

Near-Surface-Mounted Titanium Alloy Reinforcing Bars: A High-Performance Solution for Strengthening Concrete Bridges

by Dr. Christopher Higgins, Oregon State University

Thousands of reinforced concrete and prestressed concrete bridges built in the mid-20th century were designed to requirements that we now recognize have deficiencies. Many of these structures have inadequate shear reinforcement by current codes and poorly detailed flexural steel, and in many cases, designers did not properly account for the interactions of moment and shear on both the shear strength and flexural steel demands. When modern load-rating methods are applied and heavier trucks are considered, such bridges receive low ratings that seem to indicate a need for posting or replacement. However, in many cases, the deficiencies are localized, and much of the rest of the bridge structure is adequate. Rather than expend resources to replace or load post deficient bridges, a targeted strengthening method can sometimes be used to safely extend the life of the bridge. Many materials and techniques are available, and all have relative benefits and costs. Among the more

promising recent developments are the use of titanium alloy bars (TiABs) as near-surface-mounted (NSM) reinforcement. Titanium alloy is well established in aerospace structural applications, and research has now demonstrated that NSM-TiABs are an effective and cost-competitive solution for both flexural and shear strengthening of existing concrete structures.

The development of TiABs for strengthening concrete structures began at Oregon State University (OSU) in 2012 through research sponsored by the Oregon Department of Transportation (ODOT).¹ Multiple research programs have since been completed to refine and validate the materials and methods through testing of full-scale bridge girders. That work has now moved from the laboratory to the field, with the first commercial field deployment completed in 2014. Since that time, 30 in-service structures across the United States and New Zealand have been strengthened with NSM-TiABs. The development

of the American Association of State Highway and Transportation Officials' *Guide for Design and Construction of Near-Surface Mounted Titanium Alloy Bars for Strengthening Concrete Structures* (AASHTO NSMT-1)² and ASTM International's *Standard Specification for Titanium Alloy Bars for Near Surface Mounts in Civil Structures* (ASTM B1009-24)³ now give engineers the tools to specify and use NSM-TiABs with confidence.

The NSM-TiAB Technique

NSM strengthening was originally developed for fiber-reinforced polymer materials and subsequently adapted for bonding TiABs into shallow saw-cut grooves in the concrete cover of members (**Fig. 1**). For flexural strengthening, grooves are cut longitudinally in the tension face of the girder over the region to be strengthened. Hammer-drilled holes are made at the ends of the grooves in which the hooked ends of the TiABs are anchored. For shear strengthening,

Figure 1. Installation of near-surface-mounted titanium alloy bars (TiABs): Saw-cut groove in cover concrete and hammer-drilled hook anchorage hole into core (left); bending of TiAB with 90-degree hooked ends (center); TiAB is installed and grooves filled with structural epoxy with exposed surfaces taped for a clean surface finish (right). Photo: C. Higgins, Oregon State University



grooves are cut vertically in the web faces and horizontally across the web soffit, and the TiABs are fabricated into U-shaped stirrups with 90-degree hooks that anchor into hammer-drilled holes at the ends of the web grooves beneath the deck soffit. In both applications, structural epoxy bonds the bar to the concrete substrate. The hooked ends provide mechanical anchorage so that the bond along the length is not the sole mechanism to develop the strength of the bar.

The hooked ends of the TiABs that provide the mechanical anchorage are a key feature of the system. Even if bond along the bar length is lost, the TiABs can maintain their load-carrying capacity through the hooks, producing a ductile and progressive response with visible warning signs before failure. Installation is straightforward and is typically done on in-service bridges while under traffic. Groove cutting, epoxy placement, bar installation, and curing can typically be completed during standard maintenance windows without shoring or lane closures.

Why Titanium Alloy?

Ti-6Al-4V, the titanium alloy bars described in ASTM B1009, is the same aerospace-grade alloy that aircraft manufacturers specify for structural airframe components. It is manufactured to strict aerospace quality standards with tightly controlled chemical composition and mechanical properties, resulting

in very low variability in strength and elongation. That manufacturing precision, developed over decades, translates directly to consistent and predictable structural performance in bridge applications.

The properties of Ti-6Al-4V are well suited to NSM applications. The most commonly used yield strength is 130 ksi. This high yield strength means that designs can develop the required tensile force with fewer bars of smaller diameters than would be necessary when using other types of reinforcement. As a result, the number of grooves cut, the volume of epoxy required, and the installation labor on projects are all reduced. The unit weight of 276 lb/ft³ is about half that of steel, which makes the bars easy to handle in the field. The material has an elastic modulus (15,500 ksi) in the same range as that of carbon-fiber-reinforced polymer (CFRP). Titanium is completely corrosion resistant in structural engineering environments, including marine and deicing-salt exposure. The minimum specified elongation of 10% provides high ductility, so the bars yield and sustain deformations under increasing load, which provides clear visual warning before failure. **Figure 2** shows typical uniaxial tension properties with the yield stress established based on 0.2% offset. These properties are for bars with surface deformations. The surface deformations enable bond between the TiABs and concrete

through epoxy or other bonding material.

Flexural Strengthening

The OSU flexural-strengthening research program tested 11 full-scale tee and inverted tee girder specimens designed to replicate conventional mid-20th century reinforced concrete deck-girder construction materials and designs. Each specimen had intentional flexural steel anchorage deficiencies, with flexural bars extending only one-third of the required development length past a 45-degree diagonal crack. NSM-TiAB strengthening increased the load capacity by 31% to 44% and deformation by 85% to 174% compared with baseline control specimens that had not been strengthened.⁴

The failure mode also changed. The control specimens failed in brittle shear-tension at the cutoff locations of the flexural bars, with little warning. Strengthened specimens failed in ductile flexural modes with extensive distributed cracking, giving engineers and inspectors clear visual indication of distress well before capacity was reached.

Long-term durability of the NSM-TiAB flexural system was also investigated. A full-scale strengthened girder was simultaneously subjected to 1.6 million fatigue cycles and 200 cycles of freezing and thawing, representing more than 50 years of equivalent service, and then tested to failure. No meaningful change in stiffness or service-level response was observed during the exposure period. The postexposure failure load and ductility were within 1% of a companion specimen that had not been subjected to any fatigue or environmental exposure. The results confirm that the NSM-TiAB flexural strengthening system performs well under long-term in-service conditions.

Shear Strengthening

Shear strengthening with NSM-TiABs configured as either double-legged U-shaped or single-legged J-shaped stirrups was investigated for reinforced concrete bridge girders with insufficient transverse reinforcement. Seven full-scale tee and inverted tee specimens were strengthened with ¼-in.-diameter TiAB stirrups installed in vertical grooves

Figure 2. Example stress-strain responses for titanium alloy bars for a variety of different surface deformation patterns (inset) showing high strength with excellent ductility (>12%). Yield strength is determined with a 0.2% offset. Figure: C. Higgins, Oregon State University.

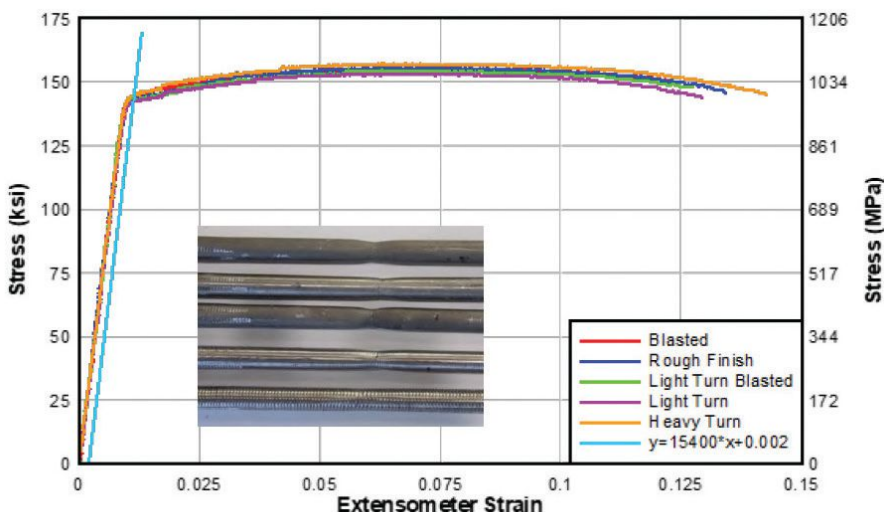




Figure 3. A crack with vertical offset at web soffit that was observed during a routine biennial inspection of Mosier Bridge no. 07626A in 2013 (left); flexural bar cutoff location superimposed over the interior girder of the bridge (right). The bridge was immediately shored pending analysis and strengthening. Photo: Oregon Department of Transportation.

on both web faces and hooks anchored beneath the deck soffit. Compared with the control specimens, the NSM-TiAB specimens demonstrated increases in shear strength ranging from 34% to 47%.⁵

One finding from this program is directly relevant to designers. Design provisions for some NSM materials limit the design strain to values below the actual material limit. TiAB stirrups with mechanical end anchorage develop their full yield strain. In addition, fractured TiABs were observed at the controlling diagonal cracks after failure. The experimental data support using the full yield strength of the TiABs in shear design calculations, which simplifies design and makes effective use of the material strength.

Durability of the shear system was confirmed for specimens bonded with high-performance epoxy. After 2.4 million fatigue cycles combined with 120 cycles of freezing and thawing, representing more than 50 years of service in the Pacific Northwest, no reduction in strength or stiffness was observed. The *AASHTO LRFD Bridge Design Specifications*,⁶ the American Concrete Institute's *Building Code Requirements for Structural Concrete and Commentary* (ACI 318),⁷ and the *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* (ACI 440.2R)⁸ conservatively predict specimen strengths, with average experiment-to-predicted ratios of 1.15 to 1.17 for the durability-exposed specimens.

The Mosier Bridge: From the Laboratory to the Field

Mosier Bridge no. 07626A, a 1953 reinforced concrete deck girder

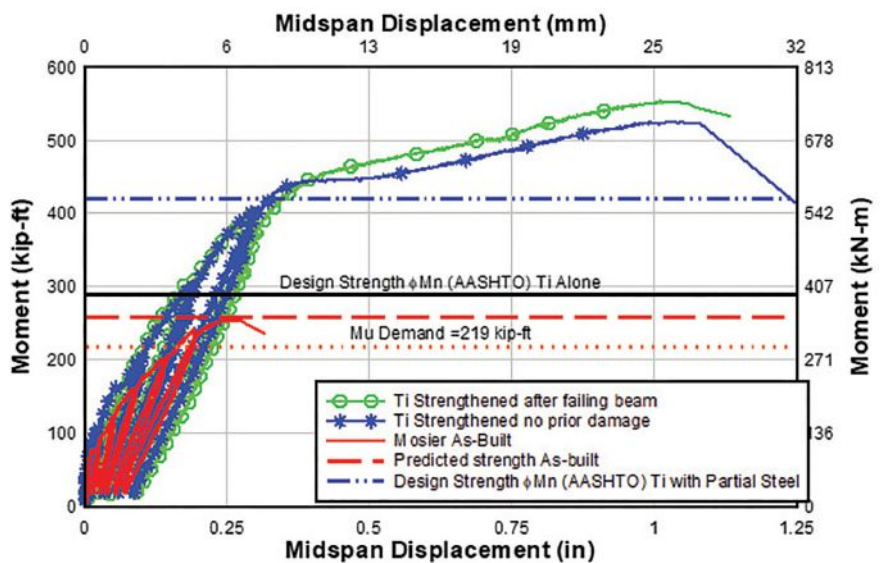


Figure 4. Moment versus midspan displacement for full-scale specimens representative of the Mosier Bridge interior girder. Near-surface-mounted titanium alloy reinforcing bar strengthening, even when applied to a previously failed specimen, more than doubled the load capacity and quadrupled the deformation as compared to the as-built control specimen. Figure: C. Higgins, Oregon State University.

(RCDG) overcrossing of Interstate 84 near Mosier, Ore., is a good example of how the OSU research applies to real bridges. This two-lane, three-span continuous RCDG bridge has four girder lines with girders spaced at 8 ft 8 in. and a 6.5-in.-thick deck. A routine biennial inspection in 2013 found a 0.03-in.-wide crack with a vertical offset in an interior girder, which is characteristic of flexural anchorage distress at a bar cutoff location (Fig. 3). The bridge was shored immediately. Analysis using the AASHTO LRFD specifications showed that the factored moment demand was 26.5% greater than the design strength from the AASHTO LRFD specifications, and NSM-TiABs were the most practical strengthening option given the geometry of the haunch at the critical section.

As a proof of concept, investigators used materials that reflected the vintage concrete and reinforcing steel to build and test full-scale specimens proportioned to match the Mosier Bridge interior girder.¹ The control specimen failed at a 64-kip point load placed at midspan with 0.26 in. of midspan displacement, and the observed cracking pattern matched what inspectors observed in the field, which validated the approach. Two NSM-TiAB-strengthened specimens reached 131- and 138-kip loadings with midspan displacements greater than 1.0 in., more than doubling the load capacity and quadrupling the deformation at the moment capacity (Fig. 4). Both specimens failed in a ductile flexural mode with extensive visual distress evident before ultimate was achieved (Fig. 5). Even the most

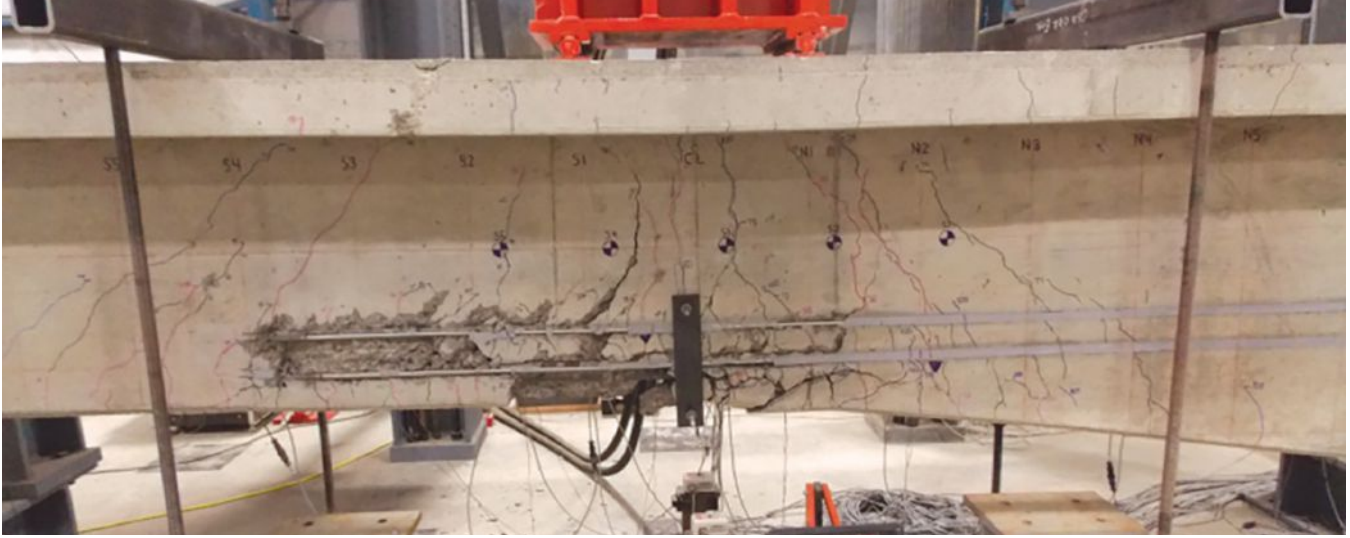


Figure 5. Condition of the replica of the Mosier bridge girder strengthened with near-surface-mounted titanium alloy reinforcing bars at failure in the Oregon State University laboratory. Large deformations and extensive distress give clear visual warning before ultimate failure. Photo: C. Higgins, Oregon State University.

conservative prediction—which used only the TiAB contribution for flexural strengthening and assumed that the original reinforcing steel provided no resistance at the critical section—exceeded the required factored demand. That lower-bound contribution provided by the TiABs acting alone is available to designers regardless of the residual condition of the in-place steel.

The bridge was strengthened in the field, and the installed cost was approximately 30% less than a competitively bid CFRP strengthening alternative. The savings came primarily from labor. The higher yield strength of titanium means fewer bars and fewer grooves to cut. Because labor accounts for a substantial part of the total cost of an NSM repair, a reduction in the number of bars, grooves, and structural epoxy can substantially reduce project costs. Subsequent field projects have consistently confirmed this cost differential. The structural benefits of a well-defined, highly ductile, inspectable, and corrosion-resistant material further support the use of NSM-TiABs for long-term bridge applications (Fig. 6).

In-Service Applications

Since the Mosier Bridge project, 29 other structures have been strengthened with NSM-TiABs in the United States and New Zealand. These projects span a wide range of structure types, repair conditions, and geographic locations, and illustrate how broadly the technique can be applied.

In Oregon, where the research originated, applications have included

flexural strengthening of three coastal Highway 101 bridges (Devil’s Lake, Schooner Creek, and Siltcoos River) where corrosion resistance was a primary requirement. Also in Oregon, the McKercher Bridge and SW 12th Avenue over Interstate 405 projects were emergency repairs completed under time constraints. The Abernethy Bridge, a major Willamette River crossing, required deck strengthening. Celilo Bridge required repair of hammerhead pier caps that were rated below requirements. Gold Beach Bridge is a historic landmark where 12,000 lb of TiABs were used in the rehabilitation. Oregon Route 217 and Camas Swale required crossbeam strengthening. Blowout Bridge was the first field application of the TiAB shear stirrup configuration developed in the OSU shear research program. Jefferson Bridge involved seismic reinforcement of columns. The Rogue River and Morrison bridges were historic preservation projects.

In Texas, NSM-TiABs have been used for pier cap repair on Interstate 10 over the San Jacinto River following tropical storm damage, cap and column repair on an Interstate 20 overpass, and slab bridge strengthening of U.S. Route 59 at Martin Creek and other structures. In New York, the technique was used to strengthen a salt shed at the Verrazano-Narrows Bridge complex, demonstrating that NSM-TiABs are applicable to any reinforced concrete member with accessible surfaces, not just bridge girders. In Pennsylvania, the Pennsylvania Department of Transportation is using NSM-TiABs on State Road 286 over

Humms Run for combined T-beam flexural and shear strengthening, and on the northbound and southbound Mill Hall bridges for pier cap negative-moment strengthening. In 2024, the first international application was completed in New Zealand with flexural strengthening of a beam bridge over Ngutuwerera Stream.

Across these 30 projects, the structure types include T-girder bridges, box girders, slab bridges, pier caps, crossbeams, columns, and nonbridge concrete structures. The repair types cover flexural strengthening, shear strengthening, emergency repair, historic preservation, storm damage repair, and seismic retrofit. The range of geographic locations, from Pacific Coast marine environments to Gulf Coast hurricane zones and the Southern Hemisphere, confirms that the laboratory findings translate reliably to in-service conditions with more than a decade of successful in-service performance.

Design Tools for Practice

AASHTO NSMT-1,² which was published in 2020, provides design and construction recommendations for NSM-TiAB strengthening based on the AASHTO LRFD methodology. The guide covers both flexural and shear strengthening applications and includes guidance on groove geometry, bar sizing, development length, and hooked anchorage design. ASTM B1009 was first published in 2018 and updated in 2024. It covers chemical composition, mechanical property classes, dimensional tolerances, surface deformation requirements, and bend



Figure 6. Photo of the completed Mosier Bridge no. 07626A, a two-lane, three-span continuous reinforced concrete deck girder bridge that has four girder lines with girders spaced at 8 ft 8 in. The bridge was strengthened in the field, with near-surface-mounted titanium alloy bars proving to be the most practical strengthening option given the geometry of the haunch at the critical section. Photo: W. George.

test requirements for bar sizes no. 2 through no. 6. There are two strength classes, Class 120 and Class 130, with minimum yield strengths of 120 and 130 ksi, respectively. The term “class” rather than “grade” is used because grade is reserved for other ASTM titanium standards. Together, AASHTO NSMT-1 and ASTM B1009 provide engineers with a complete, code-referenced path from condition assessment and load-rating analysis through final design and material specification.

The design approach in AASHTO NSMT-1 is adapted from ACI 440.2R and calibrated to the AASHTO LRFD specifications. TiABs with hooked anchorages reach their full yield strength, so designers use standard yield strength-based calculations. For shear design, the full yield strength of the TiABs can be used without additional reduction factors when a specification-compliant epoxy is specified. The experimental data confirm that both the AASHTO LRFD and ACI methods produce conservative predictions for NSM-TiAB-strengthened members.

Conclusion

NSM-TiABs offer an effective, durable, and cost-competitive method for strengthening existing concrete structures deficient in flexure, shear, or both. The system increases load capacity and ductility; changes brittle failure modes to ductile ones; performs well under exposure to fatigue and freezing-and-thawing conditions that represent more than 50 years of service;

and resists corrosion without ongoing maintenance. Installation is compatible with in-service bridge operations and conventional construction practices. Based on projects over the past decade, project costs are less than the costs for comparable CFRP strengthening. The technique is applicable to reinforced concrete and prestressed concrete bridge girders, pier caps, crossbeams, columns, decks, and nonbridge concrete structures. More than 12 years of field performance history and 30 successful projects across the United States and New Zealand demonstrate that the laboratory results apply to the conditions encountered in practice. With AASHTO NSMT-1 and ASTM B1009, engineers have the guidance they need to specify and design NSM-TiABs with confidence.

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