New unibody clamp anchors for posttensioning carbon-fiber-reinforced polymer rods

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- Research regarding four generations of unibody steel clamp anchors for posttensioning carbon-fiber-reinforced polymer (CFRP) rods is presented.
- The anchors performed progressively better with an increasing number of bolts, anchor length, and anchor thickness.
- Results from finite element models provided a relative comparison of the contact pressure between the anchor and CFRP rod across the four generations.

Posttensioned concrete is conventionally constructed with high-strength steel tendons. An attractive alternative to steel tendons is fiber-reinforced-polymer (FRP) tendons because of their high strength-to-weight ratio, noncorrosive nature, alkali resistance, and fatigue resistance. As with high-strength steel tendons, FRP tendons must have proper anchorage for posttensioning to occur. Because the success of implementing FRP materials in posttensioning applications depends on the anchors, much consideration is given to developing a suitable anchor.

This article presents research on the design of a new unibody clamp anchor for posttensioning FRP rods. The anchor is unique in that it provides anchorage using a combination of direct lateral contact pressure and flexure-induced contact pressure on the FRP rod from several bolts. Details of the anchor development through four anchor generations, test results, and final anchor configuration are provided. A simplified finite element analysis model that was developed to show the relative differences in performance among the four anchor generations is presented. Finally, recommendations for further development of clamp anchor systems are presented.

Previous research

A significant amount of research has been performed on several different styles of anchors for prestressing applications of FRP tendons.[1–5] Common considerations for the development of FRP anchors include anchor efficiency, minimizing stress concentrations, economics, and corrosion resistance. Concerns regarding stress concentrations are directly related to anchor efficiency; transversely, anisotropic FRP tendons can prematurely fail if transverse stress is not controlled, especially at the lead end of the anchor. The low shear strength of composite rods requires longer and larger-diameter anchors compared with those for steel tendons.[2] Such anchors create detailing problems, especially at congested beam ends. An acceptable anchor for FRP tendons must ensure that any rupture of the FRP tendon occurs outside the anchorage.[6] On the other hand, the anchor must sufficiently retain the tendon through an applied stress such that slip does not occur during the tendon stressing application or subsequent time in service. Economics must be taken into account. Finally, corrosion resistance must be considered because the anchor system should be able to meet the performance life of the noncorrosive FRP tendon.

Anchors for FRP tendons fall into one of two categories based on the method employed for imparting stress to the tendon: bond anchors and mechanical anchors.[7] Typically composed of a sleeve filled with resin, bond anchors rely on the bond between the resin and the FRP tendon to provide adequate contact pressure during prestressing or posttensioning. Different styles of bond anchors may include a tapered or conical sleeve, splayed ends of the FRP tendon, or tendon overlay materials. Bond anchors have been developed for use with FRP tendons.[8–10] However, largely dependent on development length, bond anchors tend to be longer than mechanical anchors, making them less practical where end anchorage must be compact. In addition, the dependence on resin or epoxy of bond anchors results in increased application time, labor costs, the possibility of installation error, and concerns for long-term stability.

Mechanical anchors are typically classified as wedge anchors or clamp anchors. Split wedge anchors are similar to anchors used for prestressing conventional high-strength steel tendons, and consist of wedges that surround the FRP tendon and a conical barrel outside the wedges. As stress is applied to the tendon, the wedges are seated into the barrel, applying a gripping stress to the tendon. A soft sleeve material around the tendon may or may not be included with split wedge anchors to attempt to reduce transverse stress concentrations. The number and shape of wedges have been investigated by several researchers, with variations of 2, 3, 4, and 6 wedges.[4,11,12] Different wedge materials have also been studied. Tests have been conducted on high-performance concrete anchors,[7,13] polymer anchors,[14–16] and metal anchors.[11,12,17] Although split wedge anchors have been implemented in laboratory testing to develop the ultimate strength of the tendon, slip has not always been controlled.[3] Some split wedge anchors have failed to develop the ultimate strength of the tendon due to increased transverse stresses.[18] Split wedge anchors are compact; however, they have a higher manufacturing cost than bond anchors due to the number of wedges and the machining required to produce the precise tapers and angles for the wedges and barrel.

Clamp anchors impart a mechanical stress to the FRP tendon from bolts or similar mechanical devices rather than wedges being driven into a barrel. Traditionally composed of two metal plates with a groove for the FRP tendon, clamp anchors are more compact than bond anchors. In some cases, a sleeve material has been used between the tendon and the clamp.[8,19,20] Despite research investigations of various types of FRP tendon anchors, no single type has found widespread acceptance or implementation in prestressed/precast concrete.

Clamp anchors are especially suited for overcoming the limitations of other anchor systems. Manufacturing costs for clamp anchors are lower than those for split wedge anchors because less machining is required and fewer pieces are involved in the anchor assembly. Clamp anchors are more compact than bond anchors because the clamping force applied can be adjusted with the bolts, reducing the required development length. The applied stress can be varied along the anchor to control transverse stresses and avoid premature FRP tendon failure.

Experimental investigation

Specimen geometry

Four generations of unibody anchors were studied in this research. **Figure 1** shows the generalized geometry of the unibody clamp anchor. All generations were composed of a steel block of ASTM A1018[21] flat bar with a rod hole, bolt holes, an inner slot, and an outer slot. The rod hole is positioned longitudinally along the anchor block with the inner and outer slots running parallel to the rod hole. In addition, the bolt holes and bolts run perpendicular to the rod to provide the clamping force. Therefore, as the bolts are tightened, the outer and inner slot widths are reduced and the cantilevered anchor sides are pushed inward, resulting in contact pressure on the CFRP rod. Thus, the pressure on the CFRP rod is due to both direct compressive stress and flexural stress resulting from the cantilevered anchor sides. The width of inner and outer slots controls the effect of the bolt tension. Once either slot is completely closed, an increase in bolt force simply deforms the steel anchor body while negligibly increasing the clamping pressure applied to the CFRP rod. Variables such as anchor body length, width, and thickness were varied across generations; **Table 1** is a summary of the anchor geometry for each generation. **Figure 2** shows a visual size comparison of the anchors across the four generations. Genera-

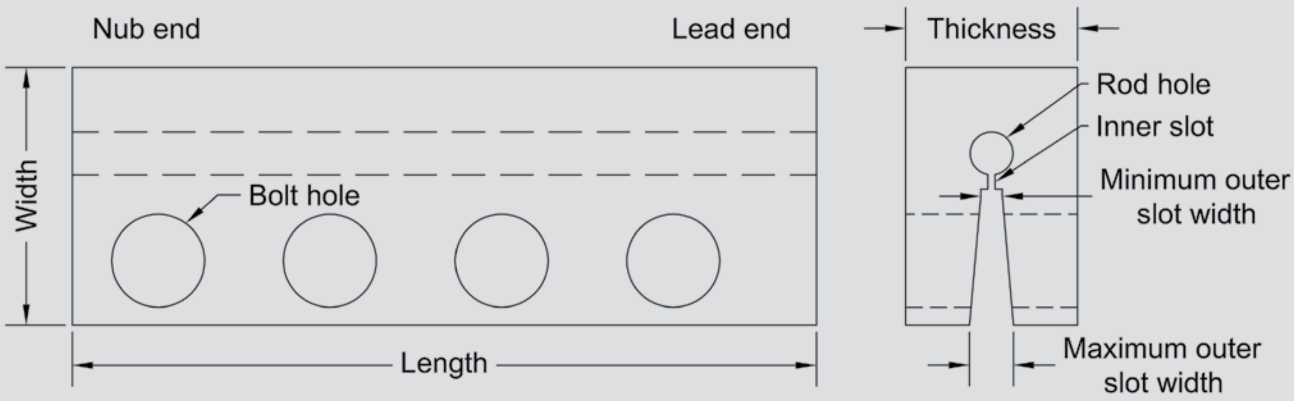


Figure 1. Unibody clamp anchor geometry.

tion IV anchors had two details. This anchor was tested both as a four-bolt and a three-bolt anchor.

Another variation among generations was implemented by varying the number and size of ASTM A325[22] steel bolts used to apply the clamping force. **Table 2** is a summary of the variation in the bolts used for each anchor generation. The bolt diameters for generations I through III and generation IV were $^{5}/_{8}$ in. (16 mm) and $^{3}/_{4}$ in. (19 mm), respectively. Generation I used two bolts, generation II three bolts, and generations III and IV four bolts with the bolt spacing held constant at $1^{1}/_{2}$ in. (38 mm). A further variation of generation IV anchors was that after testing the anchors with four bolts, they were cut down to become three-bolt anchors and retested. The applied torque for each bolt varied across generations; however, each bolt in a given anchor was subjected to the same applied torque.

Material properties

The material used in the manufacture of the unibody anchors was ASTM A1018 flat bar with a yield strength of 53.8 ksi (371 MPa), and the clamping force was provided by ASTM A325 steel bolts. The CFRP rods had the following design properties: the rod diameter was $^{3}/_{8}$ in. (9.5 mm), tensile strength was 27.5 kip (122 kN), tensile modulus was 22,500 ksi (155 GPa), and elongation at break was 1.8%. The CFRP rods are composed

Table 1. Anchor geometry details

Generation	Width, in.	Length, in.	Thickness, in.	Inner slot width, in.	Minimum outer slot width, in.	Maximum outer slot width, in.
I	2	3	1	$^{1}/_{16}$	$^{3}/_{16}$	$^{3}/_{16}$
II	2	$4^{1}/_{2}$	1	$^{1}/_{16}$	$^{3}/_{16}$	$^{3}/_{16}$
III	2	6	1	$^{1}/_{16}$	$^{3}/_{16}$	$^{3}/_{16}$
IV	$2^{1}/_{4}$	5 to $6^{1}/_{2}$	$1^{1}/_{2}$	$^{1}/_{16}$	$^{3}/_{16}$	$^{3}/_{16}$

Note: 1 in. = 25.4 mm.

Table 2. Clamping bolt details

Generation	Number of bolts	Bolt diameter, in.	Applied torque, lb-ft
I	2	$^{5}/_{8}$	200
II	3	$^{5}/_{8}$	200
III	4	$^{5}/_{8}$	200
IV	3, 4	$^{3}/_{4}$	600

Note: 1 in. = 25.4 mm; 1 lb-ft = 1.356 N-m.

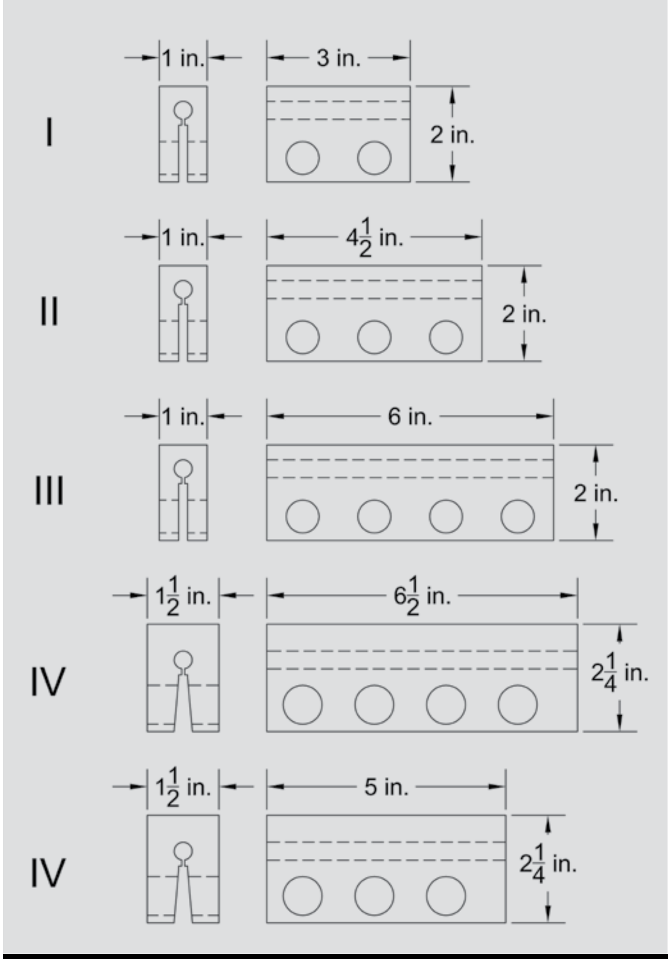


Figure 2. Anchor size comparison across generations I-III, IV four-bolt, and IV three-bolt anchors. Note: 1 in. = 25.4 mm.

Figure 3. End view of clamped generation IV anchor.

of a carbon-fiber-reinforced polymer with an epoxy resin matrix and a fiber volumetric content equal to 65%.

Test methods

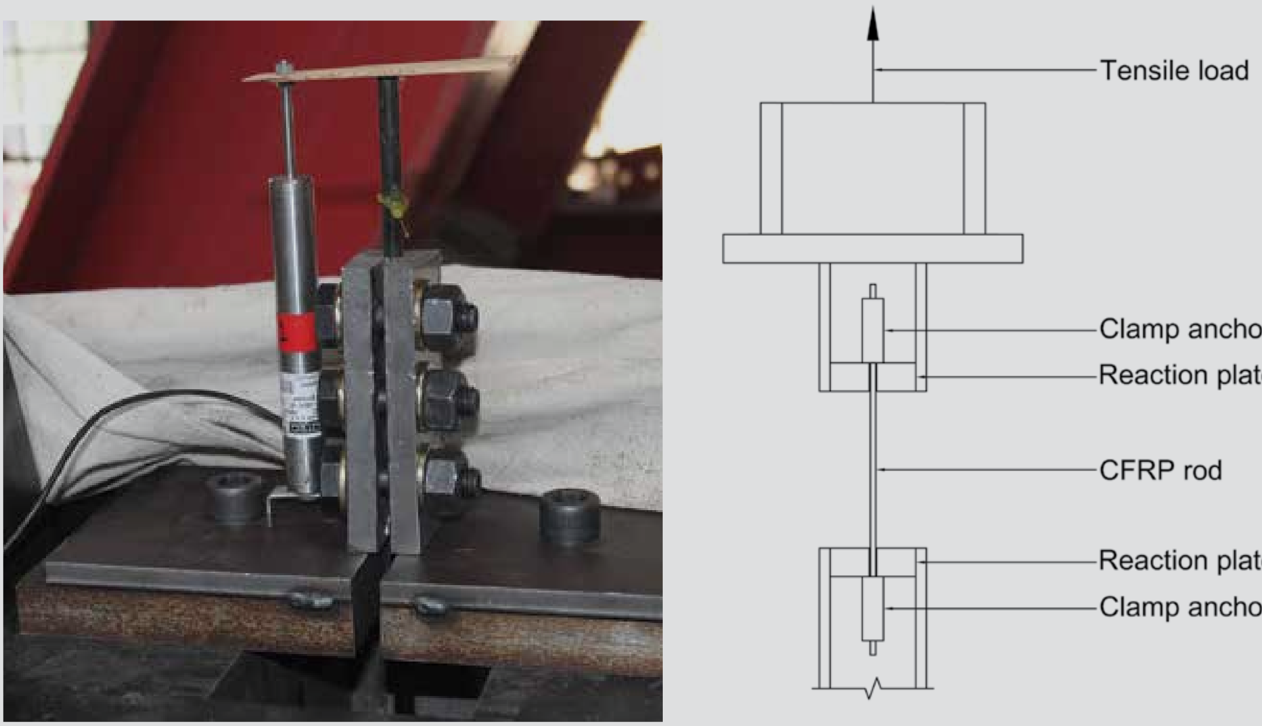
A length of CFRP rod was prepared to include the length of the anchor sections, the middle section, and a 1 in. (25 mm) nub protruding from the dead end of each anchor such that the total length exceeded 40 times the diameter of the CFRP rod. The latter length is 15 in. (380 mm), as per ACI 440.3R-04.[23] A liquid solvent was used to clean the anchors and CFRP rod test sections before clamping. Anchor clamping was accomplished with steel bolts. Each bolt was secured sequentially, beginning with the nub end and progressing toward the lead end. The clamping process occurred over several increments until the final applied torque was reached for each bolt. Generations III and IV included the use of tapered drop-forged steel washers to ensure that the clamping bolts remained perpendicular to the anchor; **Fig. 3** shows implementation of the tapered washers. A matching anchor was clamped to each end of a given CFRP rod test section, creating a test section assembly. In the later tests, two linear variable differential transducers were attached on each anchor to measure slip (**Fig. 4**).

After application of the unibody clamp anchors, the test section assemblies were tested vertically. The bottom clamp anchor was held in a fixed position by a slotted steel reaction plate, while a tensile force was applied to the test section assembly at the top clamp anchor by a hydraulic actuator (Fig. 4). Monotonic loading was applied at a rate of 0.4 in./min (10 mm/min), corresponding to an idealized stress application rate of 60 ksi/min (410 MPa/min). Termination of each test depended on rupture of the CFRP rod or more than 0.5 in. (13 mm) of total anchor slip, whichever occurred first.

Experimental results

Generation I anchor

Figure 5 shows the first-generation anchor. This was the shortest of the four generations at 3.0 in. (75 mm) long, and the clamping force was provided by two 5/8 in. (16 mm) diameter A325 bolts. **Figure 6** shows typical results from a generation I anchor. Typical generation I anchors reached a maximum load of 17 kip (76 kN), corresponding to an anchor efficiency of 62%, before slip occurred, based on the CFRP rod design ultimate strength. For loads greater than 17 kip (76 kN), large amounts of slip were present, as indicated by the curved force versus displacement line in Fig. 6. The CFRP rod remained intact during testing; however, the slip of the anchor on the rod produced a scaling effect on the CFRP rod, which is visible in Fig. 6. The $^{3}/_{16}$ in. (4.8 mm) constant-width outer slot limited the maximum clamping force due to contact between the steel surfaces at the outer edges of the outer slot (arrows in Fig. 5). Furthermore, the bolts failed because they were bent during clamping and did not remain perpendicular to the anchor.



Linear variable differential transducer setup | **General setup**

Figure 4. Test setup. Note: CFRP = carbon-fiber-reinforced polymer.

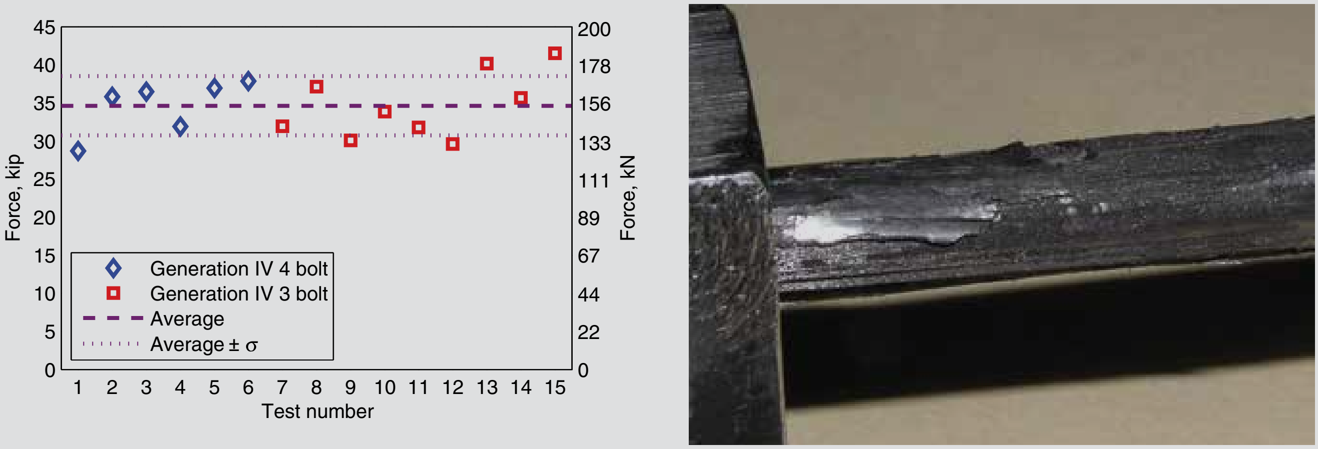
Generation II anchor

The second-generation anchor improved on the previous generation by increasing the anchor length to 4.5 in. (115 mm) and using three bolts to provide the clamping force (Fig. 2). **Figure 7** shows the closed outer slot of a typical clamped generation II anchor. **Figure 8** shows typical results from testing of a generation II anchor. Generation II anchors exhibited linear performance up to a maximum load of 20 kip (90 kN), corresponding to an anchor efficiency of 73% before slip occurred, based on the CFRP rod design ultimate strength. At applied tensile loads greater than 20 kip (90 kN), some slip was observed and the CFRP rod underwent progressive failure: the outer fibers ruptured first, and rupture progressed inward toward the center of the rod. Rod failure occurred near the lead end of the anchor (Fig. 8). Although the clamping force was limited—as with generation I—the longer anchor increased anchor efficiency for generation II compared with generation I. However, despite the increased anchor efficiency, bolt bending was still observed during clamping.

Generation III anchor

Modifications to produce generation III included lengthening the anchor to 6.0 in. (150 mm) and using four $^5/_8$ in. (16 mm) diameter bolts to control anchor slip (Fig. 2). Tapered washers were added to keep the clamping bolts perpendicular to the anchor axis. **Figure 9** shows typical test results for a generation III anchor. Generation III anchors reached a maximum load of 22 kip (98 kN) before slip occurred, corresponding to an anchor efficiency of 80% based on the CFRP rod ultimate strength. The total anchor slip above this tensile load was observed to be only 0.01 in. (0.25 mm). Failure of the CFRP rod occurred instantaneously in the middle of the test section, resulting in splintered fibers in random locations of the CFRP rod (Fig. 9). Generation III exhibited less slip compared with previous generations, and rod rupture occurred in the middle of the test section rather than at the lead edge of the

Figure 5. Generation I anchor.



Applied force versus actuator displacement

Damage caused to CFRP rod from slip

Figure 6. Generation I anchor. Note: CFRP = carbon-fiber-reinforced polymer.

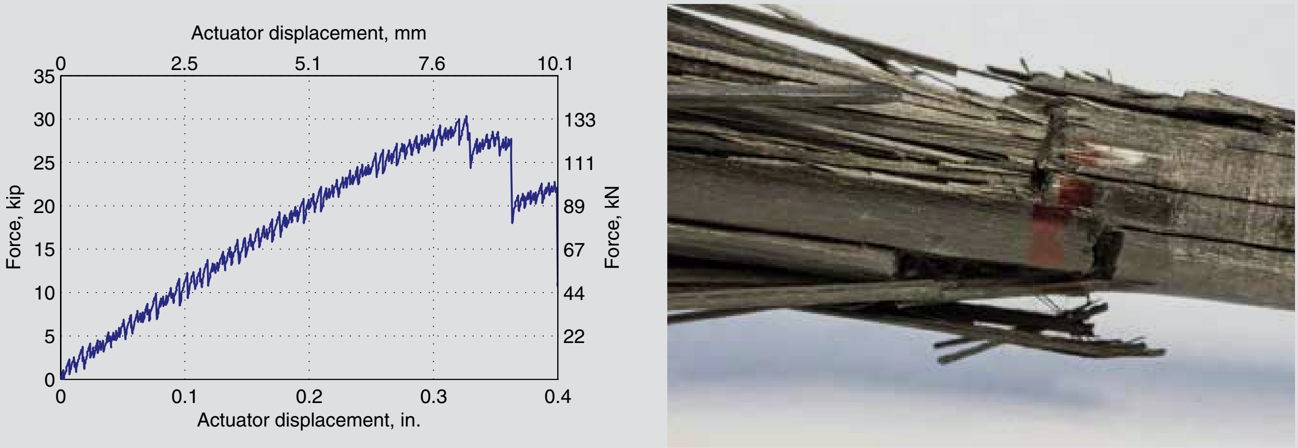
Figure 7. Generation II anchor.

anchors. The tapered washers kept the bolts straight during clamping and perpendicular to the anchor axis.

Generation IV anchor

Figure 10 shows a clamped generation IV anchor. Generation IV included increases in anchor length (at the lead edge), anchor thickness, and bolt diameter. An outer slot of varying width (corresponding to an approximate 5-degree taper) was implemented (Fig. 2). The tapered outer slot ensured that contact did not occur between the edges of the outer slot, allowing for an increase in applied clamping force. As with generation III, tapered washers maintained the clamping bolts perpendicular to the anchor. Although the bolt spacing for generations III and IV remained constant, the extra anchor length, thickness, and width were added to gradually reduce the pressure exerted by the anchor on the CFRP rod. This effect in terms of added length in the lead end is evidenced by the gradual flare in the outer slot width (Fig. 10), where the slot is wider on the lead end (section B-B) compared with the nub end (section A-A). Moreover, the bolts did not bend because of the use of tapered washers.

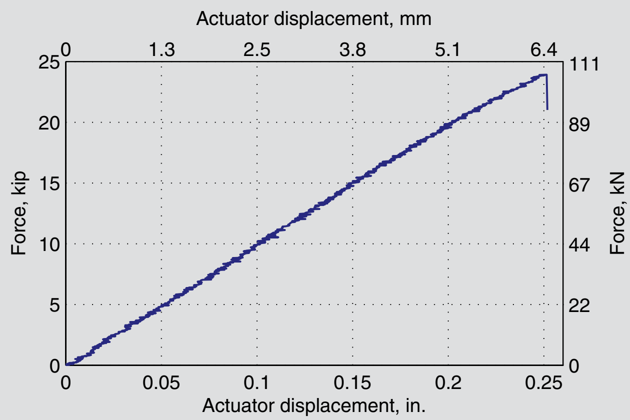
The CFRP rod failed at a load range of 28.7 kip (128 kN) to 37.9 kip (169 kN), corresponding to a true anchor efficiency of 104% to 138% based on the CFRP rod design ultimate strength. Six tests were conducted using four-bolt



Applied force versus actuator displacement

Ruptured CFRP rod located at lead edge

Figure 8. Generation II anchor. Note: CFRP = carbon-fiber-reinforced polymer.



Applied force versus actuator displacement

CFRP rod tensile failure

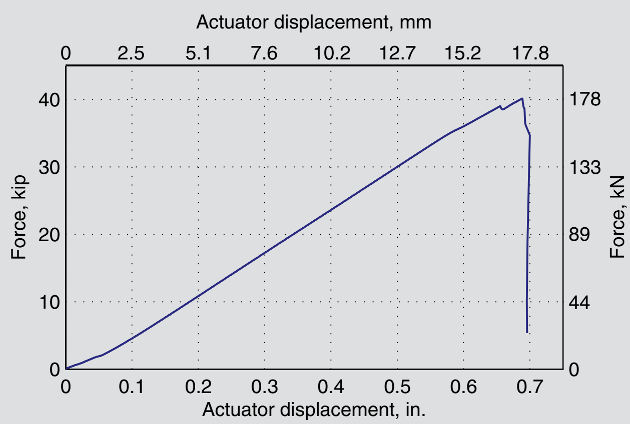
Figure 9. Generation III anchor. Note: CFRP = carbon-fiber-reinforced polymer.

anchors with an average failure load of 34.6 kip (154 kN) and a standard deviation of 3.6 kip (16 kN).

Because of the excellent performance of the four-bolt anchors of generation IV, additional tests were conducted by cutting the four-bolt anchors and removing one bolt to obtain a series of three-bolt generation IV anchors that were only 5.0 in. (125 mm) long. For the generation IV three-bolt anchors the CFRP rod failed at a load range of 29.6 kip (132 kN) to 41.5 kip (185 kN), corresponding to a true anchor efficiency of 108% to 151% based on the CFRP rod design ultimate strength. Nine tests were conducted, with an average result of 34.6 kip (154 kN) and a standard deviation of 4.3 kip (19 kN).

Figure 11 shows typical test results from a generation IV three-bolt anchor. They exhibited acceptable performance up to tensile failure of the CFRP, which shows splintered fibers at various random locations. **Figure 12** shows a distribution of the 15 generation IV tests. The four-bolt and three-bolt generation IV anchors had identical performance in terms of both the average tensile strength and standard deviation σ, which for both three- and four-bolt generation IV anchors was equal to 4.3 kip (19 kN). The tensile modulus of elasticity of the CFRP rod for both four-bolt and three-bolt generation IV anchors was measured at 22,500 ksi (155 GPa), which matches the manufacturer's recommendation.

Figure 10. Clamped generation IV anchor showing increased width of outer slot from nub to lead end (A-A to B-B).



Applied force versus actuator displacement

Tensile failure of CFRP rod

Figure 11. Generation IV three-bolt anchor. Note: CFRP = carbon-fiber-reinforced polymer.

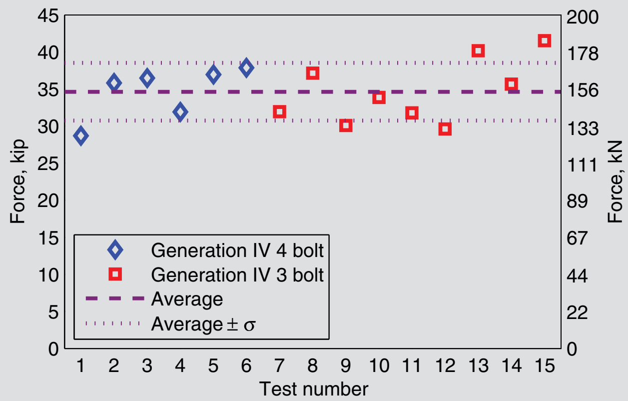


Figure 12. Distribution of generation IV test results for three-bolt and four-bolt anchors. Note: σ = standard deviation.

Finite element modeling

Model configuration

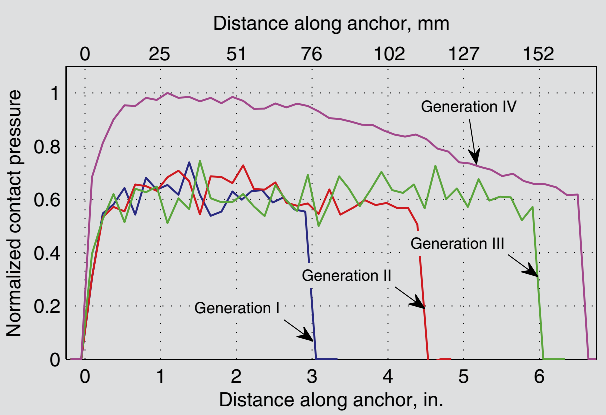
A simplified finite element model was developed for the four generations of anchors to explore the relative difference in clamping pressure. Tetrahedral elements were selected because they allow fast automatic meshing of three-dimensional models to capture the variations between generations. The intent of the finite element model was not to predict the actual behavior of the anchors but rather to show the relative difference between anchor generations in regard to the clamping force. The unibody steel anchor was modeled using a simple bilinear stress-strain relationship to reduce computation time. The CFRP rod was modeled as a transversely anisotropic material with different properties in the longitudinal and transverse directions. The contact between the unibody steel anchor and CFRP rod was modeled with contact and target elements overlaid on the CFRP rod and anchor surfaces, respectively.

For unibody clamp anchors, contact pressure is developed from the clamping force due to the bolts rather than seating force, as with split wedge anchors. For the purpose of investigating the relative difference in contact pressure across the four unibody anchor generations, a clamping force was applied. Bolt forces were calibrated to generate deflections in the model corresponding to those observed at the anchor tips of the outer slot (arrows in Fig. 5).

Model results

Results from finite element models confirm the test results: generation IV reduces stress concentrations at the lead end of the anchor and produces the highest contact pressure among the four generations at the nub end, defined in Fig. 2. **Figure 13** shows a nub end view of the generation IV model showing the deflected shape and equivalent stress, with red denoting high stresses; the tapered outer slot has essentially become a slot of constant width, as observed in testing. The effect of clamping can be seen by

Equivalent stress, end view (red denotes high contact stresses)



Normalized contact pressure on side of carbon-fiber-reinforced polymer rod for generations I through IV (0 in. [0 mm] = nub end, 6.5 in. [165 mm] = lead end)

Figure 13. Finite element results for generation IV anchor.

comparing Fig. 2 with Fig. 13. The reduction in contact pressure and consequent stress in the CFRP rod at the lead end of the anchor is illustrated in Fig. 13, which shows the pressure on the CFRP rod along the length of the anchor for generations I through IV.

Figure 13 shows that generations I through III provide approximately the same contact pressure along the entire anchor length. The generation IV anchor exhibits an increase in contact pressure in the area close to the nub end of approximately 60% (compared with generations I through III) and simultaneously a gradual 37% decrease in contact pressure toward the lead end. This decrease in contact pressure indicates that the geometric design of generation IV is able to reduce the contact pressure and consequent stress concentrations in the CFRP rod at the lead end. This is crucial because transversely anisotropic FRP tendons can fail prematurely if transverse stress is not controlled, especially at the lead end of the anchor, as demonstrated in Fig. 8 for generation II anchors. The varying width of the outer slot in generation IV increases the clamping force because the outer slot edges are prevented from touching. The best unibody clamp anchor is generation IV because of its ability to reduce stress concentrations at the lead end and its ability to apply a higher clamping force compared with generations I through III.

Practical implementation

The unibody clamp anchor developed in this research has been used in conjunction with experimental specimens of reinforced and prestressed concrete beams.[24] The anchor performed in a satisfactory manner regarding the transfer of the prestressing force from the unibody clamp device to the concrete beams. However, the beam tests were performed within one day after posttensioning, and as such, long-term losses, including creep and shrinkage of concrete, were beyond the scope of the research. In addition, creep rupture strength of the CFRP rods under sustained load was not considered. It is therefore necessary to investigate the long-term behavior of the unibody clamp anchors on actual beams before they can be used in real applications for posttensioning CFRP rods.

Conclusion

From the experimental results and finite element model simulations conducted in this research, it can be concluded that unibody clamp anchors can potentially be used for posttensioning CFRP rods. The simple geometry avoids complicated wedges, bevels, and multiple pieces. The generation IV anchor performed best. Based on the CFRP rod ultimate strength, anchor generations I through III demonstrated anchor efficiency before slip of 62%, 73%, and 80%, respectively. Generation IV anchors did not slip and demonstrated an anchor efficiency of 104% to 151% of the tensile design ultimate strength before CFRP rod rupture. The tapered outer slot included in generation IV anchors allowed for an increased clamping force compared with other generations because it prevented the edges of the outer slot from touching. In addition, the increased wall thickness, width, bolt diameter, and applied torque on the bolt also contributed to its increased efficiency.

The design of the generation IV anchor was optimized to further increase anchor efficiency by reducing its length to 5.00 in. (125 mm) with only three bolts; this resulted in a three-bolt anchor with essentially the same average efficiency as the four-bolt anchor equal to 126% of the tensile design strength of the CFRP rod. Future studies should implement the unibody clamp anchor to posttension CFRP rods on reinforced or prestressed concrete elements, simulating field applications. It is also necessary to investigate the long-term behavior of the unibody clamp anchors implemented on actual reinforced or prestressed concrete elements to evaluate prestress losses due to creep and shrinkage and the creep rupture strength of the CFRP rods. Furthermore, stainless steel should be explored as an option for the anchor stock and bolts to prevent corrosion.

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Abstract

Four generations of unibody steel clamp anchors for posttensioning carbon-fiber-reinforced polymer (CFRP) rods were tested. Geometric properties of the anchors and the number of bolts providing the clamping force for a CFRP rod of nominal $^3/_8$ in. (9.5 mm) diameter were varied. The anchors performed better with increasing number of bolts and anchor length and thickness. Finite element models provided a comparison of the contact pressure between the anchors and the CFRP rod. The generation IV anchors provided the highest contact pressure while controlling stress concentrations at the lead (load) edge. The four-bolt and three-bolt versions had similar capacities with an average efficiency of 126% based on the manufacturer-specified ultimate strength of the CFRP rod.

Keywords

CFRP; clamp anchor; composite; fiber-reinforced polymer; posttensioning.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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