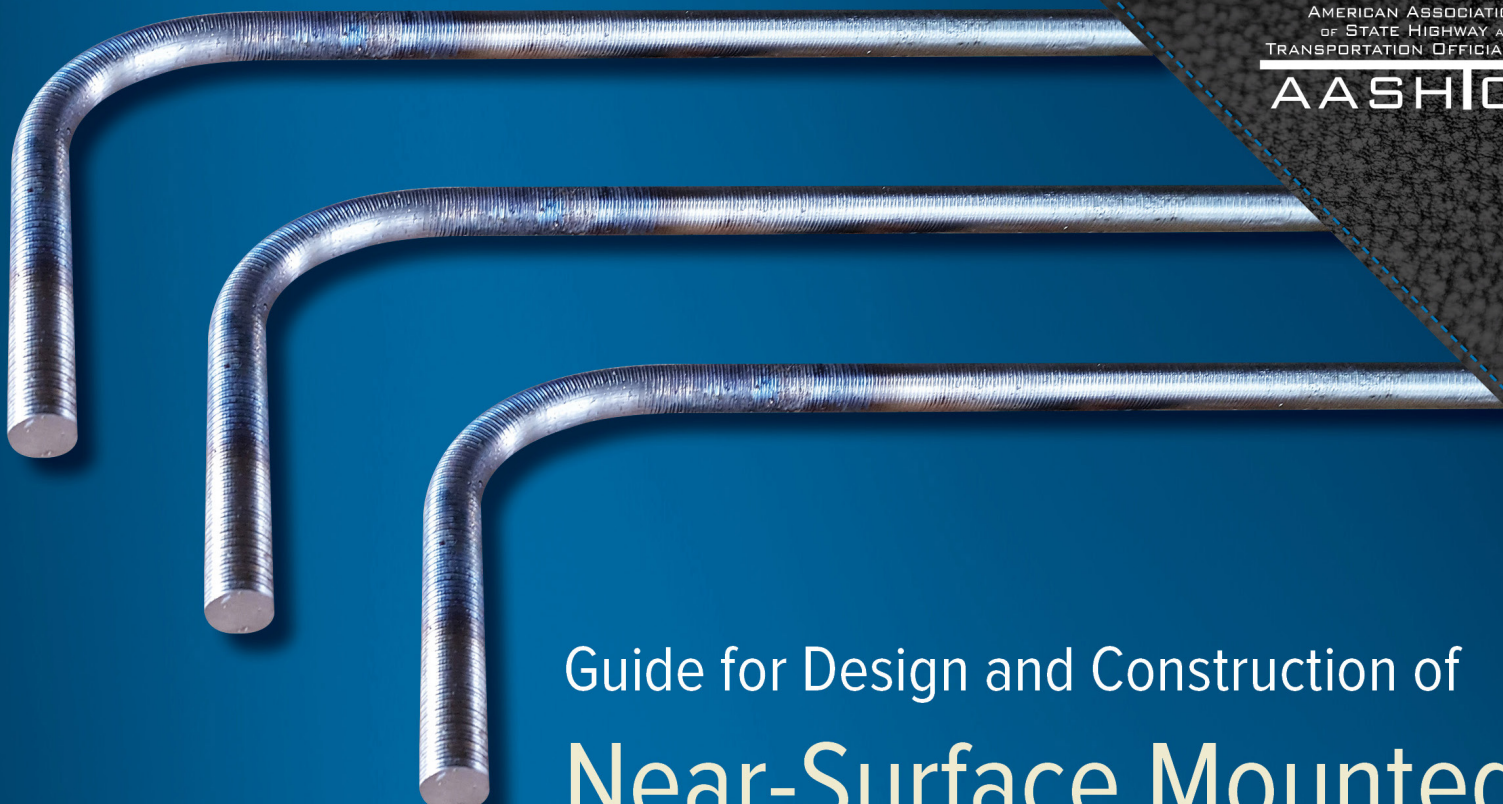


Three curved titanium alloy bars are shown against a blue background. The bars are arranged in a descending staircase pattern from top-left to bottom-right. They have a metallic, slightly textured appearance.

Guide for Design and Construction of Near-Surface Mounted Titanium Alloy Bars for Strengthening Concrete Structures



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**Near-Surface Mounted
Titanium Alloy Bars**
for Strengthening Concrete Structures



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Front Cover Photos: *Top*: Close-up look at titanium bar with end hook before installation, courtesy Oregon DOT. *Bottom*: I-84 Mosier Bridge during construction, Mosier, OR, courtesy Oregon DOT.

Back Cover Photos: *Top*: Caveman Bridge, Grants Pass, OR, courtesy Oregon DOT. *Bottom first left*: I-84 Mosier Bridge after construction, Mosier, OR, courtesy Oregon DOT. *Second and third left*: Mosier Bridge girder specimens, courtesy of Oregon State University. *Right*: McKercher Bridge, Brownsville, OR, courtesy Oregon DOT.

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NOTATION AND SYMBOLS

a = height of equivalent rectangular stress block in flexural compression zone (in.)
 A = out-to-out dimension of TiAB hook tail length (in.)
 A_{ps} = cross-sectional area of prestressing steel on the flexural tension side of the member where applicable (in.²)
 A_s = area of flexural tension steel (in.²)
 A_{Ti} = area of flexural tension TiAB (in.²)
 $\bar{A}_{Ti}$ = average area of a sample of TiABs used to establish nominal area (in.²)
 A_v = area of transverse steel (in.²)
 A_{vTi} = area of transverse TiABs (in.²)
 b_f = effective width of the compression block (in.)
 b_v = effective width of the web (in.)
 c = neutral axis location measured relative to the extreme compression fiber (in.)
 d_c = distance from the extreme tension fiber to the centroid of the steel reinforcing bars in the extreme tension layer (in.)
 d_e = effective depth from extreme compression fiber to the centroid of the tensile force in the tensile reinforcement (in.)
 d_p = distance from extreme compression fiber to the centroid of the flexural prestressing tendons (in.)
 d_s = distance from the extreme compression fiber to the centroid of the flexural steel (in.)
 d_{Ti} = distance from the extreme compression fiber to the centroid of the flexural TiABs (in.)
 d_v = effective shear depth taken as the distance between tension and compression resultants in cross section that produce internal moment at strength (in.)
 D = pin diameter used to produce 90-degree hook at ends of TiABs (in.)
 DC = load effect from dead weight of components (kip, kip-in.)
 DF_M = live-load distribution factor for moment
 D_{Ti} = diameter of TiAB (in.)
 DW = load effect from dead weight of wearing surface (kip, kip-in.)
 E_p = modulus of elasticity of prestressing steel (ksi)
 E_s = Young's modulus of steel taken as 29,000 ksi
 E_{Ti} = Young's modulus for TiABs taken as 15,500 ksi
 f'_c = concrete compressive strength (ksi)
 f_{min} = algebraic minimum live-load stress in the reinforcing steel from the Fatigue I load combined with the unfactored permanent loads, where positive is tension and negative is compression (ksi)
 f_{po} = parameter taken as the modulus of elasticity of prestressing steel multiplied by the locked-in difference in strain between the prestressing steel and the surrounding concrete (ksi)
 f_{ps} = average stress in prestressing steel at the time for which the nominal resistance of member is required (ksi)
 f_{ss} = maximum permissible stress in the extreme layer of tension reinforcing steel at service level (ksi)
 f_{Ti} = elastic stress in the TiAB from flexure (ksi)
 f_y = minimum specified yield stress of steel (ksi)
 f_{yTi} = nominal design yield stress of TiABs modified by the environmental exposure factor (ksi)
 f_{yTi}^* = minimum specified yield stress for TiAB (ksi)
 h = overall height of the element (in.)
 l_{dTi} = development length of TiAB (in.)
 LL = live-load effect from truck, tandem, or lane loads, or some combination of those load models (kip, kip-in.)
 M_n = nominal moment capacity of section (kip-in.)
 M_u = factored moment demand in section (kip-in.)
 M_{ui} = factored moment in a vertical section when the controlling axle load is located $d_v \cot \theta$ away at the tip of the projected diagonal crack (kip-in.)

n_s = number of steel reinforcing bars at the cross section
 n_{Ti} = number of titanium alloy bars at the cross section
 s = spacing of transverse reinforcing steel for shear (in.)
 s_{maxTi} = maximum permissible spacing of transverse TiABs for shear (in.)
 s_s = center-to-center spacing of the flexural reinforcing steel in the extreme tension layer (in.)
 s_{Ti} = spacing of transverse TiABs for shear (in.)
 T = net tension resultant in cross section from flexural steel and TiABs (kips)
 T_s = tension resultant in cross section from flexural steel (kips)
 T_{Ti} = tension resultant in cross section from TiABs (kips)
 TiAB = titanium alloy bar with 6 percent aluminum and 4 percent vanadium alloying elements
 V_c = nominal concrete contribution to shear resistance (kips)
 V_n = nominal shear resistance of the cross section (kips)
 V_p = component of prestressing force in the direction of the shear force; positive if resisting the applied shear (kips)
 V_s = nominal transverse steel contribution to shear resistance (kips)
 V_{Ti} = nominal TiAB contribution to shear resistance (kips)
 V_u = factored shear demand in section (kips)
 V_{ui} = factored shear that occurs coincidentally with M_{ui} in a vertical section when the controlling axle load is located at the tip of a projected diagonal crack (kips)
 w_{DC} = distributed weight of components per girder (kip/in.)
 w_{DW} = distributed weight of wearing surface per girder (kip/in.)
 w_{lane} = distributed lane load (kip/in.)
 y = location in cross section measured relative to the extreme compression fiber (in.)
 α_E = environmental sensitivity factor for bonding material
 β = concrete shear strength efficiency factor
 β_1 = factor that relates the height of the idealized rectangular stress block to the neutral axis depth (in.)
 $\beta_1 c$ = height of the equivalent rectangular stress block (in.) computed for a general section containing flexural steel and TiAB
 γ_e = exposure factor for serviceability check of flexural steel (1.0 for typical bridge elements and 0.75 for bridge members exposed to chlorides or for aesthetic considerations)
 γ_{DC} = load factor for weight of components
 γ_{DW} = load factor for weight of wearing surface
 γ_{LL} = load factor for live load
 Δf_{Ti} = change in the TiAB stress at service level along the development length (ksi)
 $(\Delta F)_{TH}$ = permissible fatigue stress range (ksi)
 ϵ_{cu} = useable concrete strain in extreme compression fiber at ultimate taken as 0.003 in./in.
 ϵ_s = strain in the flexural steel (in./in.)
 ϵ_{sDL} = strain in the flexural steel from permanent loads (in./in.)
 ϵ_{sLL} = strain in the flexural steel from live loads (in./in.)
 ϵ_t = strain in the extreme layer of flexural tension steel at nominal resistance (in./in.)
 ϵ_{Ti} = strain in TiAB from flexure (in./in.)
 ϵ_{yTi} = TiAB yield strain (in./in.)
 θ = diagonal crack angle for shear design (degrees)
 $\bar{\mu}_{Ti}$ = average bond stress in the TiABs at service levels limited to 0.5 ksi
 $\bar{\mu}_u$ = ultimate average bond strength of TiAB taken as 1 ksi
 σ_{Ti} = standard deviation of a population of TiABs used to establish the design area (in.²)
 ϕ_v = resistance factor for shear
 ϕ_b = resistance factor for flexure
 ϕR_n = design strength of existing structure without TiABs

PART 1: GENERAL

CHAPTER 1—INTRODUCTION AND SCOPE

1.1 SCOPE

This guide provides design and construction recommendations for strengthening existing reinforced concrete (RC) structures with titanium alloy bars with 6 percent aluminum and 4 percent vanadium alloying elements (TiABs) using the near-surface mounted (NSM) construction method. The overall approach and organization of this guide are based on those presented in ACI 440.2R (ACI, 2017). Recommendations are provided for shear and flexural strengthening. The design approach is based on and adapted from the *AASHTO LRFD Bridge Design Specifications* (2017), hereafter referred to as “AASHTO LRFD Design.” The recommendations are supported by experimental and analytical research as well as field experiences that have demonstrated the application of TiABs for strengthening full-scale specimens typical of bridge girders. The available experimental evidence includes the influences of combined high-cycle fatigue and environmental durability on the structural performance of NSM-TiAB-strengthened girders.

TiABs are not sensitive to environmental deterioration such as corrosion. Their use near the concrete surface will not be adversely affected by environmental degradation. Long-term durability of applications with TiABs will be controlled by the concrete substrate and bonding materials.

This guide does not address seismic strengthening applications.

1.2 APPLICATION AND LIMITATIONS

Many existing RC structures need strengthening due to inadequacies from the original design or construction, changes in usage, deterioration, damage, or other causes. Designers have many methods and materials available to strengthen RC structures. The most common modern approach is the application of fiber-reinforced polymers (FRPs). Design and construction approaches using FRPs have advanced significantly over the past two decades as documented in ACI 440.2R (ACI, 2017), and these approaches lay a foundation for application of TiABs that serve the same functionality as FRPs. TiABs offer the added benefit of ductility and inherent mechanical anchorage at terminations.

This guide applies only to the application of NSM-TiABs for strengthening existing RC structures for flexure and shear. The methods require the use of standard 90-degree hooks at both ends of the bars to provide anchorage. The methods are not applicable to straight-bar applications without hooks at the ends. The methods include interactions of flexure on shear strength. The methods are applicable to concrete substrates that are able to effectively transmit bond stresses along the length of the bars and that can anchor the hooks. The minimum required concrete compressive strength is 3 ksi.

The bond of TiABs along the NSM length provides crack control and limits deflections. At ultimate strength, significant cracking of the concrete, distress around the bonded regions, and debonding of the TiABs are anticipated.

These methods are applicable to design with TiABs when the load effects are established using conventional elastic structural analysis with the load distribution factors prescribed in *AASHTO LRFD Design* (2017). Use of this guide combined with advanced methods of structural analyses requires additional care.

CHAPTER 2—BACKGROUND

Research using TiABs for strengthening RC structures was first reported in 2013 (Higgins, 2013). However, a large body of knowledge has been developed over the past quarter century using NSM-FRP and NSM-metallics. Relevant literature for NSM-FRP is reported in ACI 440.2R (ACI, 2017). Much of the bond behavior and models for NSM-FRP are relevant to NSM-TiAB applications.

Research on the development and application of NSM-TiABs for strengthening RC structures has been reported by Higgins (2013, 2016); Higgins, Amneus, and Barker (2014, 2015a, 2015b, 2015c); Higgins et al. (2016, 2017); Knudtsen and Higgins (2017); and Vavra and Higgins (2017). Key details of these studies are reported subsequently.

Higgins, Amneus, and Barker (2015a) report results of experimental tests on full-scale RC deck girders containing poorly detailed flexural reinforcing steel representative of mid-twentieth century (1950s) design and construction practice. NSM-TiABs were used to strengthen the specimens. The beams were 48 in. (1.22 m) tall and 26 ft (7.92 m) long. The TiABs were 0.625 in. (15.9 mm) diameter and had 90-degree hooks at each end for anchorage. The beams were tested to failure under four-point bending. The authors also tested three replica beams for an in-service bridge to demonstrate design proof-of-concept prior to installation of NSM-TiABs on the bridge. TiABs were shown to effectively increase strength and to shift nonductile diagonal-tension failures to ductile flexural failure.

Vavra and Higgins (2017) tested full-scale RC deck girders similar to those in Higgins, Amneus, and Barker (2015a). One of the specimens was constructed with a flexural anchorage deficiency and strengthened with NSM-TiABs. The specimen was then subjected to simultaneous application of high-cycle fatigue loading and freeze–thaw cycle exposure prior to testing to failure. Results demonstrated that exposure to high-cycle fatigue (equivalent to over 50 years of service-level loading) and 200 freeze–thaw cycles (equivalent to between 59 and 83 years of exposure for the Pacific Northwest) had no considerable effect on the service-level behavior or ultimate strength. NSM-TiAB bond specimens were tested using $\frac{5}{8}$ in.- and $\frac{1}{4}$ in.-diameter TiABs. The specimens were inverted half-beam pullout specimens. Straight-bond length and hooked ends were investigated. Hooked ends were able to achieve much higher bond strength than straight-bar anchorages.

Knudtsen and Higgins (2017) tested full-scale RC girders strengthened in shear with TiABs. The specimens were designed to simulate 1950s-era bridge girders in materials, proportions, and construction. Two specimens were subjected to simultaneous freeze–thaw and fatigue cycles before being tested to failure. NSM-TiABs provided significant increases in the shear strength of the specimens compared to similar unstrengthened specimens. The bond between the titanium and concrete was observed to provide strains in TiABs twice that of the adjacent steel stirrups.

Vavra and Higgins (2017) also tested the use of TiABs in externally unbonded conditions. Although the unbonded specimens increased in strength and ductility, the external unbonded technique resulted in relatively low stiffness and large crack widths. The use of unbonded TiABs was recommended only for effective short-term or temporary repair of structures.

Harries and Platt (2017) assessed the effects of coupling Ti-6Al-4V and ASTM A615/A615M uncoated reinforcing steel, typical of concrete construction, to determine if galvanic corrosion develops. There was no evidence that Ti-6Al-4V reinforcing bars in close proximity to or in electrical contact with ASTM A615/A615M steel reinforcing bars produced any change in the rate or nature of corrosion.

PART 2—MATERIALS AND PROPERTIES

CHAPTER 3—TITANIUM MATERIALS

3.1 PHYSICAL AND CHEMICAL PROPERTIES

The TiABs used for RC strengthening applications shall contain the chemical composition of ASTM B348/B348M Grade 5 (Ti-6Al-4V) and meet ASTM B1009.

Ti-6Al-4V is nonmagnetic. The coefficient of thermal expansion is taken as $4.78 \times 10^{-6}/^{\circ}\text{F}$ ($8.6 \times 10^{-6}/^{\circ}\text{C}$) at operating temperatures. It is impervious to commonly encountered sources of environmental deterioration such as corrosion.

3.2 GEOMETRIC PROPERTIES

Only round bars are considered in this guide. Nominal bar diameters are shown in Table 3.2-1. Other bar diameters can be used with geometric properties interpolated between those stated in this guide.

Table 3.2-1. Bar Designations and Nominal Diameters

Bar Designation	Nominal Bar Diameter (in.)
#2	0.250
#3	0.375
#4	0.500
#5	0.625
#6	0.750

Note: Experimental data in literature are only available for #2 and #5 bar sizes.

To enhance bond along the length of the TiAB, surface deformations are required. The surface deformations may be rolled or machined. The surface deformations shall be sufficient to preclude failure of the TiAB along the TiAB–bonding material interface. The deformations must be capable of producing bond stress along the length of the TiAB as prescribed in Chapter 4. Surface deformations shall not reduce the constant amplitude fatigue limit below 40 ksi.

The cross-sectional area of TiABs with surface deformations shall be established based on the weight of a TiAB of known length. The minimum length to be used is 3 ft (1 m). The total weight of the bar shall be divided by the titanium unit weight of 0.276 kip/ft³ (4,419 kg/m³) to determine the nominal bar area. A minimum of five bars shall be used to develop the average, $\bar{A}_{Ti}$, and standard deviation, σ_{Ti} , of the cross-sectional area for a production run. The cross-sectional area used for design, A_{Ti} , shall be determined as

$$A_{Ti} = \bar{A}_{Ti} - 3.0\sigma_{Ti} \quad (3.2-1)$$

and reported by the manufacturer for use in design. No bar should fall below 96 percent of the manufacturer-reported nominal area.