HILTI METHOD FOR ANCHOR DESIGN IN GROUTED STAND-OFF CONNECTIONS

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1. INTRODUCTION

1.1 Construction

Grouted stand-off connections are leveled using nuts or shims between the steel plate and the concrete before grouting. Cast-in-place or post-installed anchors are first installed in the concrete. Generally, post-installed mechanical anchors that require torquing or displacement for proper installation must first be set and clamped in accordance with the Instructions for Use (IFU), especially in cases where leveling nuts are used.

When using leveling nuts, these and their accompanying washers are placed and threaded down onto the rod to roughly the location of where the base plate will need to sit. The steel member is then seated on top of the leveling nuts and washers, often with assistance from a crane. The location of the leveling nuts is adjusted to meet the proper member plumbness and other geometric requirements.

When using steel shims, a stack of shims is placed onto the concrete surface, after which the steel member is seated onto them. Adjustments are made by inserting thinner shims until plumbness and other geometric requirements are met.

After the steel member is appropriately leveled, top nuts and washers are placed onto the plate and the nuts are tightened, such as by using the turn-of-the-nut method.

In grouted connections, the grout can either be “dry pack” grout or flowable, non-shrink grout. Both methods of grouting require proper detailing, specification requirements, installation procedures, and inspection during and after installation. All of these are unique to the grouting method.

Dry-pack grouts, where grout is mixed to a putty-like consistency and packed around the perimeter of the connection, are susceptible to errors that could lead to incomplete filling of the space between the plate and the concrete. There is also a risk of incomplete mixing. Such conditions could lead to cracking, voids, degradation, inconsistent/low grout strength, and uneven stress transfer between the steel plate and the grout. Cracking and voids allow moisture to enter and pool, which can lead to accelerated corrosion and degradation of the connection, even in comparison to an ungrouted connection. An example of a poorly installed dry-packed grout pad is given in Figure 1, where the surface-only packing has led to corrosion and deterioration. With dry packing, a high degree of care in mixing, placement of adequate material to fill the void space, consolidation through vibration or tamping, and verification that the entire space has been filled are all essential. For these reasons, dry packing is recommended only if you can ensure the quality of installation meets engineering requirements.

Figure 1. Poorly installed dry-packed grout pad

Flowable, non-shrink grout enclosed within formwork is often employed to completely fill the void space between the steel plate and the concrete. Nevertheless, proper proportioning, mixing, and installation practices are still important for the proper functioning of the grout pad. Without proper placement, it is possible for air to become entrapped at the interface between the grout pad and the steel plate, which can be a possible location for water ingress and pooling that may lead to durability issues and uneven stress transfer between the steel plate and the grout. Care should be taken to avoid air entrapment caused by, for example, vibration, well-placed air escape holes and formwork placement. Figure 2 shows proper installation for two types of base plate connection, where a flowable grout is set inside a confined region and allowed to completely fill the intended void space.

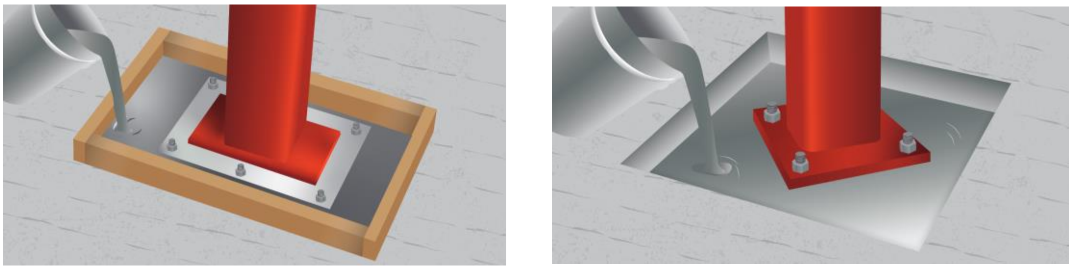


Figure 2. Installation of flowable grout for equipment support (left) and recessed column base (right)

For more information on structural grouting practices and the potential consequences of improper grouting or grouting out of sequence, see this article by Mullins and Parker [8] from STRUCTURE magazine.

1.2 Structural behavior

1.2.1 Steel resistance of anchors in grouted connections

Steel resistance of anchors in grouted connections has been studied by a number of authors, including Adihardjo and Soltis [2], Nakashima [9], Gresnigt et al. [6], Gomez et al. [5], Fichtner [4], and McBride [7]. McBride [7] provides a summary of these research studies as well as behavioral explanations.

Shear force transfer in grouted stand-off connections is complex, involving mechanisms of direct shear resistance of the anchors as well as friction due to compression forces acting on the connection. As the connection displaces in shear, cohesion at the plate/grout and grout/concrete interfaces is quickly overcome, leading to sliding along the respective planes and engagement of the anchor steel in dowel action. The deformed anchors are restrained from downward displacement and impose clamping forces on the connection that adds to the external compression forces. Figure 3 illustrates idealized force transfer mechanisms.

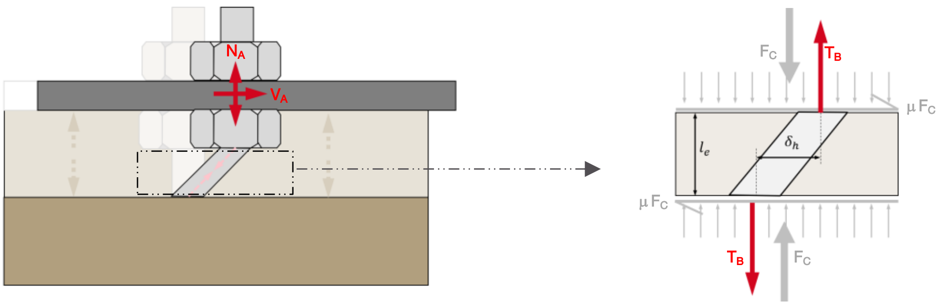


Figure 3. Idealized displaced shape of anchor in grouted stand-off connection (left). View of forces acting on free body of displaced anchor (right)

In addition, as the connection deforms in shear, struts form between anchors, causing cracking when the tensile strength of the grout is overcome. Figure 4 shows the cracking and crushing patterns from combined shear and moment on a grout pad from McBride [7].

Figure 4. Cracking behavior of grout pads under shear and moment loading: profile view (left) and plan view (right).

Compressive forces are shared between the grout pad and by anchors or shim stacks, as applicable. However, when grout pad tensile strength is exceeded by design forces, a reduced footprint of grout pad should be used for considering compressive resistance. This reduced footprint should consider the loss of grout outside the bolt line and should also consider a 45-degree cutaway from the compressive toe of the overturning moment on the connection. This translates to subtracting one grout pad thickness from the sides of the grout pad where bending is present as shown in Figure 5. For the purposes of section design, caution should be exercised when the thickness of the grout pad, t_{grout}, exceeds the distance from the edge of the steel plate to the centerline of the anchors in a grouted stand-off connection. Caution should also be exercised when the cracking strength of the grout pad is exceeded due to shear forces on the connection. It is therefore recommended as a default assumption to distribute overturning moments on the connection only to the area enclosed by anchors in a grouted stand-off connection. This should be done unless it can either be verified that design loads will not cause grout pad cracking or that active measures are made to confine the grout pad (e.g., enclosing the grout pad in an FRP wrap).

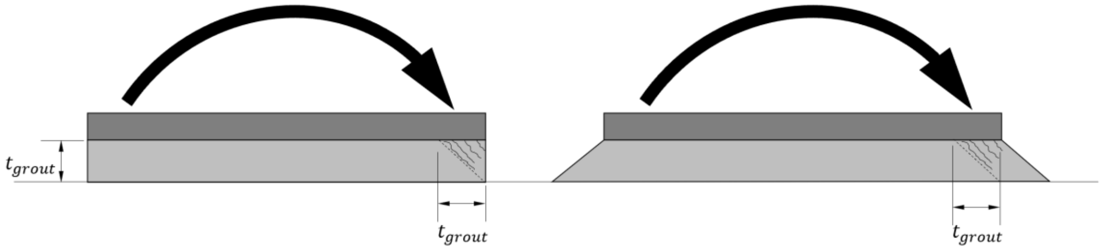


Figure 5. Crushing due to the compression toe of bending moment acting on a grout pad.

Tensile forces are taken directly by anchors in stand-off connections when the lift-off load from pre-tensioning and clamping forces are overcome. It can conservatively be assumed that all tension loads travel directly into anchors.

The interaction between shear and tensile forces in grouted connections involves all the mechanisms described above. However, McBride [7] found that the ACI 318 [1] provisions for steel resistance in grouted connections (described in Section 2.1.2 below) are adequate for describing steel resistance. Similarly, EN 1992-4 [3] provides equations for steel resistance of anchors in grouted connections based on the work of Fichtner (2012).

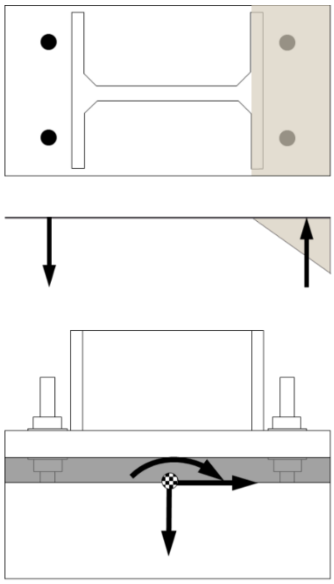
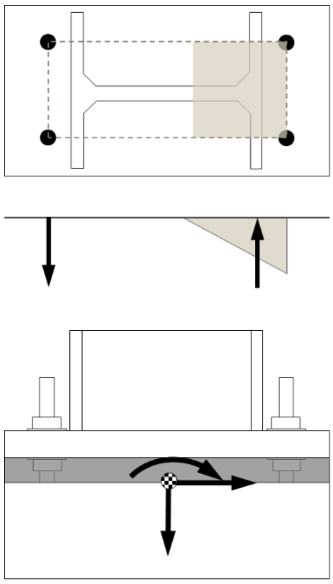
1.2.2 Concrete resistance of anchors in stand-off connections

Concrete breakout resistance in tension is assumed to be unaffected in grouted stand-off conditions. Concrete breakout forces in shear, however, may be amplified by the displacement of the anchor and by additional moment traveling through the connection. These factors should be considered for both ungrouted and grouted connections, resulting in the reduction factor given in Eq. (4). See the accompanying article on ungrouted connections for more details.

2. DESIGN METHODS

Hilti PROFIS Engineering offers two solutions for the design of anchors in grouted stand-off connections: design compliance with Eurocode EN 1992-4 [3] and the Hilti Solutions for Fastenings (SOFA) Method. The EN 1992-4 approach generally provides conservative solutions to design. The Hilti SOFA Method provides state-of-the-art solutions that are less conservative and restrictive than the Eurocode.

The primary differences between Eurocode design in accordance with EN 1992-4 design and Hilti SOFA Method are as follows:

	Eurocode design	SOFA design
Load distribution	The full area of the grout pad is considered for load distribution, per [3]. 	The compression area is defined by the centroid of the bolts. See calculation details in section 2.1.  Figure 6. Compressive area assumptions for Eurocode design (left) and SOFA design (right).
Shear steel resistance	*See Section 2.2.2.* In most cases, bolt bending verification is performed per [3] Eq. (7.37). In very specific cases, [3] Eq. (7.36) can be used.	*See Section 2.3.2.* The steel shear resistance with a grout pad is permitted to follow Eq. (2) for grout pad thickness up to 100mm for static conditions.
Steel interaction	*See Section 2.2.3.* When [3] Eq. (7.37) is used, interaction between axial and shear steel failure is satisfied directly. When [3] Eq. (7.36) is used for shear resistance, interaction is not applicable.	*See Section 2.3.3.* Steel interaction between axial and shear forces is performed using [3] Table 7.3.
Concrete failure modes in shear	*See Section 2.2.5.* Pryout is calculated per [3] Section 7.2.2.4. Concrete edge breakout should consider the additional effect of an overturning moment per “Note” in [3] Section 7.2.2.5.	*See Section 2.3.5.* Pryout is calculated per [3] Section 7.2.2.4. Concrete edge breakout is calculated per [3] Sections 7.2.2.5, but applies the reduction factor $\psi_{b,g}$ from Eq. (5) below to account for bending moment effects.
Concrete interaction	*See Section 2.2.6.* Interaction between tension and shear concrete failure modes per [3] Section 7.2.3.	*See Section 2.3.6.* Interaction between tension and shear concrete failure modes per [3] Section 7.2.3.

Minimum edge distance	When bending verification is used, larger of $10h_{ef}$ and $60d$ from the edge per [3] Section 7.2.2.5 [1]. When [3] Eq. (7.36) is used for shear resistance, minimum edge distance per cover and product requirements.	Minimum edge distance per cover and product requirements.

1. The calculation of shear resistance for EN 1992-4 designs has reduced shear resistance at larger grout pad thicknesses, whereas the Hilti SOFA Method recognizes the additional benefits of mechanical forces acting on grouted connections to permit the simplified design assumption that the shear resistance is constant with increasing grout pad thickness.
2. EN 1992-4 designs are restricted to cases with no bending moment on the connection. The Hilti SOFA Method permits designs with bending moment.
3. EN 1992-4 designs are restricted to grout pad thicknesses no greater than $40\,mm$ and $5d$, whichever is less. The Hilti SOFA Method is applicable to grout pads with thicknesses up to $130\,mm.$

2.1 Load distribution

For the purposes of bearing and bending resistance of the grout section, PROFIS Engineering removes the perimeter area encompassed by the centroid of the bolt line to account for the compressive struts between anchors. This assumption is illustrated in Figure 7. It follows that for single anchors or anchors arranged in a single row, no area will be enclosed by the bolt line, resulting in no usable grout area. In these cases, PROFIS Engineering conservatively assumes that the grout does not contribute to resistance and performs the bolt bending checks described in the accompanying ungrouted stand-off connection paper. Furthermore, if the thickness of the grout pad exceeds the distance from the centerline of any anchor to the edge of the base plate, PROFIS Engineering suggests to the user that bending of the anchors be considered due to the possibility of 45-degree crushing below the compressive toe of bending moments extending inside the bolt line. If user analysis determines that the full grout section can be used (e.g., after assessment that cracking and crushing will not occur), PROFIS Engineering will allow the full section of the grout pad to be used for section analysis.

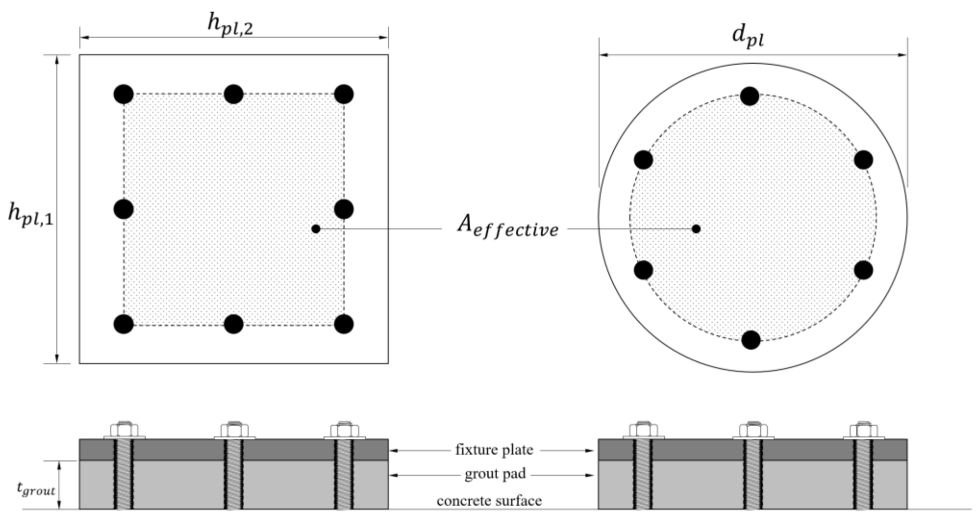


Figure 7. Default assumptions about loss of section due to cracking and crushing for analysis of cross-section forces

2.2 EN 1992-4 Design

2.2.1 Axial steel resistance

Axial steel design resistance, $N_{Rk,s}$, is determined in accordance with EN 1992-4 Section 7.2.1.3.

2.2.2 Steel shear resistance

In EN 1992-4 [3] provisions, the steel resistance of anchors with lever arm considers the failure by bolt bending, given in EN1992-4, Eq. 7.37. The bolt bending equations are given in the companion article for ungrouted stand-off connections.

In certain cases, considering the limitations from EN 1992-4, 6.2.2.3 (2), Eq. 7.36 as shown in Eq. (1) is used.

1. At least two fasteners spaced at least $10d$ apart resist shear in the direction(s) of shear force.
2. There is no bending moment or net tension on the connection.
3. The grout thickness is no greater than the minimum of $40\ mm$ and $5d$ ($5d_o$ for sleeve anchors).
4. The grout pad completely fills the void space between the steel plate and the concrete.
5. The compressive strength of the grout pad is as strong or stronger than the concrete and not less than 30 N/mm^2.

When following PROFIS Engineering's additional SOFA Method design considerations in 2.2 and 2.3, the bending moment limitation (item 2. above) may be relaxed in accordance with PROFIS Engineering's design procedure.

$$V_{Rk,s} = (1 - 0{,}01 \cdot t_{grout}) \cdot k_7 \cdot V^0_{Rk,s} \quad (1)$$

where

t_{grout} = thickness of grout pad, mm

k_7 = ductility factor in accordance with EN 1992-4, 7.2.2.3.1 (2)

$V^0_{Rk,s}$ = characteristic steel shear resistance of anchor in accordance with EN 1992-4 Section 7.2.2.3.1 (1), Eq. (7.36).

2.2.3 Interaction of shear and axial forces for steel failure

When designing for bending using EN 1992-4 Eq. (7.37), the interaction of shear and axial forces is satisfied directly and is represented as a linear relationship between bending and axial force.

By definition, any anchors in tension will make EN 1992-4 design with Eq. (1) invalid.

2.2.4 Concrete failure modes in tension

Tensile concrete failure modes described in EN 1992-4, 7.2.1 (cone, pull-out, combined pull-out and concrete, concrete splitting, and concrete blow-out failure) are determined for grouted stand-off connections in the same manner as for other connections without modification. Because Eq. (1) can only be used when there is no moment or tension on the connection, these provisions are only applicable to EN 1992-4 design when bolt bending is considered.

2.2.5 Concrete failure modes in shear

Shear pryout capacity of grouted stand-off connections remains identical to that in EN 1992-4 Section 7.2.2.4 whether Eq. (7.36) or Eq. (7.37) are used for anchor steel shear capacity.

However, when designing for bending using EN 1992-4 Eq. (7.37), design is restricted to a minimum edge distance of the larger of $10h_{ef}$ and $60d$ in accordance with EN 1992-4 Section 7.2.2.5. For edge distances larger than this value, shear breakout resistance is not required to be calculated. Where closer edge distances are needed, the EN 1992-4 does not offer a solution and it is recommended to use the Hilti SOFA Method.

2.2.6 Interaction of shear and axial forces for concrete failure

Interaction between tension and shear concrete failure modes per EN 1992-4 Table 7.3 and shall satisfy either Eq. (7.55) or Eq. (7.56). Where supplementary reinforcement is present, EN 1992-4 Section 7.2.3.2 applies.

2.3 Hilti SOFA Method Design

2.3.1 Axial steel resistance

Axial steel design resistance, $N_{Rk,s}$, is determined in accordance with EN 1992-4 Section 7.2.1.3.

2.3.2 Steel shear resistance

In ACI 318, 17.7.1.2.1[1], the steel shear resistance of anchors in grouted stand-off connections may be taken as 80% of the nominal shear steel resistance of the anchor. The Hilti SOFA Method adopts this design resistance. For the purposes of European design, variables have been translated to European terms and the k_7 has been incorporated as shown in Eq. (2). For continuity, PROFIS Engineering has maintained limitations 1., 4., and 5. from Section 2.2.2 of this document, but has relaxed limitations 2. and 3. for grout pads up to 100 mm thick.

$$V_{Rk,s,grout} = 0.8 \cdot k_7 \cdot V^0_{Rk,s} \tag{2}$$

2.3.3 Interaction of shear and axial forces for steel failure

After converting $V_{Rk,s,grout}$ and $N_{Rk,s}$ to design values $V_{Rd,s,grout}$ and $N_{Rd,s}$ in accordance with EN 1992-4, Table 7.1, the interaction of shear and tensile forces for the steel failure mode is determined in accordance with EN 1992-4, Table 7.3 as shown in Eq. (3). By definition, any anchors in tension will make EN 1992-4 design with Eq. (1) invalid, so this equation is only applicable to Hilti SOFA Method design.

$$\left(\frac{N_{Ed}}{N_{Rd,s}}\right)^2 + \left(\frac{V_{Ed}}{V_{Rd,s,grout}}\right)^2 \leq 1.0 \tag{3}$$

2.3.4 Concrete failure modes in tension

Tensile concrete failure modes described in EN 1992-4 7.2.1 (cone, pull-out, combined pull-out and concrete, concrete splitting, and concrete blow-out failure) are determined for grouted stand-off connections in the same manner as for other connections without modification.

2.3.5 Concrete failure modes in shear

Shear pryout capacity of grouted stand-off connections remains identical to that in EN 1992-4 Section 7.2.2.4.

Shear breakout resistances of ungrouted stand-off connections remain identical to those in EN 1992-4, 7.2.2.5 with the multiplier $\psi_{b,g}$ as given in Eq. (5) on the resistances in EN 1992-4 Eq. (7.40) to account for the bending forces transmitted through the anchor bolt to the concrete.

$$\psi_{b,g} = \frac{1}{1 + \frac{C t_{grout}}{d^{3/4}}} \tag{4}$$

where

C = a constant representing the elastic interaction between the anchor and concrete

= 0.043 for grouted connections and carries units of $1/mm^{0.25}$

2.3.6 Interaction of shear and axial forces for concrete failure

Interaction between tension and shear concrete failure modes per EN 1992-4 Table 7.3 and shall satisfy either Eq. (7.55) or Eq. (7.56). Where supplementary reinforcement is present, EN 1992-4 Section 7.2.3.2 applies.

3. PROFIS ENGINEERING FUNCTIONALITY

Within the Hilti PROFIS Engineering software concrete fixing module, stand-off functionality (2) can be found in the base plate tab (1), as shown in Fig. 8. When stand-off with grouting is selected (3), the default restraint level is assumed to be $\alpha_M = 2$. The user can modify this value (4). By default, Hilti high strength epoxy grout CB-G EG is selected, with a compressive strength of 120N/mm^2 (5). The user can also select any multipurpose grout and enter the desired concrete strength (6).

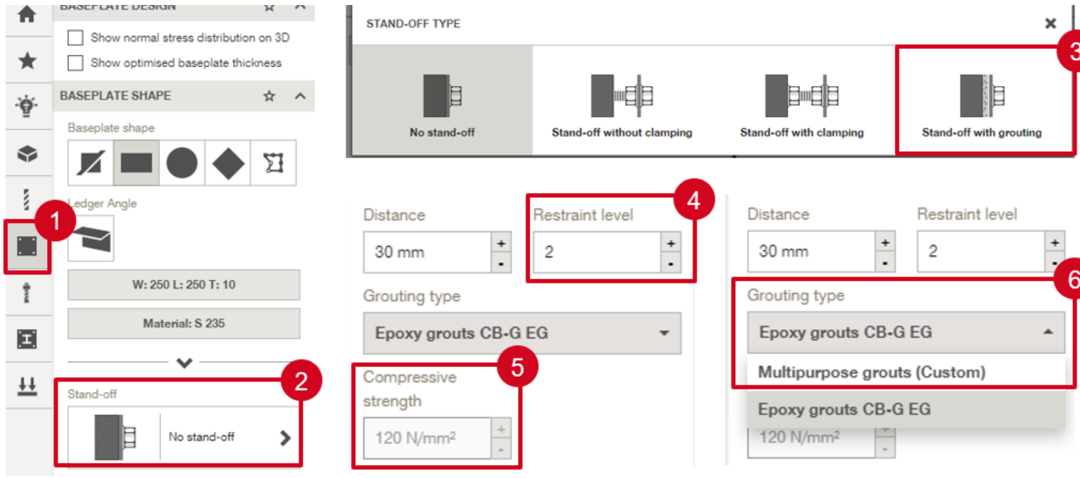


Figure 8. Clamping, restraint, and grout property options in PROFIS Engineering.

Within the loads tab (1) there are several options for design, and by default the standoff verification is undertaken according to EN 1992-4 ((2), Fig. 8).

To proceed with the SOFA standoff design method, select this from within the standoff section (3).

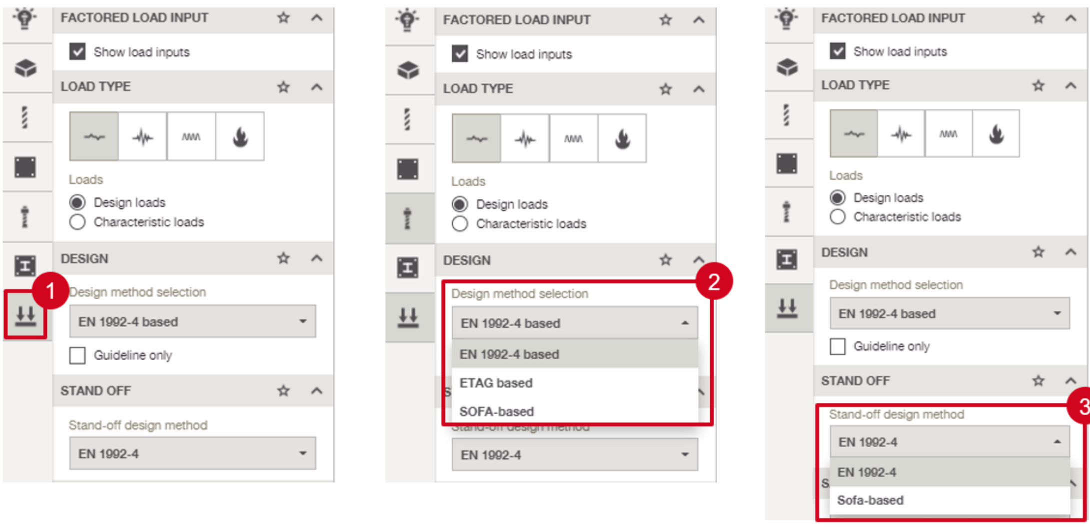


Figure 9. Choice of design method in PROFIS Engineering.

4. DESIGN EXAMPLE

Problem statement:

1. Verify the steel resistance of the anchors in the grouted stand-off base plate connection below for both EN 1992-4 design and for Hilti SOFA Method design. Assume $\alpha_m = 2.0$.
2. Determine the value of the multiplication factor $\psi_{b,g}$ to be applied to the shear concrete breakout failure mode.

Given:

- Hilti HIT-RE 500 V4 adhesive anchor with Grade 8.8 M24 threaded rod

d	$= 24\ mm$	
A_s	$= 352.7\ mm^2$	
f_{uk}	$= 800\ N/mm^2$	
γ_{Ms}	$= 1.5$	ETA-20/0541, Table C.1 for normal resistance
γ_{Ms}	$= 1.25$	ETA-20/0541, Table C.7 for shear resistance

- Connection properties and dimensions

Grout is non-shrink, flowable, and completely fills the space between the base plate and concrete surface.

f_{ck}	$= 40\ MPa$	Characteristic concrete strength
f_{grout}	$= 50\ MPa$	Characteristic grout strength
t_{grout}	$= 44\ mm$	Grout thickness
e_1	$= 60\ mm$	Distance from center of plate to concrete
a_3	$= 12\ mm$	Assumed half-diameter spalling depth

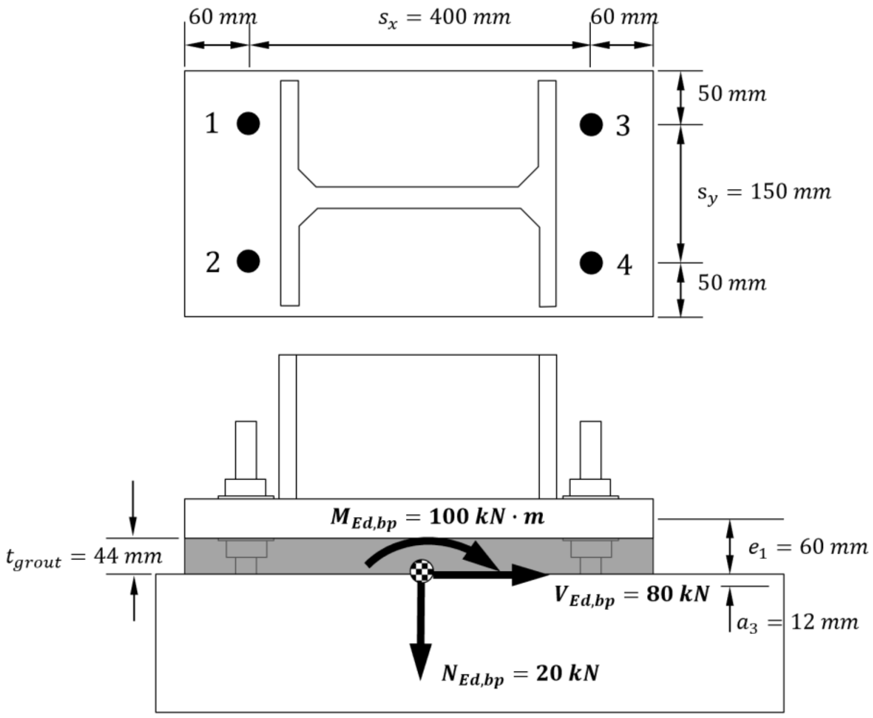


Figure 10. Design example parameters.

Initial checks from EN 1992-4, 6.2.2.3 (2):

1. At least two fasteners spaced at least $10d$ apart resist shear in the direction(s) of shear force.
   $10d = 10 \cdot 24\ mm = 240\ mm < 400\ mm$
   → Okay for both methods.
2. Bending moment or net tension on the connection are prohibited. (Only applies to EN 1992-4 design).
   Bending moment is present on the connection.
   → EN 1992-4: Not suitable for use with Eq. (1). Okay with bending calculation.
   → Hilti SOFA Method: Okay to use Eq. (2).
3. The grout thickness is no greater than the minimum of $40\ mm$ and $5d$ ($5d_o$ for sleeve anchors).
   $t_{grout} = 44\ mm > 40\ mm$
   → EN 1992-4: Not suitable for use with Eq. (1). Okay with bending calculation.
4. → Hilti SOFA Method: Okay to use Eq. (2).
5. The grout pad completely fills the void space between the steel plate and the concrete.
   Confirmed → Okay for both methods.
6. The compressive strength of the grout pad is as strong or stronger than the concrete and not less than 30 N/mm^2.
   Confirmed → Okay for both methods.

Calculation of basic threaded rod steel resistances:

$N_{Rk,s}$	= characteristic tensile resistance	
	$= A_s \cdot f_{uk}$	ETA-20/0541 Table C1
	$= 352.7\ mm^2 \cdot 800\ N/mm^2$	
	$= 282\ kN$	
$N_{Rd,s}$	$= N_{Rk,s}/\gamma_{Ms,N}$	EN 1992-4 Table 7.1
	$= 282\ kN/1.5$	
	$= 188\ kN$	
	$\geq$ 140 kN	Okay
k_6	$= 0.5$	EN 1992-4 Sec. 7.2.2.3.1 (1)
$V^0_{Rk,s}$	$= k_6 \cdot A_s \cdot f_{uk}$	EN 1992-4 Eq. (7.34)
	$= 0.5 \cdot 352.7\ mm^2 \cdot 800\ N/mm^2$	
	$= 141\ kN$	

EN 1992-4 design for steel resistance:

EN 1992-4 design is **invalid** in accordance with EN 1992-4, 6.2.2.3 (2) for the following reasons:

- Grout pad thickness $t_{grout} = 44\ mm$ exceeds maximum thickness of $40\ mm$
- Bending moment is present on the connection

Therefore, bolt bending must be calculated in accordance with EN 1992-4, 6.2.2.3 (3).

Normal forces on anchors:

N_{Ed}	$= -\left(\frac{1}{2}\frac{M_{Ed,bp}}{s_x}\right) + \frac{N_{Ed,bp}}{4}$	Anchors 1 and 2 (Fig. 12)
	$= -\left(\frac{1}{2}\frac{100\ kN\cdot m}{0.4\ m}\right) + \frac{20\ kN}{4}$	
	$= 120\ kN$	
N_{Ed}	$= \frac{1}{2}\frac{M_{Ed,bp}}{s_x} + \frac{N_{Ed,bp}}{4}$	Anchors 3 and 4 (Fig. 12)
	$= -\frac{1}{2}\frac{100\ kN\cdot m}{0.4\ m} + \frac{20\ kN}{4}$	
	$= 130\ kN$	

Shear forces on anchors:

V_{Ed}	$= \frac{V_{Ed,bp}}{4}$	All anchors (Fig. 12)
	$= \frac{80\ kN}{4}$	
	$= 20\ kN$	

Summary of loads by anchor:

Anchor	N_{Ed} (kN)	V_{Ed} (kN)
1	-120	20
2	-120	20
3	130	20
4	130	20

e_1	$= 60\ mm$	EN 1992-4 Fig. 6.6 (a)
a_3	$= \frac{d}{2}$	EN 1992-4 Eq. (6.2)
	$= \frac{24\ mm}{2}$	
	$= 12\ mm$	
l_a	$= e_1 + a_3$	EN 1992-4 Eq. (6.2)
	$= 60\ mm + 12\ mm$	
	$= 72\ mm$	
$M_{Rk,s}$	$= M^0_{Rk,s}\left(1 - \frac{N_{Ed}}{N_{Rd,s}}\right)$	EN 1992-4 Eq. (7.38)
	$= 897\ N \cdot m\left(1 - \frac{\lvert -120\ kN \rvert}{188\ kN}\right)$	Anchors 1 and 2 (Fig. 12)
	$= 325\ N \cdot m$	
	$= 897\ N \cdot m\left(1 - \frac{130\ kN}{188\ kN}\right)$	Anchors 3 and 4 (Fig. 12)
	$= 277\ N \cdot m$	
$V_{Rk,s,M}$	$= \frac{\alpha_M \cdot M_{Rk,s}}{l_a}$	EN 1992-4 Eq. (7.37)
	$= \frac{2.0 \cdot 325\ N \cdot m}{72\ mm}$	Anchors 1 and 2 (Fig. 12)
	$= 9.02\ kN$	
	$= \frac{2.0 \cdot 277\ N \cdot m}{72\ mm}$	Anchors 3 and 4 (Fig. 12)
	$= 7.70\ kN$	
$V_{Rd,s,M}$	$= V_{Rk,s,M}/\gamma_{Ms}$	EN 1992-4 Table 7.2
	$= 9.02\ kN/1.25$	Anchors 1 and 2 (Fig. 12)
	$= 7.22\ kN$	
	$= 7.70\ kN/1.25$	Anchors 3 and 4 (Fig. 12)
	$= 6.16\ kN$	
$\beta_{N,V}$	$= \frac{V_{Ed}}{V_{Rd,s,M}}$	Utilization for EN 1992-4
	$= \frac{20\ kN}{7.22\ kN}$	Anchors 1 and 2 (Fig. 12)
	= 277%	Not suitable
	$= \frac{20\ kN}{6.16\ kN}$	Anchors 3 and 4 (Fig. 12)
	= 325%	Not suitable

Hilti SOFA Method design for steel resistance

Tensile forces on anchors

Analysis does not indicate that grout cracking will not occur at ultimate load levels. Therefore, assume that the area outside of the perimeter of the bolt line is not available for force distribution.

Distances from anchor centerlines to edge of base plate are greater than the thickness of the grout pad, so 45-degree crushing of edges is assumed not to interfere with base plate behavior.

Calculate the internal lever arm between the tensile steel and the concrete compressive stress block at concrete crushing resistance. Conservatively, omit compressive anchors from section analysis. Using a parabolic compressive reaction for the forces given, an internal lever arm between centroid of Anchors 1 and 2 to centroid of compressive reaction of $z = 370\ mm$ is determined.

Normal forces on anchors:

$$N_{Ed} = -\left(\frac{1}{2}\frac{M_{Ed,bp}}{z}\right) + \frac{N_{Ed,bp}}{4} = -\left(\frac{1}{2}\frac{100\ kN{\cdot}m}{0.37}\right) + \frac{20\ kN}{4} = -140\ kN \text{ (tension)}$$

Anchors 1 and 2 (Fig. 12)

Shear forces on anchors:

$$V_{Ed} = \frac{V_{Ed,bp}}{4} = \frac{80\ kN}{4} = 20\ kN$$

All anchors (Fig. 12)

Summary of loads by anchor:

Anchor	N_{Ed} (kN)	V_{Ed} (kN)
1	140	20
2	140	20
3	0	20
4	0	20

$V_{Rk,s,grout}$	$= 0.8 \cdot k_7 \cdot V^0_{Rk,s}$	EN 1992-4 Eq. (7.36)
	$= 0.8 \cdot 1.0 \cdot 141\ kN$	Anchors 1 and 2 (Fig. 12)
	$= 112.8\ kN$	
$V_{Rd,s,grout}$	$= V_{Rk,s,grout}/\gamma_{Ms}$	EN 1992-4 Table 7.2
	$= 112.8\ kN/1.25$	Applies to tension anchors 1 and 2 (Fig. 12)
	$= 90.3\ kN$	
	$\geq$ 20 kN	Okay
$\beta_{N,V,1/2}$	$= \left(\frac{N_{Ed}}{N_{Rd,s}}\right)^2 + \left(\frac{V_{Ed}}{V_{Rd,s,grout}}\right)^2$	SOFA interaction utilization; Equation (3)
	$= \left(\frac{\lvert -140\ kN\rvert}{188\ kN}\right)^2 + \left(\frac{20\ kN}{90.3\ kN}\right)^2$	Applies to tension anchors 1 and 2 (Fig. 12)
	= 60%	Okay
$\beta_{N,V,3/4}$	$= \frac{V_{Ed}}{V_{Rd,s,M}}$	Shear utilization only
	$= \frac{20\ kN}{90.3\ kN}$	Applies to compression anchors 3 and 4 (Fig. 12)
	= 22%	Okay

*Summary of tensile design capacities and utilizations for EN 1992-4 and Hilti SOFA**

	EN 1992-4*			SOFA		
Anchor	N_{Ed} (kN)	N_{Ed} (kN)	β_N (%)	N_{Ed} (kN)	$N_{Rd,s}$ (kN)	β_N (%)
1	-120	188	64%	140	188	74%
2	-120	188	64%	140	188	74%
3	130	188	69%	0	188	n/a
4	130	188	69%	0	188	n/a

*Note that the EN 1992-4 calculations in the table above are only used in the calculation of $V_{Rd,s,M}$ in the shear summary tables below. The SOFA calculations apply to the tensile calculations of an anchor with the assumed load distribution above due to the presence of grout.

Summary of shear design capacities and utilizations for EN 1992-4 and Hilti SOFA

	Both	EN 1992-4		SOFA	
Anchor	V_{Ed} (kN)	$V_{Rd,s,M}$* (kN)	β_V (%)	$V_{Rd,grout}$ (kN)	β_V (%)
1	20	7.2	277%	90.3	22%
2	20	7.2	277%	90.3	22%
3	20	6.2	325%	90.3	22%
4	20	6.2	325%	90.3	22%

*Reduced grout pad thickness needed to use EN 1992-4 Eq. (7.36)

Summary of interaction design utilizations for EN 1992-4 and Hilti SOFA

Anchor	EN* $\beta_{N,V}$ (EN)	SOFA β_N (%)	β_V (%)	$\beta_{N,V,}$ (SOFA)
1	277%	74%	22%	60%
2	277%	74%	22%	60%
3	325%	n/a	22%	22%
4	325%	n/a	22%	22%

*The combined tensile and shear utilization for EN 1992-4 is incorporated directly into the equation for shear resistance in EN 1992-4 Eq. (7.37). Therefore, the shear utilizations and the combined utilizations are identical.

Calculation of multiplier $\psi_{b,g}$

The multiplier $\psi_{b,g}$ is automatically applied to the shear breakout failure mode in the Hilti SOFA Method design.

$$\psi_{b,g} = \frac{1}{1+\frac{C t_{grout}}{d^{3/4}}} \quad \text{Equation (5)}$$

$$= \frac{1}{1+\frac{0.043/mm^{-1/4}\ 44\ mm}{(24\ mm)^{3/4}}}$$

$$= 0.85$$

The shear breakout resistance will be multiplied by 0.85 in SOFA design.

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