Anchor Reinforcement for Anchor Channels

An advanced concept for increasing the concrete shear capacity at small edge distances

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Increasing worldwide urbanization pushes city centers to grow in height. The skylines of cosmopolitan cities are increasingly dominated by tall buildings clad with curtain wall façade panels (Fig. 1(a)). In many cases, these panels are attached to the structure by anchor channels. One of the challenges of this is that the concrete decks are becoming thinner and connection points of the façade panels are moving closer to the edge to maximize floor space. The solution is an anchor channel supplemented with anchor reinforcement, for which an advanced concept has been developed.

The prefabricated curtain wall façade panels are typically installed in quick succession as the structure rises. The façade panels are set on brackets (Fig. 1(b)) that have been preinstalled with channel bolts in cast-in anchor channels. Before loading, the channel bolts may be moved along the slot of the anchor channel, allowing the fastening of the brackets at any point along the length of the anchor channel. Together with the slotted holes in the brackets oriented in the perpendicular direction, construction tolerances can be easily accommodated by adjusting all connection points before the façade panels are installed.

The Story of Anchor Channels

Anchor channels are a success story over 100 years old.[1] Anchor channels consist of anchors either forged or welded to C-channels that are cast flush in reinforced concrete elements and allow the installation of matching channel bolts, also known as T-bolts. The robust anchor system can take relatively high tension and shear loads, and it can transfer loads in all directions by mechanical interlock. The installation of anchor channels as well as channel bolts is fail-safe because of the simple installation shown in Fig. 2. First, the channel is nailed to the formwork (for front-face installation) or to a template (for top-of-slab installation) before concreting (Fig. 2(a)). After the concrete has set and

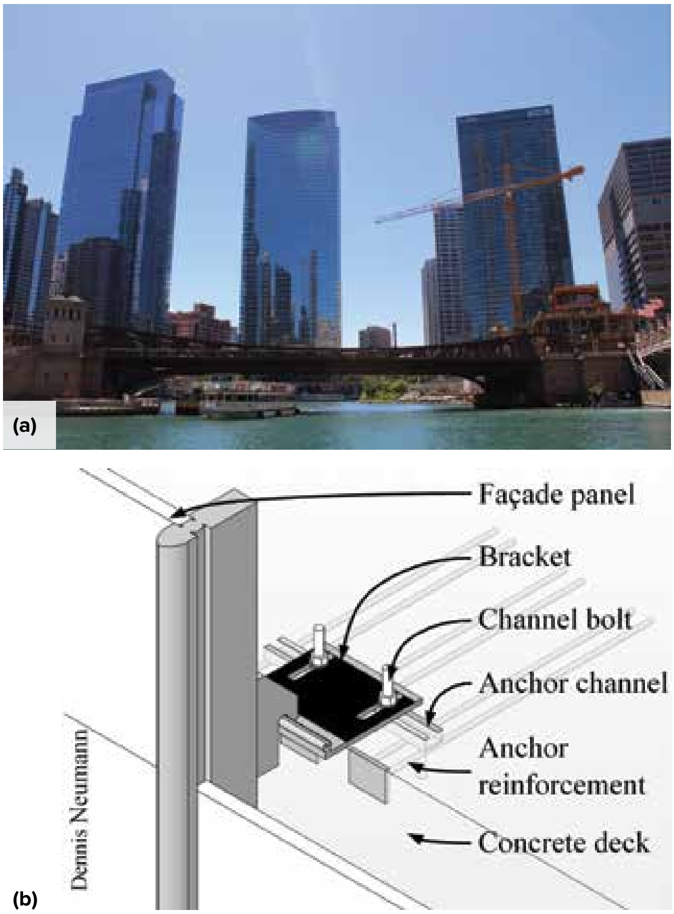


Fig. 1: Modern tall buildings typically have curtain wall façade panels: (a) new examples at Wolf Point Chicago *(photo courtesy of Chris6d - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=72101208)*; **and (b) façade panels engage brackets fastened with channel bolts to a cast-in anchor channel enhanced with anchor reinforcement**

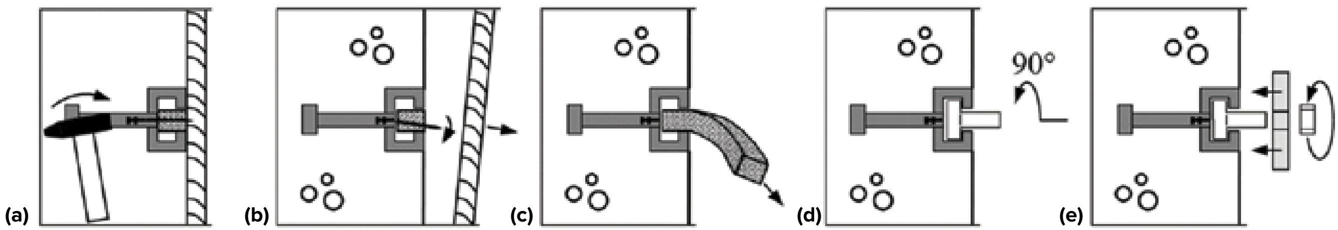


Fig. 2: Anchor channel installation sequence: (a) anchor channel is nailed to formwork or template and concrete is placed; (b) formwork is stripped after concrete has set; (c) filler material is removed from channel; (d) channel bolt is inserted and rotated 90 degrees to engage channel lip; and (e) components are fastened to the channel bolt

the formwork or template is removed, the pliable filler material, which prevents the concrete from leaking into the profile during placement, is removed from the channel (Fig. 2(b) and (c)). Channel bolts are then inserted and twisted in the slot of the anchor channel, allowing the fastening of components at any point along the length of the channel (Fig. 2(d) and (e)).

Qualification and Design of Anchor Channels

Independent third-party testing to ensure the performance of anchor channels started as early as the 1970s,[2] and well-established design rules are now available for design engineers. Highly loaded anchor channels embedded near the edge of concrete elements (for example, for façade installations) have, however, remained a critical design situation to date. In particular, it has been a challenge to safely anchor assemblies that impose high loads in thin concrete decks. However, anchor reinforcement can be used to considerably increase the capacity of such assemblies, and so it offers an efficient and safe solution. An advanced concept of anchor reinforcement is presented in the following discussion.

The design of anchor channels and channel bolts is codified in ACI 318-19[3] and ICC-ES AC232.[4] The latter document provides Acceptance Criteria (AC) for the extensive qualification of the anchor system to attain Evaluation Service Reports (ESR) with product-specific parameters (for example, ICC ESR-2854[5]). The design procedure is elaborate and involves the calculation of capacities against 20 possible failure modes and their interactions. Any of the failure modes can be decisive. Safety is ensured by the application of lower-strength reduction factors for brittle concrete-related failure modes with higher scattering, and the application of higher-strength reduction factors for ductile steel-related failure modes with lower scattering. Details of the design concept and the qualification procedure are discussed elsewhere.[6]

In the following sections, only two failure modes (concrete edge breakout and reinforcing bar yielding of the anchor reinforcement) are considered, as they are most relevant for anchor channels installed close to the edge of concrete elements and loaded by shear forces perpendicular to the channel axis.

Concrete Edge Breakout

Concrete edge breakout may occur if an anchor channel close to an edge is overloaded in shear applied toward the edge and breaks off the concrete between the anchor channel and edge. The corresponding capacity is calculated as

$$V_{ch} = V_b \cdot \psi_i = \alpha_{ch,V} \cdot \sqrt{f_c'} \cdot c_{a1}^{4/3} \cdot \psi_i$$

The product specific parameter $\alpha_{ch,V}$ takes into account the influence of the anchor channel geometry (typically determined as 10.5 $lb^{0.5}/in.^{0.33}$); and the modification factors ψ_i account for various other influences (for example, if the anchor channel is placed near a corner); f_c' is the specified concrete compressive strength; and c_{a1} is the edge distance to the anchor (Fig. 3). Note that the first step of the verification is the distribution of the loads imposed by the channel bolts to the anchors of the channel. That is, anchors closer to the applied load are assigned a higher load and vice versa. In the second step, the steel- and concrete-related failure modes involving anchors are verified anchor by anchor ("anchor under consideration"). This approach allows total flexibility of the number and location of the channel bolts as well as the length of the channel. To carry out extensive calculations, the engineer can use free design software (for example, JORDAHL® EXPERT).

Early studies on shear-loaded anchors showed that anchor reinforcement such as hairpins will substantially increase the shear capacity.[7] Also, reinforcing bars with end plates without concrete cover have been used to tie back the shear load.[8] This is a method that is common in reinforced concrete design to resist high-shear loads at bearing pedestals, end bearings of beams, or pinned connections of precast elements. Another focus has included the surface reinforcement typically present at the edges of concrete decks (vertically placed hairpins combined with horizontal edge reinforcement oriented parallel to the slab edge and passing through the hairpin bend) forming the basis for codified design rules for concrete anchors and anchor channels (Fig. 4).[2]

Reinforcing Bar Yielding of Anchor Reinforcement

Provided the anchor reinforcement has sufficient bond length in the concrete edge breakout body and end anchorage length outside that body (Fig. 4), reinforcing bar yielding of the anchor reinforcement may occur if the shear load transferred from the loaded anchor of the channel to the reinforcing bars surpasses the yield strength of the reinforcing bars. Taking the eccentricity into account, the corresponding shear capacity is calculated as

$$V_{ca,y} = N_{ca,re} \big/ (1 + e_s/z) = \sum A_s \cdot f_y \big/ (1 + e_s/z)$$

The eccentricity e_s is defined as the distance between the shear load applied through the channel bolt and the reinforcing bar. The internal lever arm of compression and tension force in the concrete element z is estimated as $0.85 \cdot \min(h - h_{ch} - 0.5d_b;\ 2h_{ef},\ 2c_{a1})$, where h is the height of the concrete element (for example, the concrete deck); h_{ch} is the height of the anchor channel; d_b is the diameter of the reinforcing bar; and h_{ef} is the embedment depth of the anchor channel (Fig. 3 and 4). A_s and f_y are the total cross-sectional area and the yield strength of the reinforcing bars, respectively. Note that the lateral distance between the anchor reinforcement and anchor must not exceed $0.5c_{a1}$ and that an edge reinforcement must be provided.[4] So far, the design of anchor reinforcement for anchor channels has been codified only for surface reinforcement and has not been codified for hairpins.

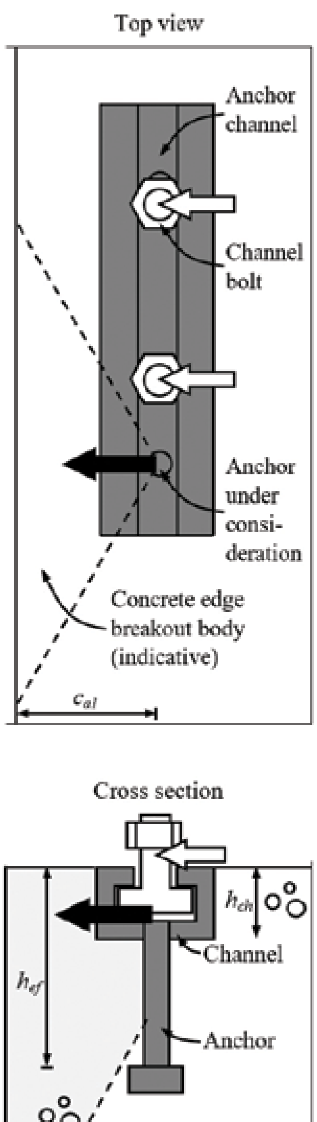


Fig. 3: Assumed load transfer from the channel bolt via the channel to the anchor (schematic, ignoring equilibrium of forces)

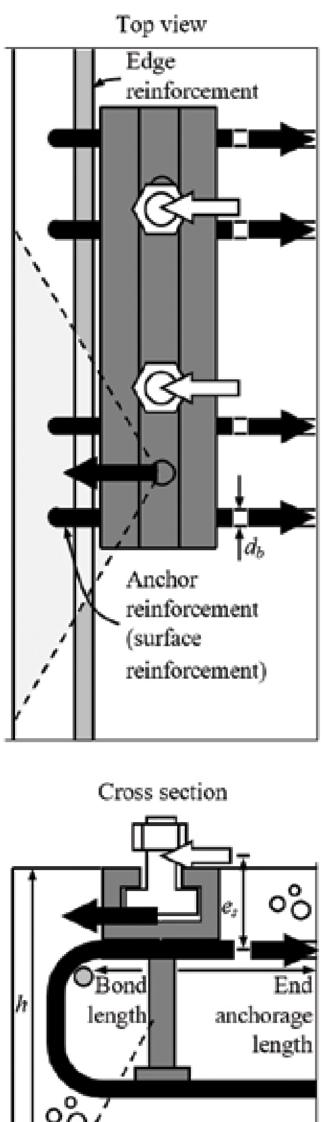


Fig. 4: Surface reinforcement used as anchor reinforcement can be hardly anchored in the concrete edge breakout body

Advanced Concept of Anchor Reinforcement for Anchor Channels

Conventionally, shear-loaded anchor channels close to concrete edges are designed by checking either for concrete edge breakout, if no anchor reinforcement is provided, or the reinforcing bar yielding, if anchor reinforcement is provided and designed with sufficient bond length in the concrete edge breakout body and sufficient anchorage length outside the assumed breakout body. This means that in the latter case, only the reinforcing bar capacity is taken into account and the contribution of the concrete capacity is neglected. For typical anchor channel applications, where the edge distance c_{a1} is small, however, the design capacity of the anchor reinforcement is limited because of a relatively short bond length within the concrete edge breakout body.

To overcome the problem of bond failure of the anchor reinforcement in the concrete edge breakout body, the JORDAHL® Edge confinement JEC was developed (Fig. 5(a)) to enhance the capacity of JORDAHL® Anchor channels JTA. The JEC anchor reinforcement consists of an end plate with welded reinforcing bars—melted and made in the United States or Canada. One pair of anchor reinforcement with the end plate is placed at every anchor of the channel without a structural connection. Anchor channel and edge confinement are included in the free design software JORDAHL® EXPERT (Fig. 5(b)).

Due to the presence of the end plate, bond failure in the concrete edge breakout body is precluded and the yielding capacity of the anchor reinforcement can be used with sufficient end anchorage length outside the concrete edge breakout body (Fig. 6).

To back up the advanced concept that combines concrete capacity and reinforcing bar capacity for anchor channels with edge-confining anchor reinforcement, and to observe the hierarchy of failure modes as well as crack patterns, nonlinear finite element simulations and tests on cast-in anchor channels loaded by one or two channels bolts were carried out:

- The nonlinear finite element simulations were performed to investigate the performance of anchor channels with JEC anchor reinforcement in terms of load-displacement behavior and to optimize the anchor reinforcement to match with the capacity of the anchor channels (Fig. 7(a)). The finite element simulations allowed parametric studies on the influence of edge distance, anchor spacing, diameter of reinforcing bars, thickness of concrete element, and

(a)

(b)

Fig. 5: An anchor channel with edge confinement: (a) JORDAHL® Anchor channel JTA W50/30 with JORDAHL® Edge confinement JEC; and (b) free design software JORDAHL® EXPERT

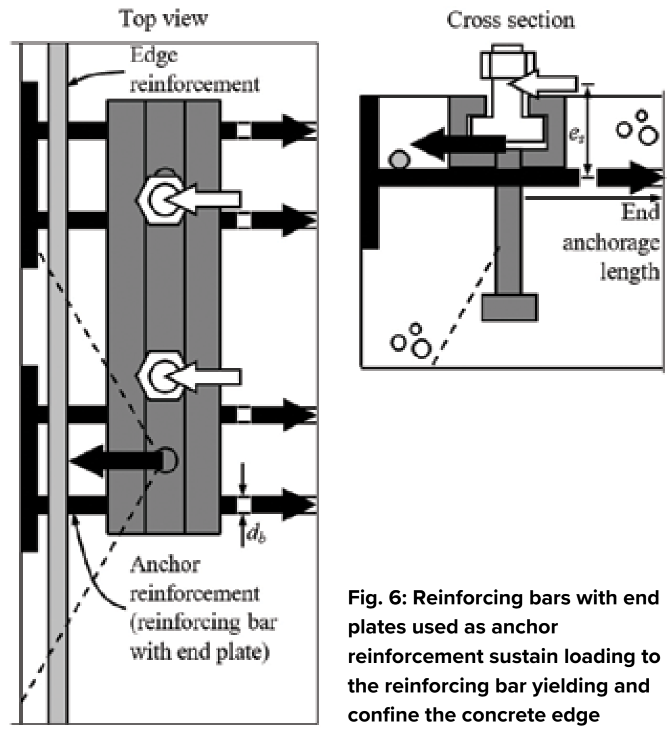
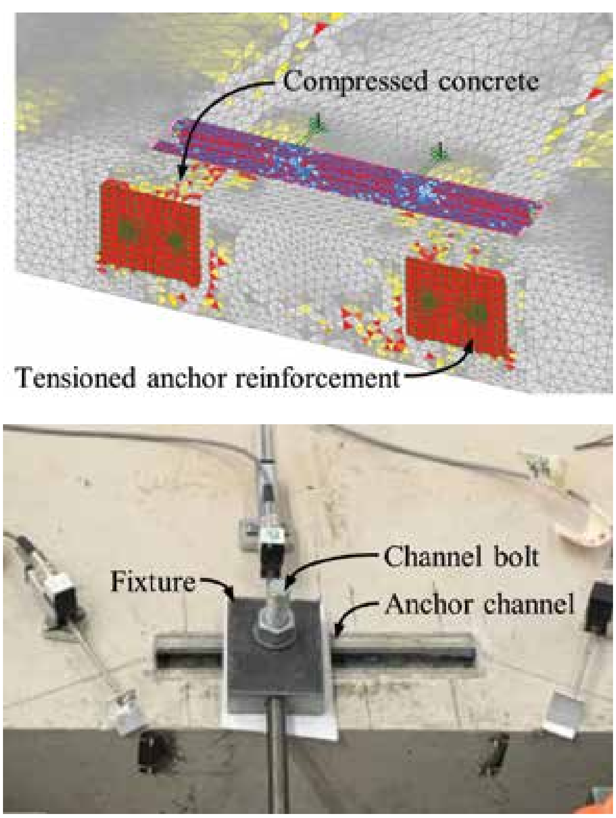


Fig. 6: Reinforcing bars with end plates used as anchor reinforcement sustain loading to the reinforcing bar yielding and confine the concrete edge

positioning of channel bolts. Moreover, the interaction of tension and shear load was analyzed; and

- The tests on cast-in anchor channels without anchor reinforcement and with JEC anchor reinforcement were conducted to verify the design concept (Fig. 7(b)). The experimental campaign was carried out at the Institute of Construction Materials (IWB), University of Stuttgart, Stuttgart, Germany. Including shear and tension tests, the tests comprised eight test series, each of which was tailored to study a particular failure mode. The reinforcing bars of the anchor reinforcement were strain gauged to measure the load share taken up by reinforcing bars. The channel bolts were loaded by an actuator with a calibrated load cell. The displacement of the loading fixture and the concrete in the breakout zone were measured. The displacements of the concrete were used to verify crack widths for the serviceability limit state.

The finite element simulations and tests showed that once the applied shear load approaches the concrete edge breakout capacity of the corresponding anchor channel without anchor reinforcement, the anchor reinforcement increasingly picks up the load. The concrete significantly contributes to the total capacity at design load levels (Fig. 8(a)). The maximum contribution of the concrete is approximately equal to the total concrete edge breakout capacity of anchor channels without anchor reinforcement because the brittle concrete cracks prior to the activation of the ductile reinforcing bars of the anchor reinforcement. At higher loads, well above design load levels,



(a)

(b)

Fig. 7: Simulations and physical tests were used to investigate behavior of the anchors and anchor reinforcement: (a) finite element simulation; and (b) test on cast-in anchor channel with anchor reinforcement

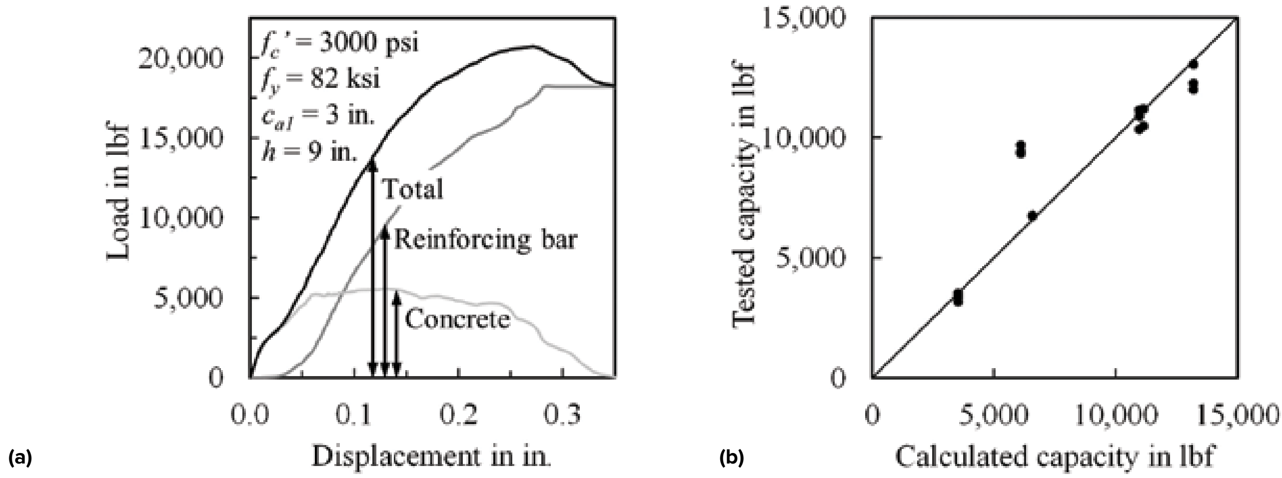


Fig. 8: Example test results: (a) contribution of concrete and JORDAHL® Edge confinement JEC reinforcing bars for a test on JORDAHL® Anchor channels JTA W50/30 with channel bolts JB; and (b) verification of the design model for most loaded anchor[10]

the concrete struts that form between the loaded bolts and the end plates may fail and the channel may experience considerable lateral bending. The observations are in agreement with the findings of a recent research project,[9] which verified that the ultimate capacity of a shear-loaded anchor plate is determined by a combination of concrete capacity and reinforcing bar capacity. Thus, higher utilization can be allowed, resulting in more economic designs of anchor plates.

The anchor reinforcement with edge confinement increases the shear capacity of an anchor channel by a factor of up to four compared to the same anchor channel without anchor reinforcement. The tested high capacity confirmed the advanced concept to combine concrete capacity and reinforcing bar capacity. This quantity, the increase factor, is high because the anchor reinforcement can develop yielding.[10] Amendments to the existing set of design equations were made to limit lateral bending of the channel and to avoid strut failure. For verification of the advanced concept, the calculated mean capacity was compared with the tested capacity (Fig. 8(b)). Though one of the newly introduced design equations for shear appears to be somewhat conservative, the comparison showed a good agreement (test-calculated capacity ratio of 1.07, coefficient of variation equal to 20% for p-value of 0.90). Moreover, the amended set of design equations correctly predicts the governing failure mode for any particular case (for example, yielding of reinforcing bars).

For common applications, the design of interacting tension and shear loads is decisive. Typically, concrete elements (for example, concrete decks of tall buildings) are too thin to accommodate anchor reinforcement for the tension load. In cases for which anchor reinforcement is feasible for the shear load only, the anchor reinforcement will result in a lower increase factor of the overall capacity for anchor channels under combined tension and shear than for anchor channels loaded only in shear.

In Summary

As with concrete anchors, the overall shear capacity of anchor channels installed close to the edge of concrete elements is typically governed by the concrete edge breakout capacity. It can be improved by anchor reinforcement for which the maximum capacity is determined by reinforcing bar yielding. This capacity, however, can rarely be used due to the small bond length of the anchor reinforcement in the concrete edge breakout body. For this reason, JORDAHL® Edge confinements JEC have been developed as an anchor reinforcement for JORDAHL® Anchor channels JTA. The anchor reinforcements consist of a pair of reinforcing bars with end plates that confine the concrete edge and eliminate bond failure, allowing the utilization of the yielding capacity of the anchor reinforcement, if sufficient end anchorage length is provided outside the concrete edge breakout body.

Another aim was to take the contribution of concrete capacity additionally into account. Nonlinear finite element simulations and tests on cast-in anchor channels were done to analyze the advanced concept. The advanced concept was successfully verified, and additional design checks were proposed.

Thus, the capacity of anchor channels installed close to the concrete edge loaded in shear toward the edge is considerably increased. The increase in capacity is up to four times the concrete capacity, though the effect is diluted to some extent if the anchor channel is loaded in combined tension and shear due to the required interaction design checks.

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Selected for reader interest by the editors.

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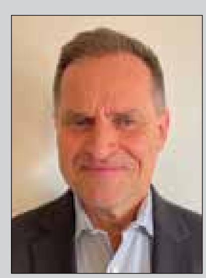

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