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DESIGN OF SINGLE POST-INSTALLED STEEL SCREW ANCHOR: A NOMOGRAM MODEL AND REASSESSMENT OF EUROCODE 2 PART 4

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ABSTRACT

EN 1992-4:2018 covers the design of post-installed steel screw anchors considering the tensile failure modes such as concrete cone failure, pull-out failure, concrete splitting failure, and steel failure. However, recent findings from the literature have shown that the prediction from the Concrete Capacity Design method, which is the basis for EN 1992-4:2018, may overpredict the resistances of screw anchors due to unique mechanical characteristics and failure behaviour of the screw anchor. Given that screw anchors are widely used in structural and non-structural applications, a graphical tool is presented in this paper that aims to review the design for screw anchors in EN 1992-4:2018 in order to bridge the gap in research knowledge. A novel approach through the introduction of a graphical tool (called nomogram) is proposed by collecting 197 experimental data and verified with four models from product European Technical Assessment (ETA) to provide a rapid and reliable estimation of the resistances (i.e., tensile and shear) of screw anchors for concrete-related failures. The predicted resistances are corroborated with experimental results, and it was shown that approximately 48% to 69% of the predicted results exceeded the experimental results if the coefficient of variation is ranging from 10% to 15%. In the majority of cases, the Concrete Capacity Design method can be unconservative compared to the experimental results. The nomogram is foreseen to be useful for quick preliminary estimation of screw anchor capacities without the need to use detailed design software. It can also serve as an independent verification tool for senior engineers reviewing designs prepared by junior engineers in consulting offices.

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1. Introduction

Fasteners, also known as anchors, are used in steel-concrete connections to create robust joints that effectively transfer forces from steel elements to surrounding concrete [1, 2]. A steel screw anchor is a type of post-installed mechanical anchor in which the load is transferred through the mechanical interlock over the anchor threads and concrete. Screw anchors are relatively new compared to the more conventional expansion and undercut anchors. The use of screw anchors in concrete construction has gained popularity due to their advantages of reliable performance, convenience, and speed of installation [3]. Expansion anchors transfer the load to concrete through the expansion and friction forces at the interface between the anchor and the side wall of the drilled hole in the concrete [4]. On the contrary, undercut anchors transfer the load to concrete through the mechanical interlock at the tip of the anchor.

However, the load transfer mechanism of screw anchors is different from expansion or undercut anchors, and it can be complicated given that there will be multiple struts forming perpendicular to the surface of the screw threads, as compared to concentrated strut at the tip of common mechanical anchors. Kuenzlen and Eligehausen [5] pioneered experimental tests of 500 screw anchors of 8 mm to 18 mm diameter with embedment depth ranging from 30 mm to 110 mm installed in cracked and uncracked concrete of cube compressive strength of 30 MPa. It was observed that the failure modes of screw anchors are similar to bonded anchors, which are concrete cone failure (see Fig. 1(c)) and combined failure (see Fig. 1(e)), depending on the embedment depth of the anchors. Concrete cone failure is characterised by the formation of cone-shaped fractures in concrete, while combined failure is the combination of the pull-out of an anchor with a shallow cone-shaped concrete. The failure loads increased proportionally to $h_{ef}^{1.5}$ (where, h_{ef} is the effective embedment depth of the anchor), which is about 20% less than expansion and undercut anchors under the same embedment depth. Based on the Concrete Capacity Design (CCD) method, Kuenzlen [6] proposed an equation to calculate the reduced effective embedment depth for screw anchors (see Eq. (1)) and incorporated it into an equation developed by Fuchs et al. [7] for expansion and undercut anchors (see Eq. (2)), to predict the characteristic tensile resistance of screw anchors for concrete cone failure [3, 8].

$$h_{ef} = 0.85(h_{nom} - 0.5h_t - h_S) \tag{1}$$

where, h_{nom} is the overall depth of the screw anchor embedded into the concrete, h_t is the distance of the thread pitch, and h_s is the distance between the tip of the screw anchor and first thread.

$$N_{u,c}^0 = k_c\left(\sqrt{f_{ck}}\right)\left(h_{ef}^{1.5}\right) \tag{2}$$

where, k_c is taken as 14.64 for uncracked concrete in SI units, f_{ck} is the characteristic concrete cylinder compressive strength, and h_{ef} is the effective embedment depth of the anchor.

Olsen et al. [3] further expanded the database evaluated by Kuenzlen and Eligehausen [5] by considering another 353 tension tests. The diameter of screw anchors ranged from 6.35 mm to 19.05 mm with h_{ef} ranged from 25.4 mm to

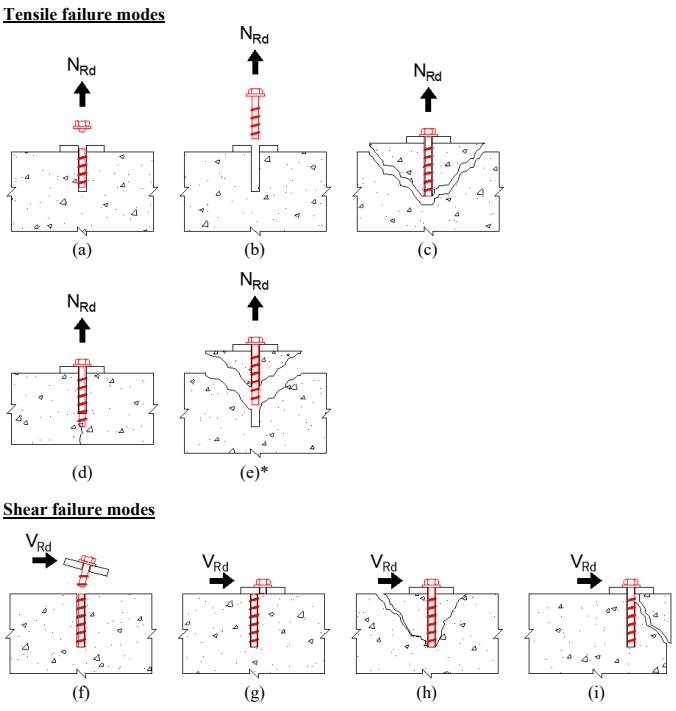

Fig. 1 The failure modes of post-installed screw anchors under tensile load: (a) steel failure, (b) pull-out failure, (c) concrete cone failure, (d) concrete splitting failure, (e) combined pull-out and concrete failure (**Note: This failure mode is not explicitly mentioned in EN 1992-4:2018*), and under shear load: (f) steel failure with a lever arm, (g) steel failure without a lever arm, (h) concrete pry-out failure, (i) concrete edge failure

127 mm. It was concluded in the study that the modified CCD method proposed by Kuenzlen [6] fits their experimental results. Moreover, it was recommended to limit the design model for the spacing between two anchors (minimum spacing taken as the maximum of $0.6h_{\mathrm{ef}}$ or $3.5D$) and the embedment depth (40 mm < h_{nom} < $11D$). Mohyeddin et al. [9] also concluded that the modified CCD method shows a good agreement with their experimental results based on 70 tension tests on screw anchors in early age concrete (24 hours, 36 hours, 48 hours, 72 hours, 7 days, 14 days and 28 days).

Mohyeddin et al. [8] stated that the modified CCD method by Kuenzlen [6] included the results from both concrete cone failure and combined failure. Hence, the tensile resistance of the anchor might be overestimated due to combined failure, and the resistance may be underestimated due to concrete cone failure. Mohyeddin et al. [8] further conducted 182 tension tests and proposed a prediction model based on individual failure modes (i.e., pull-out, combined, and concrete cone failures). The database consists of screw anchors with a diameter ranging from 6.5 mm to 16 mm and h_{ef} ranging from 38 mm to 115 mm. In their study, about 60% of the specimens failed in a combined failure followed by pull-out failure. Chen et al. [10] further proposed a prediction model on combined failure modes. The proposed model was based on the database of 144 tension tests on three types of screw anchors with a diameter ranging from 6.35 mm to 12.7 mm and h_{nom} ranging from 38.1 mm to 101.6 mm. The concrete strengths are between 31.4 MPa and 32.4 MPa. The combined failure dominated about 80% of the test results for both shallow and deep embedment depths.

These experimental works have led to the inclusion of screw anchors in design standards (e.g., EN 1992-4:2018 [11]) for use in normal concrete. The screw anchor design, in accordance with EN 1992-4:2018 [11], follows the post-installed mechanical anchor design. However, the screw anchor may exhibit a similar failure behaviour to bonded anchor, which is a combined pull-out and concrete failure. Even though the CCD method adopted in EN 1992-4:2018 [11] has accounted for combined pull-out and concrete failure, however, recent studies [8, 10] have shown that it may still overpredict the resistance of the screw anchors. The design process stipulated in EN 1992-4:2018 [11] appears to be complicated for engineers who are not familiar with the anchor design, particularly in countries where EN 1992-4 was recently adopted, such as Malaysia [12]. Consequently, Ng et al. [13, 14] developed two-dimensional graphical tools for quick estimation of tensile and shear resistances of post-installed mechanical and bonded anchors. The studies discovered that the controlling failure mechanisms were found varied according to the types of anchors (mechanical or bonded) and the embedment depth of the anchor. It was foreseen that the graphical tools would be useful for practicing engineers for quick estimation of anchor resistances; however, the graphical tools were limited to anchors installed in C30/37 cracked concrete with 125 mm thick concrete members. In addition, there is no reported study to provide generalized solutions for screw anchor design.

This paper reviews the design methodology for screw anchors outlined in EN 1992-4:2018 [11] and introduces a novel graphical tool, referred to as a nomogram, for estimating screw anchor resistances in tension and shear. The nomogram represents anchor resistance as a function of the normalised effective embedment depth and edge distance, with details provided in subsequent sections. While not intended to replace detailed design software (e.g., Hilti PROFIS Engineering [15] or C-Fix Online by Fischer [16]), the nomogram offers a rapid preliminary estimation tool for screw anchor resistances and serves as an independent verification method for completed designs.

2. Design philosophy in EN 1992-4:2018 for anchors

The design principles in accordance with EN 1992-4:2018 [11] involved the calculation of the characteristic resistance (i.e., tensile and shear) of the anchor for each of the potential failure modes that could occur. The failure mode with the lowest resistance will govern the anchor design. Fig. 1 shows the schematic diagrams of the relevant failure modes for screw anchors under tensile and shear loads. The tensile failure modes are steel failure, pull-out failure, concrete cone failure, concrete splitting failure, and combined pull-out and concrete failure. It should be noted that combined pull-out and concrete failure is not explicitly mentioned in EN 1992-4:2018 [11]. On the other hand, the shear failure modes are steel failure with or without a lever arm, concrete pry-out failure, and concrete edge failure. The characteristic resistance of steel failure (under tensile and shear loads) and pull-out failure (under tensile load) is dependent on the material and mechanical properties of the anchors, which can be acquired from the relevant European Technical Assessment (ETA) reports. This work focuses on anchors without a lever arm. Hence, the steel failure with a lever arm is omitted in the present investigation.

Eqs. (3 to 21) are the equations to calculate the characteristic tensile and shear resistances for relevant concrete-related failure modes adopted from EN 1992-4:2018 [11]. The design in EN 1992-4:2018 [11] caters for the concrete strength classes ranging from C12/15 to C90/105, where the first number with a prefix 'C' denotes the characteristic concrete cylinder compressive strength and the second number denotes the characteristic concrete cube compressive strength. However, the characteristic concrete cylinder compressive strength (f_{ck}) shall not exceed 60 MPa even if a higher concrete strength class is used.

2.1. Tensile failure modes

(a) Concrete cone failure ($N_{\mathrm{Rk,c}}$)

The concrete cone failure ($N_{\mathrm{Rk,c}}$) is calculated using Eq. (3).

$$N_{\mathrm{Rk,c}} = N^{0}_{\mathrm{Rk,c}} \left(\frac{A_{\mathrm{c,N}}}{A^{0}_{\mathrm{c,N}}}\right) (\varphi_{\mathrm{s,N}})(\varphi_{\mathrm{re,N}})(\varphi_{\mathrm{ec,N}})(\varphi_{\mathrm{M,N}}) \tag{3}$$

where, $N^{0}_{\mathrm{Rk,c}}$ is calculated using Eq. (4).

$$N^{0}_{\mathrm{Rk,c}} = k_1 \left(\sqrt{f_{\mathrm{ck}}}\right) (h_{\mathrm{ef}})^{1.5} \tag{4}$$

where, k_1 is taken as 7.7 for cracked concrete and 11.0 for uncracked concrete. $A^{0}_{\mathrm{c,N}}$ is calculated as $s_{\mathrm{cr,N}}{}^2$, where $s_{\mathrm{cr,N}}$ is considered as $3h_{\mathrm{ef}}$ (where h_{ef} is the effective embedment depth of the anchor). $A_{\mathrm{c,N}}$ is calculated using Eq. (5).

For single anchor,

$$A_{\mathrm{c,N}} = \left(c_1 + 0.5 s_{\mathrm{cr,N}}\right)\left(c_2 + 0.5 s_{\mathrm{cr,N}}\right) \tag{5}$$

$\varphi_{\mathrm{s,N}}$ is calculated using Eq. (6).

$$\varphi_{\mathrm{s,N}} = 0.7 + 0.3 \left(\frac{c}{c_{\mathrm{cr,N}}}\right) \leq 1 \tag{6}$$

where, c is the smallest edge distance and $c_{\mathrm{cr,N}}$ is considered as $1.5h_{\mathrm{ef}}$.

$\varphi_{\mathrm{re,N}}$ is calculated using Eq. (7).

$$\varphi_{\mathrm{re,N}} = 0.5 + \frac{h_{\mathrm{ef}}}{200} \leq 1 \tag{7}$$

$\varphi_{\mathrm{re,N}}$ is taken as 1 if the provided spacing of the reinforcement is more than 150 mm for reinforcement size with any diameter or the provided spacing of the reinforcement is more than 100 mm for reinforcement size with diameter of 10 mm or smaller.

$\varphi_{\mathrm{ec,N}}$ is taken as 1 if there is no tensile load eccentricity, otherwise it shall be calculated using Eq. (8).

$$\varphi_{\mathrm{ec,N}} = \frac{1}{1 + 2(e_{\mathrm{N}} / s_{\mathrm{cr,N}})} \leq 1 \tag{8}$$

where, e_{N} is the eccentricity of resultant tensile force of anchors in respect to the centre of gravity of the anchors.

$\varphi_{\mathrm{M,N}}$ is the factor to cater for the effect of a compression force between fixture and concrete in cases of bending moments with or without axial force. For single anchor, $\varphi_{\mathrm{M,N}}$ can be taken as 1. The remaining symbols have been defined previously.

(b) Concrete splitting failure ($N_{\mathrm{Rk,sp}}$)

The concrete splitting failure ($N_{\mathrm{Rk,sp}}$) is calculated using Eq. (9).

$$N_{\mathrm{Rk,sp}} = N^{0}_{\mathrm{Rk,sp}} \left(\frac{A_{\mathrm{c,N}}}{A^{0}_{\mathrm{c,N}}}\right) (\varphi_{\mathrm{s,N}})(\varphi_{\mathrm{re,N}})(\varphi_{\mathrm{ec,N}})(\varphi_{\mathrm{h,sp}}) \tag{9}$$

where, $N^{0}_{\mathrm{Rk,sp}} = \min\{N_{\mathrm{Rk,p}}\,;\, N^{0}_{\mathrm{Rk,c}}\}$. $A_{\mathrm{c,N}}$, $A^{0}_{\mathrm{c,N}}$, $\varphi_{\mathrm{s,N}}$, $\varphi_{\mathrm{re,N}}$, and $\varphi_{\mathrm{ec,N}}$ shall be calculated according to concrete cone failure (refer to Eqs. (5 to 8)), however the values $c_{\mathrm{cr,N}}$ and $s_{\mathrm{cr,N}}$ shall be replaced by $c_{\mathrm{cr,sp}}$ and $s_{\mathrm{cr,sp}}$, which is acquired from the relevant ETA reports.

$\varphi_{\mathrm{h,sp}}$ is calculated using Eq. (10).

$$\varphi_{\mathrm{h,sp}} = \left(\frac{h}{h_{\mathrm{min}}}\right)^{2/3} \leq \max\left\{1\,;\, \left(\frac{h_{\mathrm{ef}} + 1.5c_1}{h_{\mathrm{min}}}\right)^{2/3}\right\} \leq 2 \tag{10}$$

where, $h_{\min}$ is the minimum allowed thickness of the concrete member. The remaining symbols have been defined previously.

2.2. Shear failure modes

(a) Concrete pry-out failure ($V_{Rk,cp}$)

For anchor without supplementary reinforcement, the concrete pry-out failure ($V_{Rk,cp}$) is calculated using Eq. (11).

$$V_{\mathrm{Rk,cp}} = k_8 \left(N_{\mathrm{Rk,c}}\right) \tag{11}$$

where, k_8 is acquired from the relevant ETA reports. $N_{Rk,c}$ is calculated using Eq. (3).

(b) Concrete edge failure ($V_{Rk,c}$)

The concrete edge failure ($V_{Rk,c}$) is calculated using Eq. (12).

$$V_{\mathrm{Rk,c}} = V^0_{\mathrm{Rk,c}} \left(\frac{A_{\mathrm{c,V}}}{A^0_{\mathrm{c,V}}}\right)(\varphi_{\mathrm{s,V}})(\varphi_{\mathrm{h,V}})(\varphi_{\mathrm{ec,V}})(\varphi_{\alpha,\mathrm{V}})(\varphi_{\mathrm{re,V}}) \tag{12}$$

where, $V^0_{Rk,c}$ is calculated using Eq. (13).

$$V^0_{\mathrm{Rk,c}} = k_9 (d_{\mathrm{nom}})^{\alpha} (l_{\mathrm{f}})^{\beta} (f_{\mathrm{ck}})^{1/2} (c_1)^{1.5} \tag{13}$$

where, k_9 is taken as 1.7 for cracked concrete and 2.4 for uncracked concrete. α is calculated as $0.1(l_{\mathrm{f}}/c_1)^{0.5}$, and β is calculated as $0.1(d_{\mathrm{nom}}/c_1)^{0.2}$. d_{nom} and l_{f} are acquired from the relevant ETA reports; the limiting values of l_{f} is shown in Eqs. (14) and (15).

For case $d_{\mathrm{nom}} \leq 24$ mm,

$$l_{\mathrm{f}} = h_{\mathrm{ef}} \leq 12 d_{\mathrm{nom}} \tag{14}$$

For case $d_{\mathrm{nom}} > 24$ mm,

$$l_{\mathrm{f}} = h_{\mathrm{ef}} \leq \max\{8 d_{\mathrm{nom}}\,; 300 \text{ mm}\} \tag{15}$$

$A^0_{\mathrm{c,V}}$ is calculated as $4.5c_1^2$ and $A_{\mathrm{c,V}}$ is calculated using Eqs. (16) and (17). For single anchor,

$$\text{If } h \geq 1.5c_1;\ A_{\mathrm{c,V}} = 1.5c_1(c_2 + 1.5c_1) \tag{16}$$

$$\text{If } h < 1.5c_1;\ A_{\mathrm{c,V}} = h\,(c_2 + 1.5c_1) \tag{17}$$

$\varphi_{\mathrm{s,V}}$ is calculated using Eq. (18).

$$\varphi_{\mathrm{s,V}} = 0.7 + 0.3\left(\frac{c_2}{1.5c_1}\right) \leq 1 \tag{18}$$

$\varphi_{\mathrm{h,V}}$ is calculated using Eq. (19).

$$\varphi_{\mathrm{h,V}} = \left(\frac{1.5c_1}{h}\right)^{0.5} \geq 1 \tag{19}$$

$\varphi_{\mathrm{ec,V}}$ is taken as 1 if there is no shear load eccentricity, otherwise it shall be calculated using Eq. (20).

$$\varphi_{\mathrm{ec,V}} = \frac{1}{1 + 2(e_{\mathrm{V}} / 3c_1)} \leq 1 \tag{20}$$

where, e_{V} is the eccentricity of resultant shear force of anchors in respect to the centre of gravity of the anchors.

$\varphi_{\alpha,\mathrm{V}}$ is calculated using Eq. (21).

$$\varphi_{\alpha,\mathrm{V}} = \left(\frac{1}{(\cos \alpha_{\mathrm{V}})^2 + (0.5 \sin \alpha_{\mathrm{V}})^2}\right)^{1/2} \geq 1 \tag{21}$$

where, α_{V} is the angle between design shear load V_{Ed} and a line perpendicular to the verified edge ($0° \leq \alpha_{\mathrm{V}} \leq 90°$).

$\varphi_{\mathrm{re,V}}$ shall be taken as 1 for anchor in uncracked and cracked concrete without edge reinforcement or stirrups, and 1.4 for anchor in cracked concrete with edge reinforcement and closely spaced stirrups or wire mesh with spacing $a \leq 100$ mm and $a \leq 2c_1$. It is noted that a factor $\varphi_{\mathrm{re,V}} > 1$ for applications in cracked concrete shall only be applied, if the h_{ef} of the anchor is at least 2.5 times the concrete cover of the edge reinforcement. The remaining symbols have been defined previously, in a consistent manner.

3. Nomogram for screw anchors design

The equations in EN 1992-4:2018 [11] can be complicated for many engineers, given that many parameters are required in the design. Hence, this work aims to develop a new graphical diagram (called nomogram) for a quick estimation of the preliminary design of screw anchors. The nomogram provides the resistances (i.e., tensile and shear) of the screw anchor encompassing all concrete-related failures based on the effective embedment depth of the anchor (h_{ef}), and edge distance (c), in a cracked concrete condition.

3.1. Parameters selection

Table 1 shows the range of parameters adopted from various ETA reports for post-installed screw anchors. Based on Table 1, typical anchor sizes of M6, M8, M10, M12, M14, and M16 are selected in this research. The effective embedment depth ratio (h_{ef}/D) ranges from 3 to 16. The minimum allowable thickness of the concrete member ($h_{\min}$) is taken as the maximum of 100 mm

Table 1
Range of parameters for post-installed screw anchors

ETA	Anchor size	h_{ef}/D	$h_{\min}$ (mm)	$c_{\mathrm{cr,sp}}$ (mm)	k_8	d_{nom} (mm)	l_{f} (mm)
ETA-08/0307 [17]	M6, M8, M10, M14	3.7 to 7.5	max (100 mm; $1.8h_{\mathrm{ef}}$ to $2.7h_{\mathrm{ef}}$)	$1.5h_{\mathrm{ef}}$ to $1.8h_{\mathrm{ef}}$	1.5 to 2	Equal to D	Equal to h_{ef}
ETA-13/1038 [18]	M6, M8, M10, M14	3.5 to 7	max (80 mm; $2.2h_{\mathrm{ef}}$ to $2.7h_{\mathrm{ef}}$)	$1.5h_{\mathrm{ef}}$ to $2h_{\mathrm{ef}}$	1 to 2	Equal to D	Equal to h_{ef}
ETA-19/0170 [19]	M8, M10	5.9 to 6.5	max (100 mm; $2.2h_{\mathrm{ef}}$)	$1.3h_{\mathrm{ef}}$ to $1.5h_{\mathrm{ef}}$	2	Equal to D	Equal to h_{ef}
ETA-20/0867 [20]	M8, M10, M12, M14, M16	3.5 to 8	max (80 mm; $1.8h_{\mathrm{ef}}$ to $2.7h_{\mathrm{ef}}$)	$1.5h_{\mathrm{ef}}$ to $1.8h_{\mathrm{ef}}$	1 to 2	Equal to D	Equal to h_{ef} or h_{nom}
ETA-15/0352 [21]	M6, M8, M10, M12, M14	3.5 to 7.3	max (80 mm; $1.8h_{\mathrm{ef}}$ to $2.5h_{\mathrm{ef}}$)	$1.5h_{\mathrm{ef}}$	1 to 2	Equal to D	Equal to h_{nom}
ETA-17/0740 [22]	M8, M10, M12	3.9 to 6.8	max (100 mm; $1.8h_{\mathrm{ef}}$ to $2.5h_{\mathrm{ef}}$)	$1.5h_{\mathrm{ef}}$	1 to 2	Equal to D	Equal to h_{nom}
ETA-16/0043 [23]	M6, M8, M10, M12, M14	4.1 to 7.3	max (80 mm; $1.5h_{\mathrm{ef}}$ to $2.6h_{\mathrm{ef}}$)	$1.4h_{\mathrm{ef}}$ to $1.9h_{\mathrm{ef}}$	1 to 2	Equal to D	Equal to h_{ef}
ETA-20/0731 [24]	M6, M8, M10, M12, M14	4.1 to 7.3	max (80 mm; $1.5h_{\mathrm{ef}}$ to $2.6h_{\mathrm{ef}}$)	$1.4h_{\mathrm{ef}}$ to $1.9h_{\mathrm{ef}}$	1 to 2	Equal to D	Equal to h_{ef}

Notes: D is the diameter of the anchor, d_{nom} is the outer diameter of the anchor, h_{ef} is the effective embedment depth of the anchor.

or two times the effective embedment depth of the anchor ($2\,h_{ef}$). The characteristic edge distance for concrete splitting failure ($c_{cr,sp}$) is taken as $1.5h_{ef}$. According to EAD 330232 [25], the resistance to pry-out failure test is optional, and default values of k_8 (i.e., k_8 equals 1 if the effective embedment depth (h_{ef}) is less than 60 mm, and k_8 equals 2 if the effective embedment depth (h_{ef}) is equal to or greater than 60 mm) can be used if the tests are not performed. It is noted that this assumption might give a lower bound of characteristic resistance of concrete pry-out failure. d_{nom} is taken as D (diameter of the anchor), and l_f is taken as h_{ef} with limitation as shown in Eqs. (14) and (15). Importantly, cracked concrete was assumed, given that it is challenging to ensure concrete will not crack in the actual construction and also throughout the service life of the connection. Also, dense reinforcement is assumed, as most concrete structures are provided with reinforcements. This assumption will give more conservative results.

3.2. Development of nomogram

The conceptual flowchart for creating the nomogram is shown in Fig. 2. As mentioned earlier, the characteristic resistance of steel failure (under tensile and shear loads) and pull-out failure (under tensile load) depends on the material and mechanical properties of the anchors, which can be acquired from the relevant ETA reports.

The graphs in the nomogram provide the characteristic resistances of the screw anchor for relevant concrete-related failures (i.e., concrete cone failure and concrete splitting failure under tensile load, and concrete pry-out failure and concrete edge failure under shear load) in terms of the effective embedment depth of the anchor (h_{ef}) and edge distance (c), in a cracked concrete condition with the material partial safety factor excluded. User of the nomogram is required to apply the safety factor after getting the characteristic values, to arrive at a design resistance. A design spreadsheet is first created to automate the computation of the characteristic resistance (i.e., tensile and shear) of screw anchors for each concrete-related failure. The design spreadsheet was verified using commercial software, e.g., Hilti PROFIS Engineering [15] or C-Fix Online by Fischer [16]. Then, the characteristic resistance is rationalised into xy-plane (x-axis is h_{ef}/D and y-axis is c/D). Lastly, a smoothened and harmonised line is drawn on the data to represent the generalised solution for screw anchor design. Nomograms for tensile and shear resistances for different anchor sizes are presented in Appendix A and Appendix B, respectively.

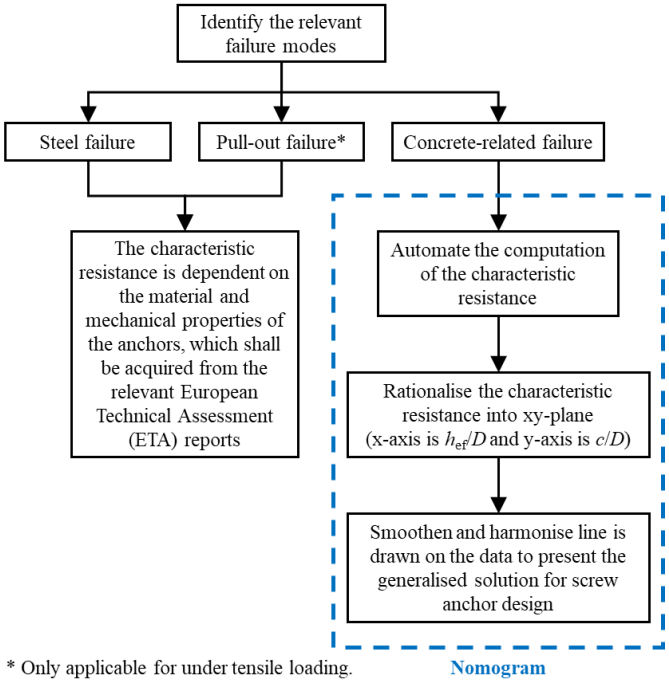

Fig. 2 Flowchart of the procedure for creating the nomogram

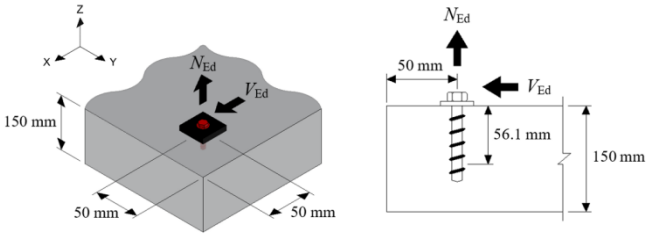

Fig. 3 Details of Model 1

3.3. Verification of the nomogram

An explicit check on the screw anchor design that incorporates the nomogram is proposed and discussed here. Four models were verified using variables such as anchor size, concrete cylinder compressive strength (f_{ck}), effective embedment depth of the anchor (h_{ef}), edge distance (c), and concrete member thickness (h). An example of details for Model 1 is shown in Fig. 3. The edge distance for Models 1 and 3 is less than the characteristic edge distance ($c < c_{cr,N}$), while for Models 2 and 4, the edge distance is equal to or greater than the characteristic edge distance ($c \geq c_{cr,N}$). Table 2 shows a summary of the details and compares the results from the commercial software with those from the nomogram.

From Table 2, it can be seen that the results of the explicit checks concur well (within 7%) with the results obtained from the commercial software. The discrepancy in the results could be due to the smoothened line in producing the nomogram, as the round-off values for the reading were done manually. In subsequent discussions (see Section 5), the effect of the coefficient of variation (CV_F) was found to range from 10% to 15%. Therefore, the observed 7% discrepancy using the nomogram falls within the allowable variation range for anchor capacity and is deemed acceptable, making it suitable for preliminary estimation purposes. In the case of shear resistance for Model 2, the proposed nomogram underestimated the shear resistance for concrete pry-out failure. It is due to assumptions made for the k_8 values (k_8 value is equal to 1 for $h_{ef} <$ 60 mm, and 2 for $h_{ef} \geq 60$ mm). A higher k_8 value is expected if the anchor product is tested for pry-out failure. Hence, readers are advised to obtain the tested k_8 value from the relevant ETA reports and incorporate it into Eqs. (22) and (23), if more accurate prediction is required.

$$\text{For } h_{ef} < 60 \text{ mm}, \quad V_{Rk,cp\ (modified)} = V_{Rk,cp}\left(k_{8\ (ETA)}\right) \tag{22}$$

Table 2
Details for verification of nomograms

Model	Anchor size	f_{ck} (MPa)	h_{ef} (mm)	c (mm)	h (mm)	Tensile					Shear				
						Design resistance (kN)		$\frac{N_{sw}}{N_{nom}}$	Failure mode		Design resistance (kN)		$\frac{V_{sw}}{V_{nom}}$	Failure mode	
						N_{sw} software	N_{nom} nomogram		Software	Nomogram	V_{sw} software	V_{nom} nomogram		Software	Nomogram
1	M8	30	56.1	50	150	5.1	5.3	0.96	C or SP	C	2.7	2.7	1.00	CE	CE
2				200	250	9.2	9.3	0.99	C	C	16.6	9.2*	1.80	CE	CP*
												16.9+	0.98		CE+
3	M12	50	79.9	80	500	14.6	15.7	0.93	C	C	7.4	7.8	0.95	CE	CE
4				300	300	23.3	23.9	0.97	C	C	35.9	35.9	1.00	S	S

Notes:
The anchor size is equal to the diameter of the anchor (D); S is steel failure; C is concrete cone failure; SP is concrete splitting failure; CE is concrete edge failure; CP is concrete pry-out failure.
* The result is based on the default value of k_8 assumed in the nomogram.
+ The result is based on the k_8 value obtained from ETA.

For $h_{ef} \geq 60$ mm, $V_{Rk,cp\ (modified)} = V_{Rk,cp}\left(\frac{k_{8\ (ETA)}}{2}\right)$ (23)

where, $V_{Rk,cp}$ is the characteristic resistance of concrete pry-out failure obtained from the nomograms. $k_{8\ (ETA)}$ is acquired from the relevant ETA reports.

3.4. Applicable range and limitations of the nomogram

Some assumptions were made while developing the nomograms. The applicable range and limitations of the nomogram are highlighted below:

(a) applicable for the design of single screw anchor sizes of M6, M8, M10, M12, M14, and M16 in cracked concrete with no eccentricity;
(b) effective embedment depth ratio (h_{ef}/D) ranges from 3 to 16;
(c) edge distance (c) ranges from $2D$ to greater than $c_{cr,N}$. One edge distance in the x-direction and one edge distance in the y-direction, which are not less than $c_{cr,N}$ or $c_{cr,sp}$. Edge distance in the x-direction is equal to edge distance in the y-direction;
(d) dense reinforcement is assumed (i.e., spacing between reinforcements < 100 mm for reinforcement diameter ≤ 10 mm, or spacing between reinforcements < 150 mm for others reinforcement diameter);
(e) the minimum thickness of the concrete member allowed is assumed as h_{min} = max (100 mm ; $2h_{ef}$);
(f) characteristic edge distance for concrete splitting failure ($c_{cr,sp}$) is assumed equal to concrete cone failure, which is $1.5h_{ef}$;
(g) default values of k_8 were assumed. k_8 value is equal to 1 for h_{ef} < 60 mm, and 2 for $h_{ef} \geq 60$ mm; and
(h) applicable for concrete-related failures, i.e., concrete cone failure and concrete splitting failure for tensile, and concrete pry-out failure and concrete edge failure for shear.

4. Guide and a worked example of using the nomogram

The use of the proposed nomograms for screw anchor design is herein demonstrated. Flowcharts are provided in Fig. 4 for tensile resistance and Fig. 5 for shear resistance to facilitate the explanation.

4.1. Tensile resistance for screw anchor

Refer to Fig. 4, the tensile resistance of screw anchors can be estimated in 6 steps.

Step 1: Select the type of screw anchor prior to calculating the anchor resistance.

Step 2: Define the anchor diameter (D), characteristic concrete cylinder compressive strength (f_{ck}), effective embedment depth (h_{ef}), edge distance (c), and concrete member thickness (h).

Step 3a: Obtain the characteristic resistance ($N_{Rk,s}$) and partial factor ($\gamma_{Ms,N}$) for steel failure.

$N_{Rk,s}$ is dependent on the material and mechanical properties of the anchors, which shall be acquired from the relevant ETA reports.

Step 3b: Calculate the design resistance of steel failure ($N_{Rd,s}$) using Eq. (24).

$$N_{Rd,s} = \frac{N_{Rk,s}}{\gamma_{Ms,N}} \quad (24)$$

Step 4a: Obtain the characteristic resistance ($N_{Rk,p}$) and installation factor (γ_{inst}) for pull-out failure.

$N_{Rk,p}$ is dependent on the material and mechanical properties of the anchors, which shall be acquired from the relevant ETA reports. It should be noted that an influence factor of concrete strength ($\varphi_{f_{ck}}$) shall be multiplied, and as shown in Eq. (25).

$$N_{Rk,p} = \varphi_{f_{ck}}\left(N_{Rk,p\ (C20/25)}\right) \quad (25)$$

Step 4b: Calculate the design resistance of pull-out failure ($N_{Rd,p}$) using Eq. (26).

$$N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}} \quad (26)$$

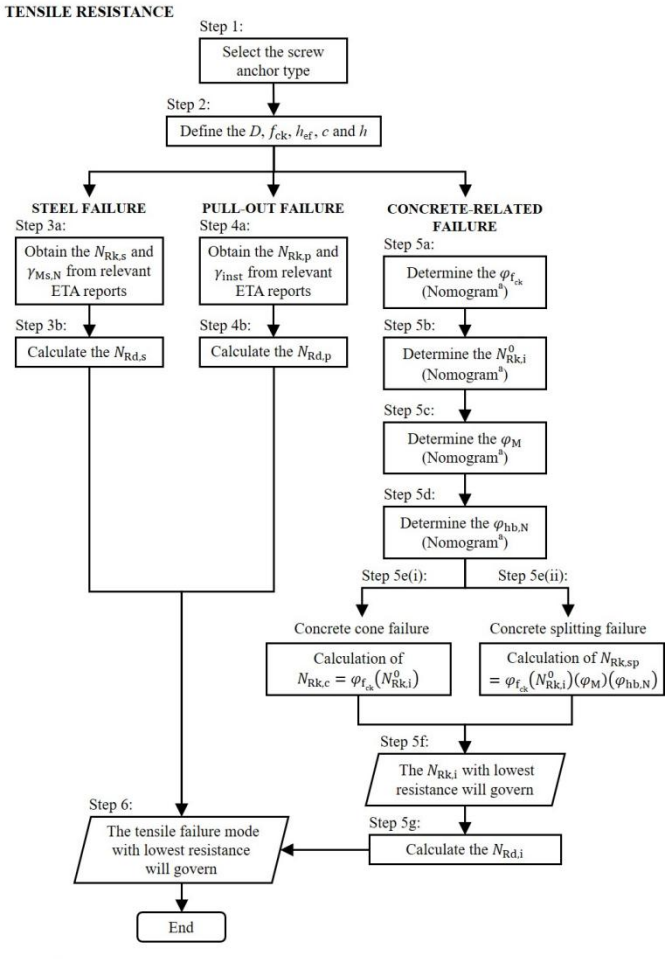

Fig. 4 Flowchart of using the nomogram for tensile resistance

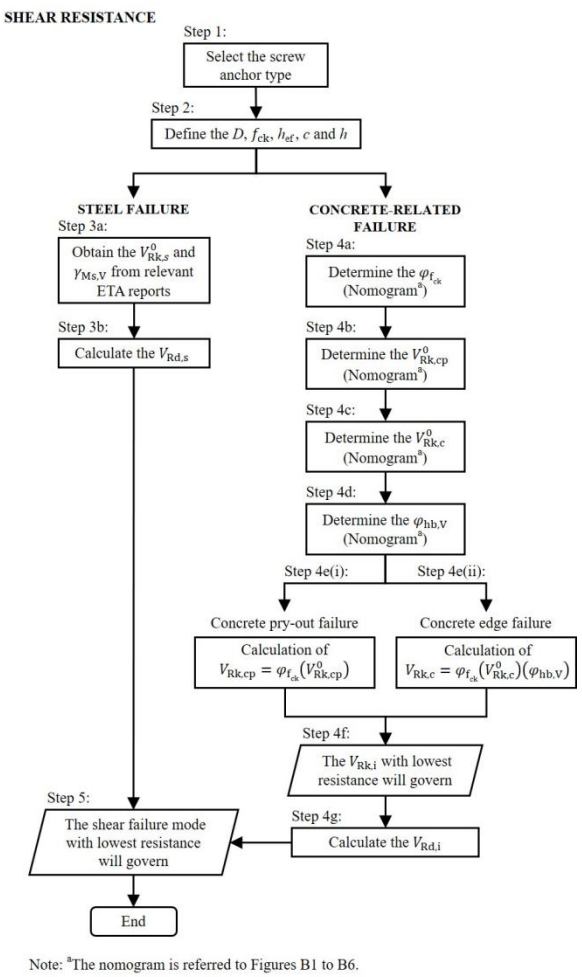

Fig. 5 Flowchart of using the nomogram for shear resistance

where, $\gamma_{Mp} = \gamma_c(\gamma_{inst})$. The value γ_c can be taken as 1.5 in accordance with EN 1992-1-1.

Step 5a: Determine the influence factor of concrete strength ($\varphi_{f_{ck}}$).

$\varphi_{f_{ck}}$ is determined using the nomogram proposed in Appendix A (refer to the bottom left diagram in Figs. A1(a) to A6(a), where the details for Figs. A1 to A6 will be demonstrated in a worked example later). As mentioned earlier, the characteristic concrete cylinder compressive strength (f_{ck}) shall not exceed 60 MPa even if a higher concrete strength class is used.

Step 5b: Determine the characteristic resistance for concrete-related failure ($N^0_{Rk,i}$).

$N^0_{Rk,i}$ is determined using the nomogram proposed in Appendix A (refer to the top right diagram in Figs. A1(b) to A6(b)). First, the normalised effective embedment depth (h_{ef}/D) and edge distance (c/D) are calculated. The identified point is the value of $N^0_{Rk,i}$.

Step 5c: Determine the modification factor (φ_M).

φ_M is determined using the nomogram proposed in Appendix A (refer to the middle right diagram in Figs. A1(c) to A6(c)). First, the $N^0_{Rk,sp\,(C20/25)}$ and h_{ef}/D are located. The identified point is the value of φ_M.

Step 5d: Determine the influence factor of member thickness for the tensile load ($\varphi_{hb,N}$).

$\varphi_{hb,N}$ is determined using the nomogram proposed in Appendix A (refer to the bottom right diagram in Figs. A1(d) to A6(d)). Two identified points are positioned. The first identified point is based on h_{ef}/D and c/D, another identified point is based on h_{ef}/D and h. The identified point with the lowest value is taken as $\varphi_{hb,N}$.

Step 5e(i): Calculate the characteristic resistance for concrete cone failure using Eq. (27).

$$N_{Rk,c} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right) \tag{27}$$

Step 5e(ii): Calculate the characteristic resistance for concrete splitting failure using Eq. (28).

$$N_{Rk,sp} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)(\varphi_M)\left(\varphi_{hb,N}\right) \tag{28}$$

Step 5f: Obtain the $N_{Rk,i}$.

$N_{Rk,i}$ is obtained as the minimum of $N_{Rk,c}$ and $N_{Rk,sp}$ calculated in Eqs. (27) and (28), respectively. The lowest resistance is chosen and will govern the concrete-related failure.

Step 5g: Calculate the design resistance of concrete-related failure ($N_{Rd,i}$) using Eq. (29).

$$N_{Rd,i} = \frac{N_{Rk,i}}{\gamma_{Mc}} \tag{29}$$

where, $\gamma_{Mc} = \gamma_c(\gamma_{inst})$. The value γ_c can be taken as 1.5 in accordance with EN 1992-1-1.

Step 6: Compute the tensile resistance of the screw anchor.

The tensile resistance of the screw anchor is obtained by comparing the design resistance of steel failure, $N_{Rd,s}$ (Eq. 24), pull-out failure, $N_{Rd,p}$ (Eq. 26), and concrete-related failure, $N_{Rd,i}$ (Eq. 29). The tensile failure mode with the lowest resistance will govern the design.

4.2. Shear resistance for screw anchor

Refer to Fig. 5, the shear resistance of screw anchors can be estimated in 5 steps.

Step 1: Select the type of screw anchor prior to calculating the anchor resistance.

Step 2: Define the anchor diameter (D), characteristic concrete cylinder strength (f_{ck}), effective embedment depth (h_{ef}), edge distance (c), and concrete member thickness (h).

Step 3a: Obtain the characteristic resistance of a single anchor ($V^0_{Rk,s}$) and partial factor ($\gamma_{Ms,V}$) for steel failure.

It should be noted that the characteristic resistance for steel failure ($V_{Rk,s}$) is taken as $V^0_{Rk,s}$, as the ductility factor (k_7) for single anchor is taken as 1. $V^0_{Rk,s}$ is dependent on the material and mechanical properties of the anchors, which shall be acquired from the relevant ETA reports.

Step 3b: Calculate the design resistance of steel failure ($V_{Rd,s}$) using Eq. (30).

$$V_{Rd,s} = \frac{V_{Rk,s}}{\gamma_{Ms,V}} \tag{30}$$

Step 4a: Determine the influence factor of concrete strength ($\varphi_{f_{ck}}$).

$\varphi_{f_{ck}}$ is determined using the nomogram proposed in Appendix B (refer to the top right diagram in Figs. B1(a) to B6(a), where the details for Figs. B1 to B6 will be demonstrated in a worked example in Section 4.3 in this paper). As mentioned earlier, the characteristic concrete cylinder compressive strength (f_{ck}) shall not exceed 60 MPa even if a higher concrete strength class is used.

Step 4b: Determine the characteristic resistance for concrete pry-out failure ($V^0_{Rk,cp}$).

$V^0_{Rk,cp}$ is determined using the nomogram proposed in Appendix B (refer to the bottom left diagram in Figs. B1(b) to B6(b)). First, the normalised effective embedment depth (h_{ef}/D) and edge distance (c/D) are calculated. The identified point is the value of $V^0_{Rk,cp}$.

Step 4c: Determine the characteristic resistance for concrete edge failure ($V^0_{Rk,c}$).

$V^0_{Rk,c}$ is determined using the nomogram proposed in Appendix B (refer to the bottom middle diagram in Figs. B1(c) to B6(c)). The h_{ef}/D and c/D are located, and the identified point is the value of $V^0_{Rk,c}$.

Step 4d: Determine the influence factor of member thickness for the shear load ($\varphi_{hb,V}$).

$\varphi_{hb,V}$ is determined using the nomogram proposed in Appendix B (refer to the bottom right diagram in Figs. B1(d) to B6(d)). The c/D and h are located, and the identified point is the value of $\varphi_{hb,V}$.

Step 4e(i): Calculate the characteristic resistance for concrete pry-out failure using Eq. (31).

$$V_{Rk,cp} = \varphi_{f_{ck}}\left(V^0_{Rk,cp}\right) \tag{31}$$

Step 4e(ii): Calculate the characteristic resistance for concrete edge failure using Eq. (32).

$$V_{Rk,c} = \varphi_{f_{ck}}\left(V^0_{Rk,c}\right)\left(\varphi_{hb,V}\right) \tag{32}$$

Step 4f: Obtain the $V_{Rk,i}$.

$V_{Rk,i}$ is obtained as the minimum of $V_{Rk,cp}$ and $V_{Rk,c}$, where they can be calculated in Eqs. (31) and (32), respectively. The lowest resistance governs the concrete-related failure.

Step 4g: Calculate the design resistance of concrete-related failure ($V_{Rd,i}$) using Eq. (33).

$$V_{Rd,i} = \frac{V_{Rk,i}}{\gamma_{Mc}} \tag{33}$$

where, $\gamma_{Mc} = \gamma_c(\gamma_{inst})$. The value γ_c can be taken as 1.5 in accordance to EN 1992-1-1.

Step 5: Compute the shear resistance of the screw anchor.

The shear resistance of the screw anchor is obtained by comparing the design resistance of steel failure, $V_{Rd,s}$ (Eq. 30), and concrete-related failure, $V_{Rd,i}$ (Eq. 33). The shear failure mode with the lowest resistance will govern the design.

4.3. Design example

Detailed calculations on the nomogram used to calculate the tensile and shear resistances of screw anchors are demonstrated in Appendix C. The design example refers to a single post-installed screw anchor used in a reinforced-concrete structure, as shown in Fig. 3. The details are based on Model 1, as shown in Table 2. The considered concrete grade is C30/37. The anchor size is M8 (D = 8 mm), with effective embedment depth, h_{ef} = 56.1 mm, and edge distance, c = 50 mm. The structure has a thickness, h = 150 mm.

5. Corroboration of predicted resistance in EN 1992-4:2018 with experimental results

A total of 197 test results were collected and used for further analysis in this study. The experimental test databases were collected from previous works of literature [8, 9, 10, 26, 27, 28, 29, 30, 31], and only the tensile resistance of the screw anchors have been compared with nomograms developed as a part of this study. It is known that shear failure of screw anchors is unlikely, except for situation where the anchors are located near the edge. Also, there are limited data available in the literature for shear tests of screw anchors. Table 3 shows the summary of the screw anchor database. The analysis focuses on concrete-related failures under tension, which include concrete cone failure, and combined pull-out and concrete failure. This is because the steel failure and pull-out failure due to the material and mechanical properties of anchors were excluded in the nomogram; hence is also excluded in the screw anchor database. The cracked or uncracked concrete conditions are also documented in Table 3.

Table 3
Summary of the screw anchor database

Data source	Diameter range (mm)	Embedment depth range (mm)	Concrete strength* (MPa)	State of concrete	Number of tests	Failure mode
Abdul-Hamid et al. [26]	6.4 to 12.7	49.3 to 75.9	33.7	Uncracked	14	CO
Chen et al. [10]	6.4 to 12.7	38.1 to 101.6	31.4 to 32.4	Uncracked	100	C/CO
Hoehler & Eligehausen [27]	12	76	21.8+ to 26.8+	Cracked	5	C
Mohyeddin et al. [8]	6.5 to 12	38 to 98	33.5 to 35.4	Uncracked	20	CO
Mohyeddin et al. [9]	16	115	9.9 to 41.8	Uncracked	12	CO
Mohyeddin et al. [28]	10	53.8 to 74.2	37.5 to 49.5	Uncracked	29	C/CO
Mohyeddin et al. [29]	16	115	25 & 40	Uncracked	4	CO
Obayes et al. [30]	12	80	6.1 to 22	Uncracked	11	C
Ng et al. [31]	10	45 & 75	20.3 & 29.3	Uncracked	2	C/SP
Total	6.4 to 16	38 to 115	6.1 to 49.5	Cracked/Uncracked	197	C/CO/SP

Notes:
Pull-out failure has been excluded from the database as it is product-dependent.
C is concrete cone failure; CO is combined pull-out and concrete failure; SP is concrete splitting failure.
* The concrete strength refers to concrete cylinder compressive strength.
+ The concrete cylinder compressive strength is taken as 0.85 of the concrete cube compressive strength.

The resistance obtained using EN 1992-4:2018 [11] is the characteristic value. Hence, a conversion from the characteristic to the mean value of resistance is required to corroborate with the experimental results. EAD 330232 [25] stipulated $F_{\mathrm{u,5\%}} = F_{\mathrm{u,m}}(1 - k_{\mathrm{s}}CV_{\mathrm{F}})$. The ratio of mean resistance to characteristic resistance is very much dependent on the coefficient of variation (CV_{F}) of the failure load in the test. As stipulated in EAD 330232 [25], the CV_{F} value shall not exceed 30%. However, from the author's experience [8, 9, 28, 29], the CV_{F} value for screw anchor typically ranges from 10% to 15%. Fig. 6 shows the comparison of results between the nomogram and the experimental results. For a fair comparison, the characteristic values obtained from the nomogram for cracked concrete condition were converted to uncracked concrete condition using a linear conversion (i.e., Eq. (4) stipulated k_1 = 7.7 for uncracked concrete and k_1 = 11 for cracked concrete, then the linear conversion factor to get the uncracked concrete condition is 11/7.7 = 1.43). Assuming a small variation of CV_{F} = 10% (see Fig. 6(a)), the mean resistance is about 1.2 times the characteristic resistance ($F_{\mathrm{u,m}}/F_{\mathrm{u,5\%}}$ = 1.197). Comparing the nomogram results with the experimental results, the average is good, but approximately 48% of the nomogram results overestimated the resistance of the screw anchor. The overestimation percentage is increased to approximately 69% if the CV_{F} = 15% (see Fig. 6(b)), and further increased to 83% if the CV_{F} = 20% (see Fig. 6(c)). If the failure load results are very scattered in the tests, i.e., CV_{F} = 30% (see Fig. 6(d)), the mean value is about two times the characteristic resistance ($F_{\mathrm{u,m}}/F_{\mathrm{u,5\%}}$ = 1.974), which is unlikely to occur, with 100% of the results being unconservative. In general, the modified CCD method adopted in EN 1992-4:2018 [11] seemingly overestimated the resistance of the screw anchor, which may lead to unconservative results.

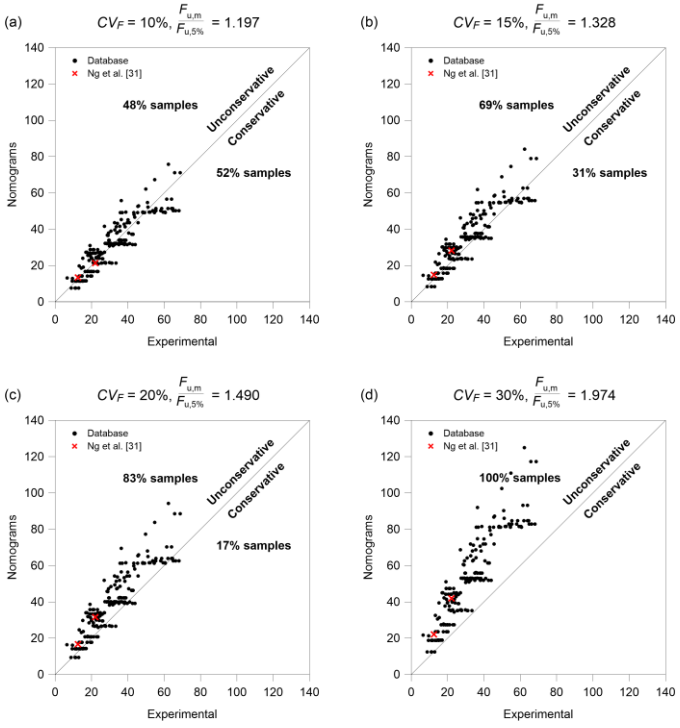

Fig. 6 Comparison of nomogram results and experimental results: (a) CV_{F} = 10%, (b) CV_{F} = 15%, (c) CV_{F} = 20%, and (d) CV_{F} = 30%

6. Conclusions

Screw anchors exhibit a different failure behaviour (i.e., combined pull-out and concrete failure) as compared to other post-installed mechanical anchors (e.g., undercut anchor and expansion anchor with steel failure, pull-out failure, concrete cone failure, and concrete splitting failure being the common failure modes). The screw anchor design following the post-installed mechanical anchor design in EN 1992-4:2018 may lead to unconservative resistance predictions. Hence, this paper has reviewed the screw anchor design in EN 1992-4:2018 and corroborated with experimental results.

A novel graphical tool (called nomogram) is proposed to facilitate the quick estimation of the characteristic resistances (tensile and shear) of screw anchors for concrete-related failures in EN 1992-4:2018, for cracked concrete condition. The effectiveness of the proposed nomograms was demonstrated and illustrated with an example. The authors anticipate that the proposed nomograms could serve as a useful tool for practising engineers to obtain a quick and reliable estimation of screw anchor resistance within the limitations of the nomograms. The readers are advised to obtain the tested k_8 value from the relevant ETA reports and incorporate it into Eqs. (22) and (23) for a more accurate prediction of shear resistance for concrete pry-out failure.

This study demonstrated that the modified CCD method adopted in EN 1992-4:2018 seemingly overestimated the resistance of the screw anchor. Approximately 48% to 69% of the predicted results exceeded the experimental results if CV_{F} is ranging from 10% to 15%. Hence, further research is required for a better method to design the screw anchors; for example, a mechanical model can be developed. In addition, the proposed nomogram can be further extended to group anchors or other specific conditions, such as anchors with a lever arm, different reinforcement configurations or more complex loading conditions.

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References

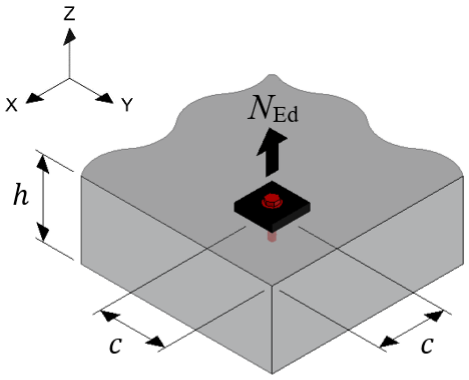
[1] Yan J., Liew R.J.Y. and Zhang M., "Shear-tension interaction strength of J-hook connectors in steel-concrete-steel sandwich structure", Advanced Steel Construction, 11(1), 73-94, 2015.
[2] Shan Z., Su R.K.L., Looi, D.T.W. and Chen L., "A review of direct fastening steel jacket for

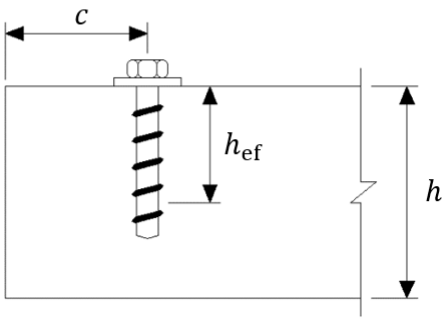
strengthening of reinforced concrete columns", Advanced Steel Construction, 19(4), 383-388, 2023.
[3] Olsen J., Pregartner T. and Lamanna A.J., "Basis for design of screw anchors in concrete", ACI Structural Journal, 109(4), 559-567, 2012.
[4] Karmazínová M., Melcher J. and Kala Z., "Design of expansion anchors to concrete based on results of experimental verification", Advanced Steel Construction, 5(4), 390-405, 2009.[5] Kuenzlen J.H.R. and Eligehausen R., "Load bearing behaviour of fastenings with concrete screws", Otto-Graf Journal, 13, 27-51, 2002.
[6] Kuenzlen J.H.R., Load-bearing behaviour of screw anchors under axial tension [dissertation], University of Stuttgart, Stuttgart, 2005. (in German)
[7] Fuchs W., Eligehausen R. and Breen J.E., "Concrete capacity design (CCD) approach for fastening to concrete", ACI Structural Journal, 92(1), 73-94, 1995.
[8] Mohyeddin A., Gad E.F. and Lee J., "Failure modes and tensile strength of screw anchors in non-cracked concrete", Construction and Building Materials, 221, 501-513, 2019.
[9] Mohyeddin A., Gad E.F., Yangdon K., Khandu R. and Lee J., "Tensile load capacity of screw anchors in early age concrete", Construction and Building Materials, 127, 702-711, 2016.
[10] Chen Z., Nassiri S. and Lamanna A., "Investigation of a combined failure mode for screw anchors under tension", Advances in Structural Engineering, 23(13), 2803-2812, 2020.
[11] EN 1992-4, European Standard: Design of concrete structures - Part 4 Design of fastenings for use in concrete, British Standard Institution, 2018.
[12] MS EN 1992-4, Malaysia Standard: Design of concrete structures - Part 4 Design of fastenings for use in concrete, Department of Standards Malaysia, 2023.
[13] Ng L.T., Wong E.S.W. and Looi D.T.W., "Feasible design tensile capacity of post-installed anchors based on the new Eurocode 2: Part 4 (2018)", In: Belayutham S., Che Ibrahim C.K.I., Alisibramulisi A., Mansor H. and Billah M., editors, Proceedings of the 5th International Conference on Sustainable Civil Engineering Structures and Construction Materials (SCESCM 2020), Lecture Notes in Civil Engineering, Springer, Singapore, 819-836, 2022.
[14] Ng L.T., Looi D.T.W., Lee J. and Ng A.L.Y., "A simplified design solution for shear capacity of post-installed anchors encompassing all failure modes in EC2-4 (2018)", In: Kwong K.Z., Alengaram U.J., Raman S.N., Jumaat Z., Ng S.C., Chua Y.S. and Alisibramulisi A., editors, Proceedings of the 15th International Conference on Concrete Engineering and Technology (CONCET2022), Journal of Physics: Conference Series, IOP Publishing, 2521, 012014, 2023.
[15] Hilti, PROFIS Engineering [Internet], Malaysia: Hilti, 2024 [cited 2024 April 3], Available from: https://www.hilti.com.my/content/hilti/A2/MY/en/engineering/software/profis-engineering1.html
[16] Fischer, FiXperience Online [Internet], Singapore: Fischer, 2024 [cited 2024 April 17], Available from: https://www.fischer.sg/en-sg/service/planning-aids/fixperience
[17] European Organisation for Technical Approvals (EOTA), ETA-08/0307, Hilti HUS-HR/HUS-CR screw anchor, 2018.
[18] European Organisation for Technical Approvals (EOTA), ETA-13/1038, Hilti HUS3 screw anchor, 2020.
[19] European Organisation for Technical Approvals (EOTA), ETA-19/0170, Hilti HUS2-H screw anchor, 2019.
[20] European Organisation for Technical Approvals (EOTA), ETA-20/0867, Hilti HUS4 screw anchor, 2022.
[21] European Organisation for Technical Approvals (EOTA), ETA-15/0352, fischer screw anchor ULTRACUT FBS II, 2020.
[22] European Organisation for Technical Approvals (EOTA), ETA-17/0740, fischer screw anchor ULTRACUT FBS II A4, 2018.
[23] European Organisation for Technical Approvals (EOTA), ETA-16/0043, Würth concrete screw W-BS/S, W-BS/A4, W-BS/HCR, 2021.
[24] European Organisation for Technical Approvals (EOTA), ETA-20/0731, AnkaScrew Xtrem, 2020.
[25] European Organisation for Technical Approvals (EOTA), EAD 330232-01-0601, Mechanical fasteners for use in concrete, 2021.
[26] Abdul-Hamid A., Braimah A. and Tai F., "Impact load effects on screw anchors in concrete:, Engineering Structures, 251(5), 113491, 2022.
[27] Hoehler M.S. and Eligehausen R., "Behavior and testing of anchors in simulated seismic cracks", ACI Structural Journal, 105(3), 348-357, 2008.
[28] Mohyeddin A., Gad E.F., Aria S. and Lee J., "Effect of thread profile on tensile performance of screw anchors in non-cracked concrete", Construction and Building Materials, 237, 117565, 2020.
[29] Mohyeddin A., Gad E.F., Lee J., Hafsia M. and Saremi M., "Adverse effect of too-small edge distances on tensile capacity of screw anchors", Australian Journal of Structural Engineering, 21(1), 94-106, 2020.
[30] Obayes O., Gad E.F., Pokharel T., Lee J. and Abdouka K., "Assessment of the tensile behaviour of post-installed screw anchors in early age concrete", Construction and Building Materials, 331, 127350, 2022.
[31] Ng L.T., Lau L.C., Looi D.T.W., Lee J. and Ng A.L.Y., "Tensile test of screw anchor in thin uncracked concrete", 16th International Conference on Concrete Engineering and Technology, CONCET2024, Selangor, Malaysia, 9-12 July 2024.

Appendix A

In this section, six nomograms for screw anchors design under tensile load are reported by varying the anchor size (i.e., M6, M8, M10, M12, M14, and M16).

Tensile resistance - 6 mm





$$N_{Rd,i} = \frac{N_{Rk,i}}{\gamma_{Mc}}$$

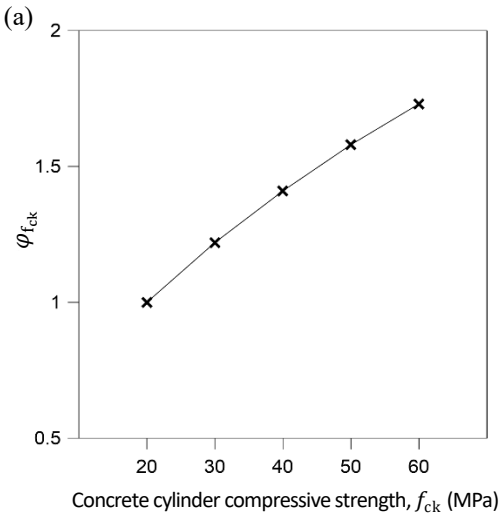
where, $N_{Rk,i} = \min\{N_{Rk,c}; N_{Rk,sp}\}$

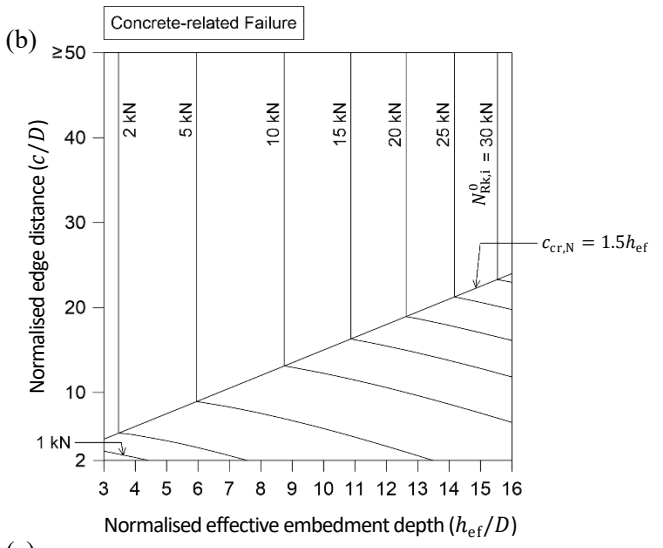
(i) Concrete cone failure

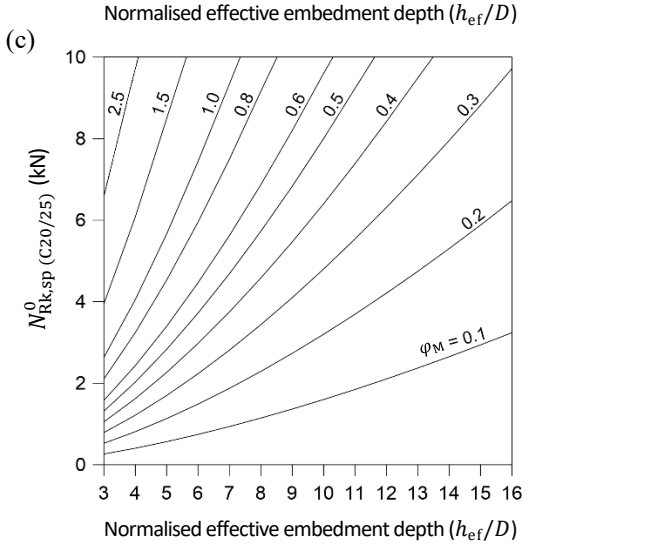
$$N_{Rk,c} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)$$

(ii) Concrete splitting failure

$$N_{Rk,sp} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)(\varphi_M)(\varphi_{hb,N})$$







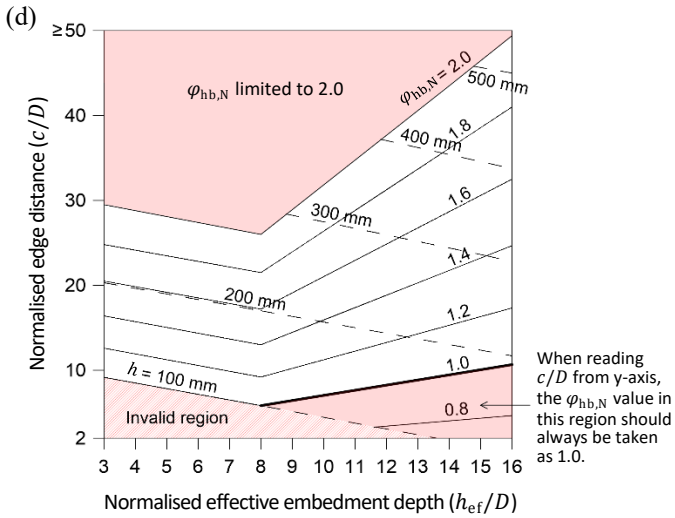
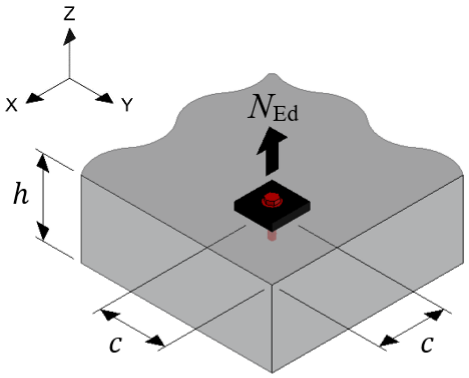
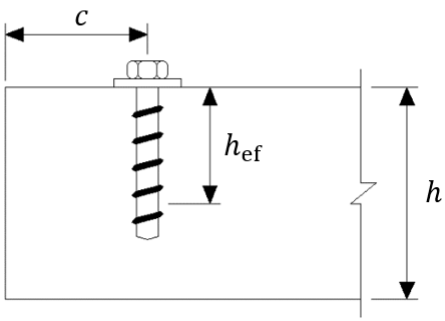


Fig. A1 Nomogram for tensile resistance for anchor size M6

Tensile resistance - 8 mm





$$N_{Rd,i} = \frac{N_{Rk,i}}{\gamma_{Mc}}$$

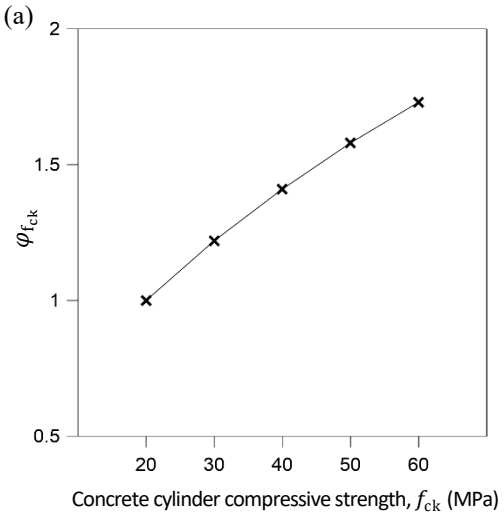
where, $N_{Rk,i} = \min\{N_{Rk,c}; N_{Rk,sp}\}$

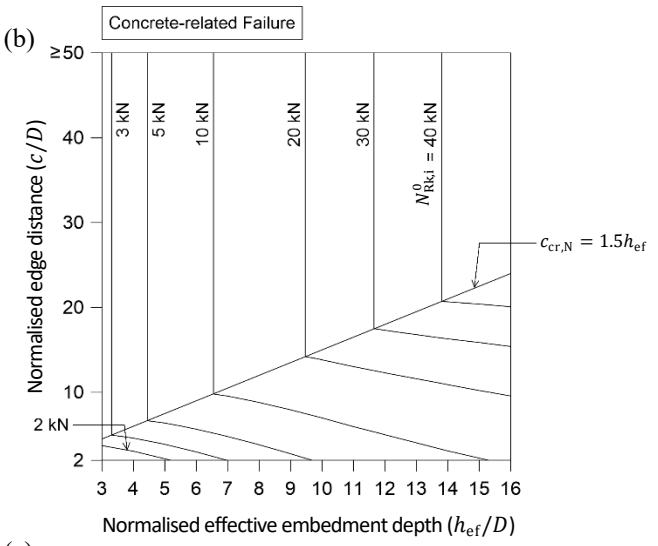
(i) Concrete cone failure

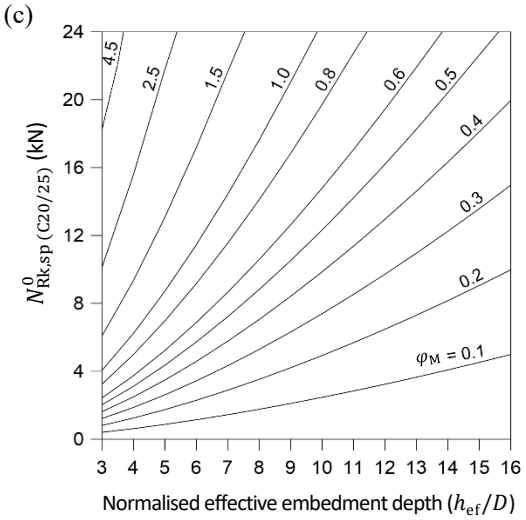
$$N_{Rk,c} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)$$

(ii) Concrete splitting failure

$$N_{Rk,sp} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)(\varphi_M)(\varphi_{hb,N})$$







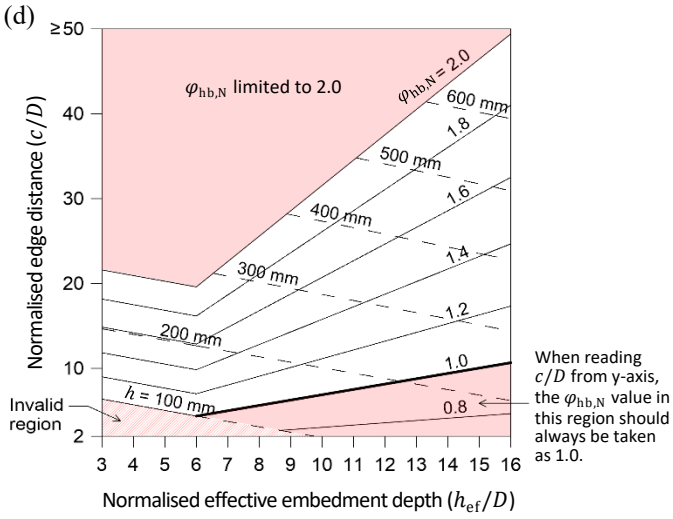
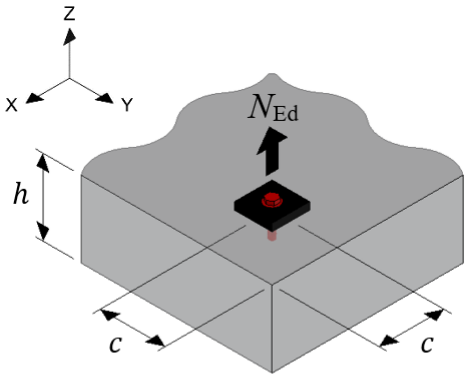
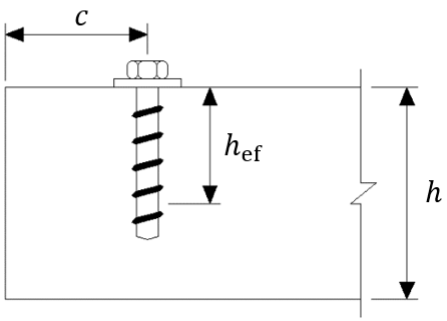


Fig. A2 Nomogram for tensile resistance for anchor size M8

Tensile resistance - 10 mm





$$N_{Rd,i} = \frac{N_{Rk,i}}{\gamma_{Mc}}$$

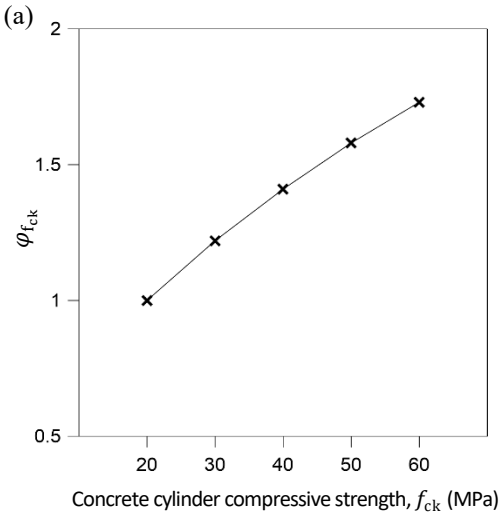
where, $N_{Rk,i} = \min\{N_{Rk,c}; N_{Rk,sp}\}$

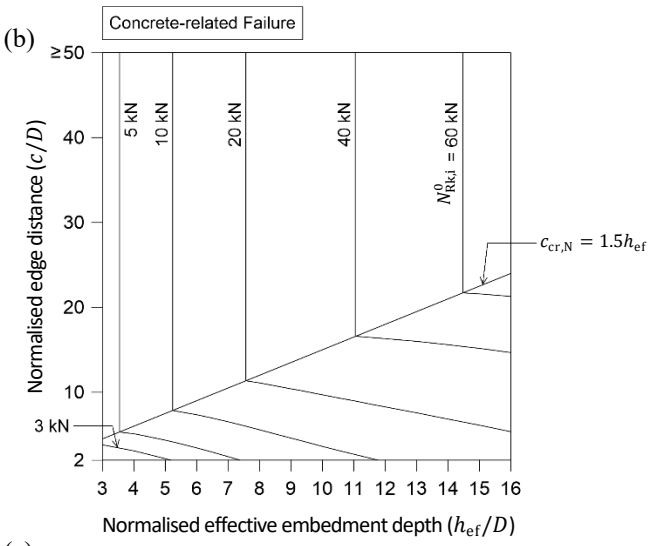
(i) Concrete cone failure

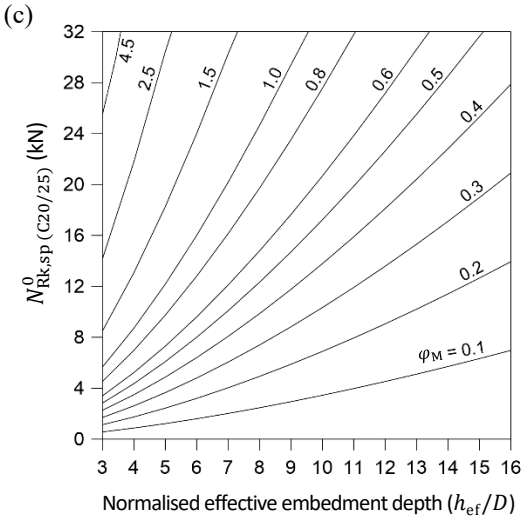
$$N_{Rk,c} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)$$

(ii) Concrete splitting failure

$$N_{Rk,sp} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)(\varphi_M)(\varphi_{hb,N})$$







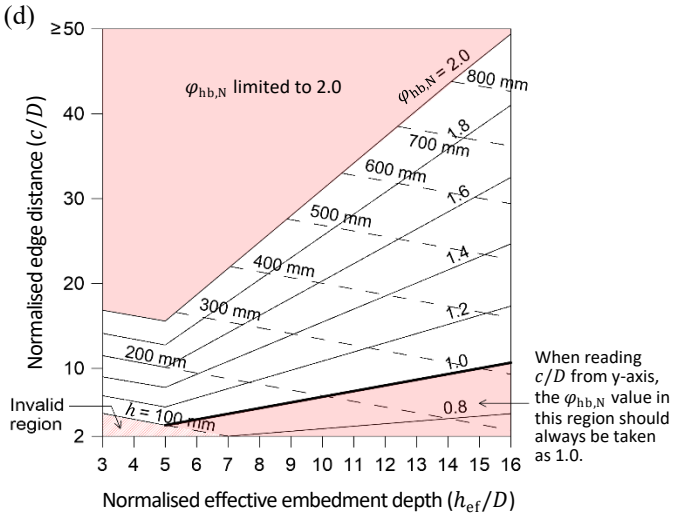
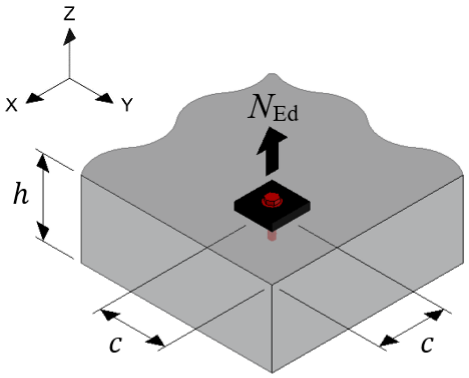
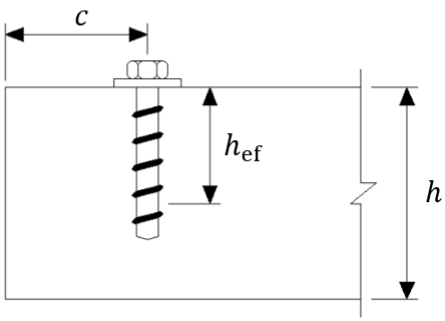


Fig. A3 Nomogram for tensile resistance for anchor size M10

Tensile resistance - 12 mm





$$N_{Rd,i} = \frac{N_{Rk,i}}{\gamma_{Mc}}$$

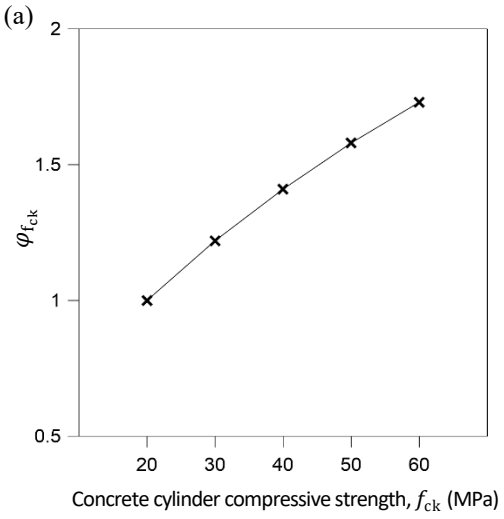
where, $N_{Rk,i} = \min\{N_{Rk,c}; N_{Rk,sp}\}$

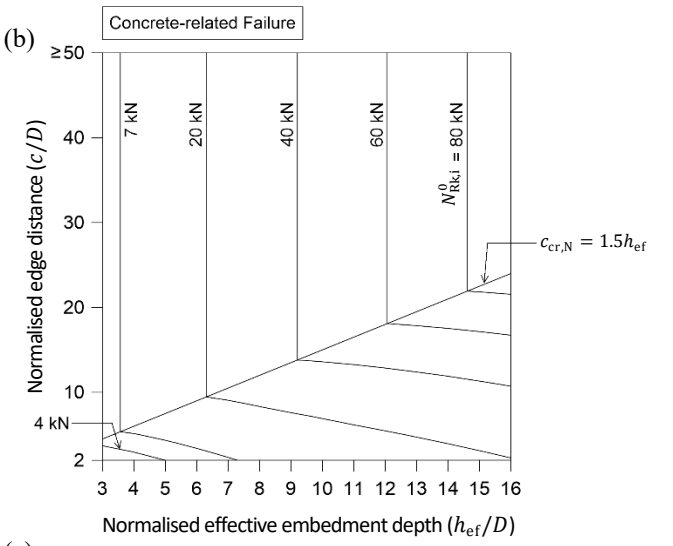
(i) Concrete cone failure

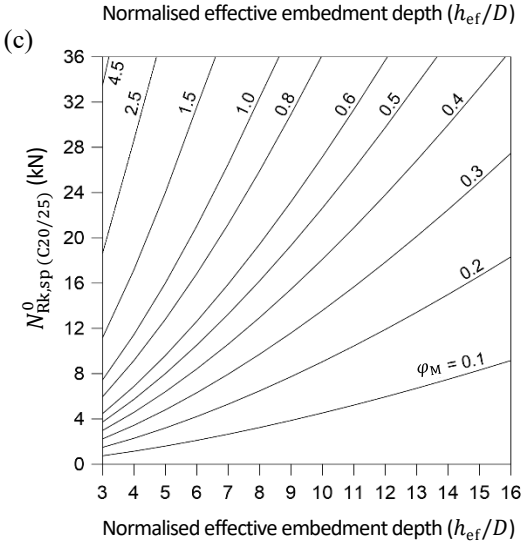
$$N_{Rk,c} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)$$

(ii) Concrete splitting failure

$$N_{Rk,sp} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)(\varphi_M)(\varphi_{hb,N})$$







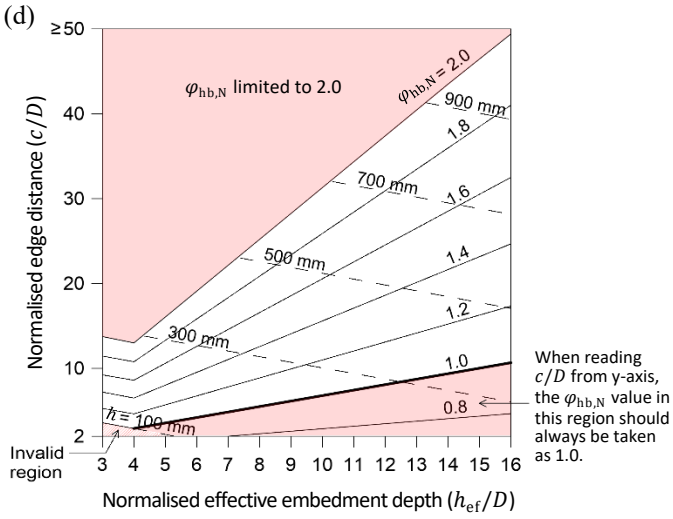
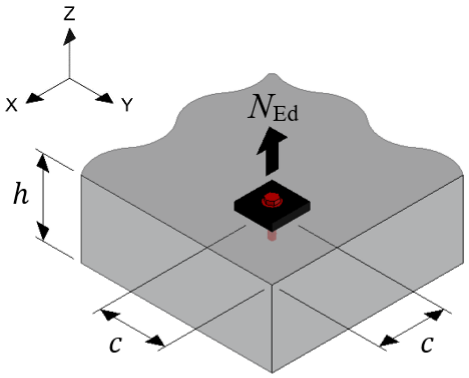
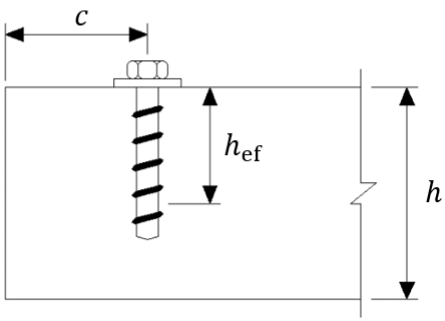


Fig. A4 Nomogram for tensile resistance for anchor size M12

Tensile resistance - 14 mm





$$N_{Rd,i} = \frac{N_{Rk,i}}{\gamma_{Mc}}$$

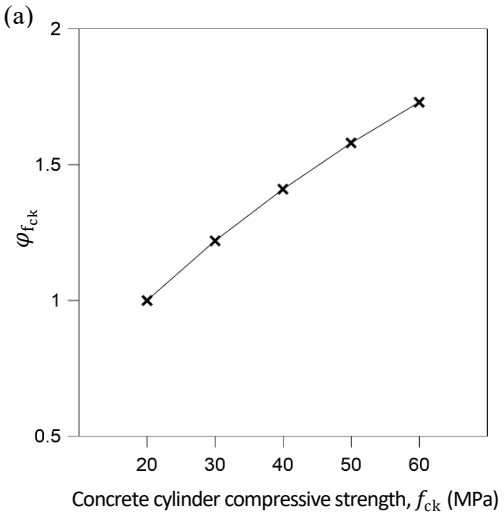
where, $N_{Rk,i} = \min\{N_{Rk,c}; N_{Rk,sp}\}$

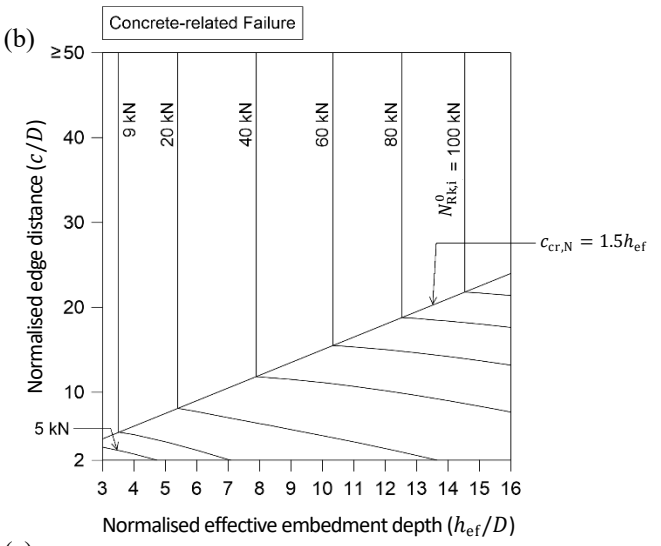
(i) Concrete cone failure

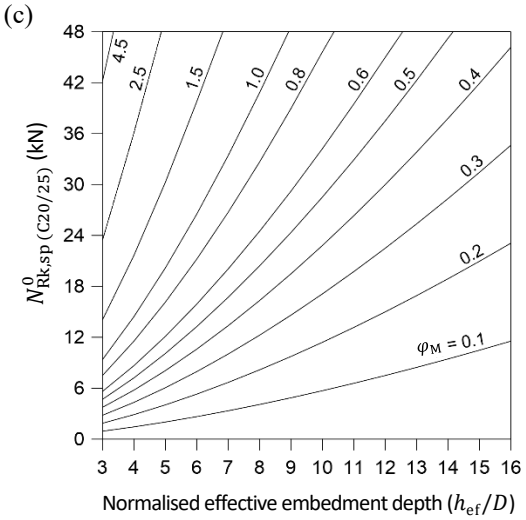
$$N_{Rk,c} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)$$

(ii) Concrete splitting failure

$$N_{Rk,sp} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)(\varphi_M)(\varphi_{hb,N})$$







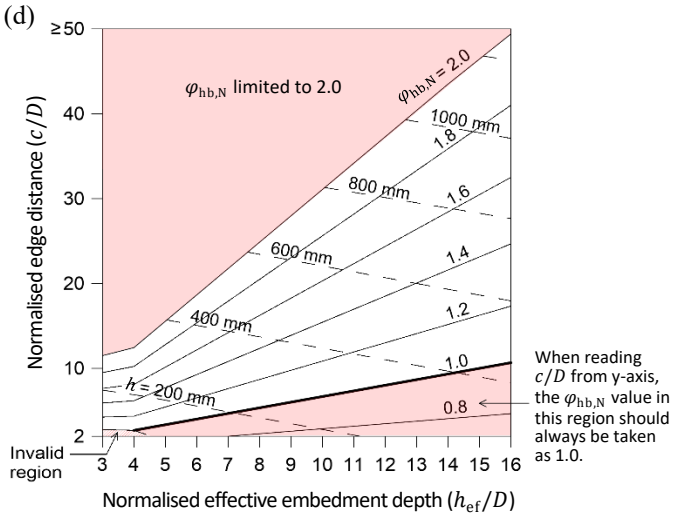
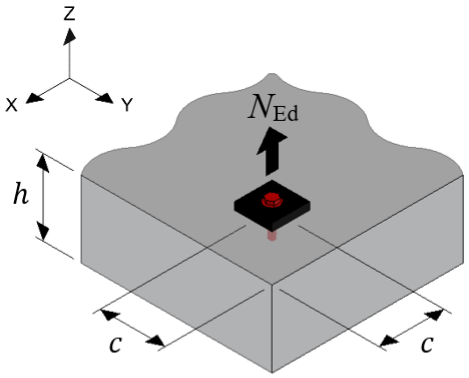
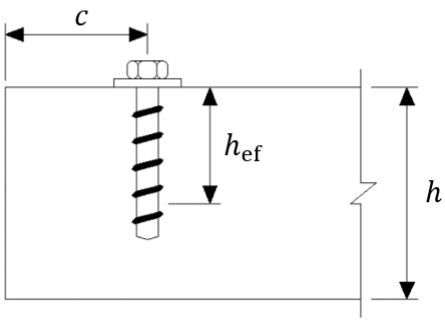


Fig. A5 Nomogram for tensile resistance for anchor size M14

Tensile resistance - 16 mm





$$N_{Rd,i} = \frac{N_{Rk,i}}{\gamma_{Mc}}$$

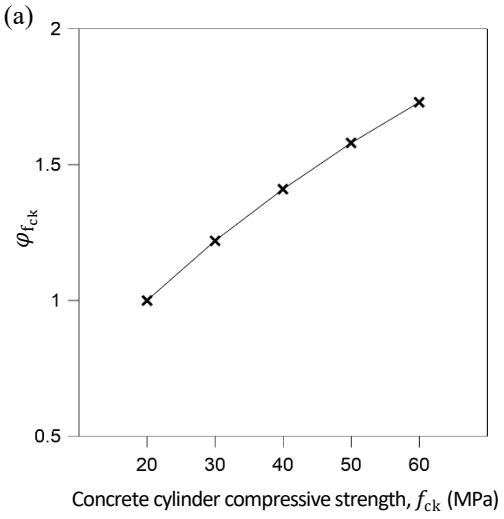
where, $N_{Rk,i} = \min\{N_{Rk,c}; N_{Rk,sp}\}$

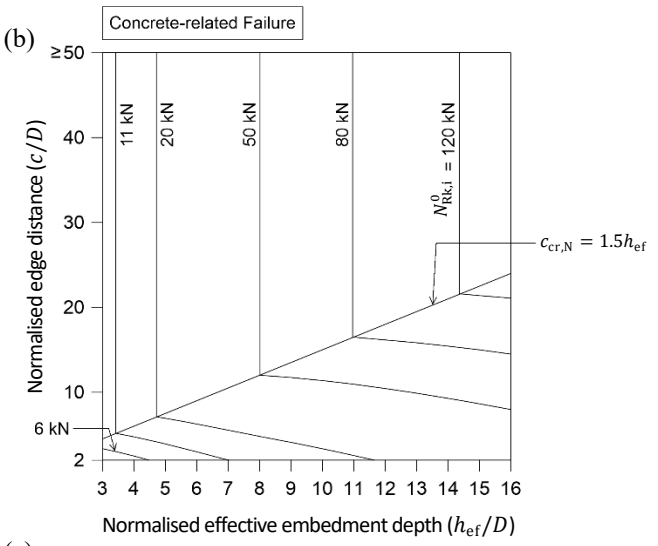
(i) Concrete cone failure

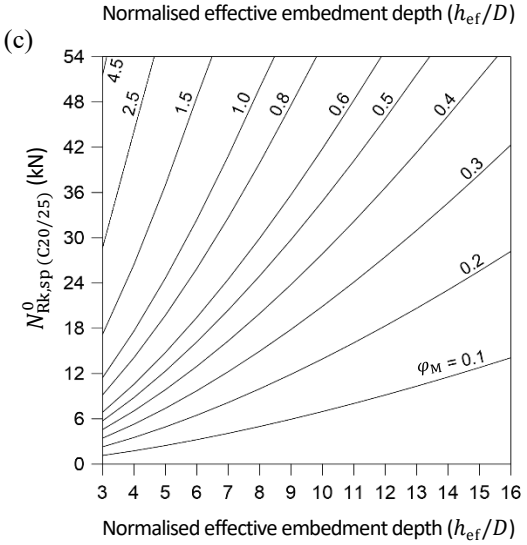
$$N_{Rk,c} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)$$

(ii) Concrete splitting failure

$$N_{Rk,sp} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)(\varphi_M)(\varphi_{hb,N})$$







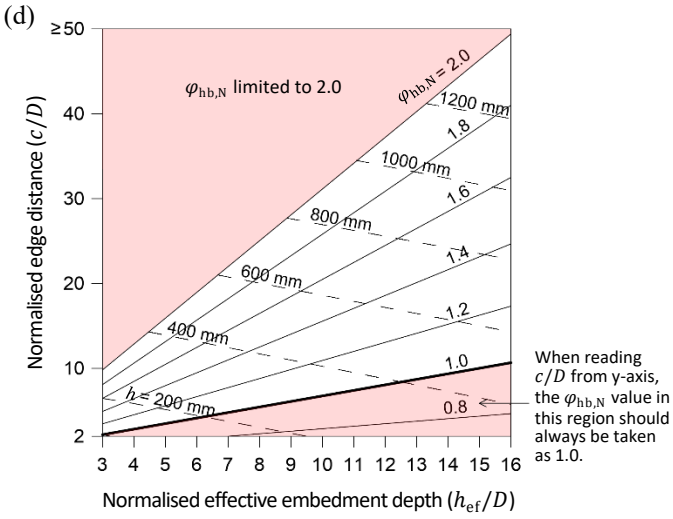


Fig. A6 Nomogram for tensile resistance for anchor size M16

Appendix B

In this section, six nomograms for screw anchors design under shear load are reported by varying the anchor size (i.e., M6, M8, M10, M12, M14, and M16).

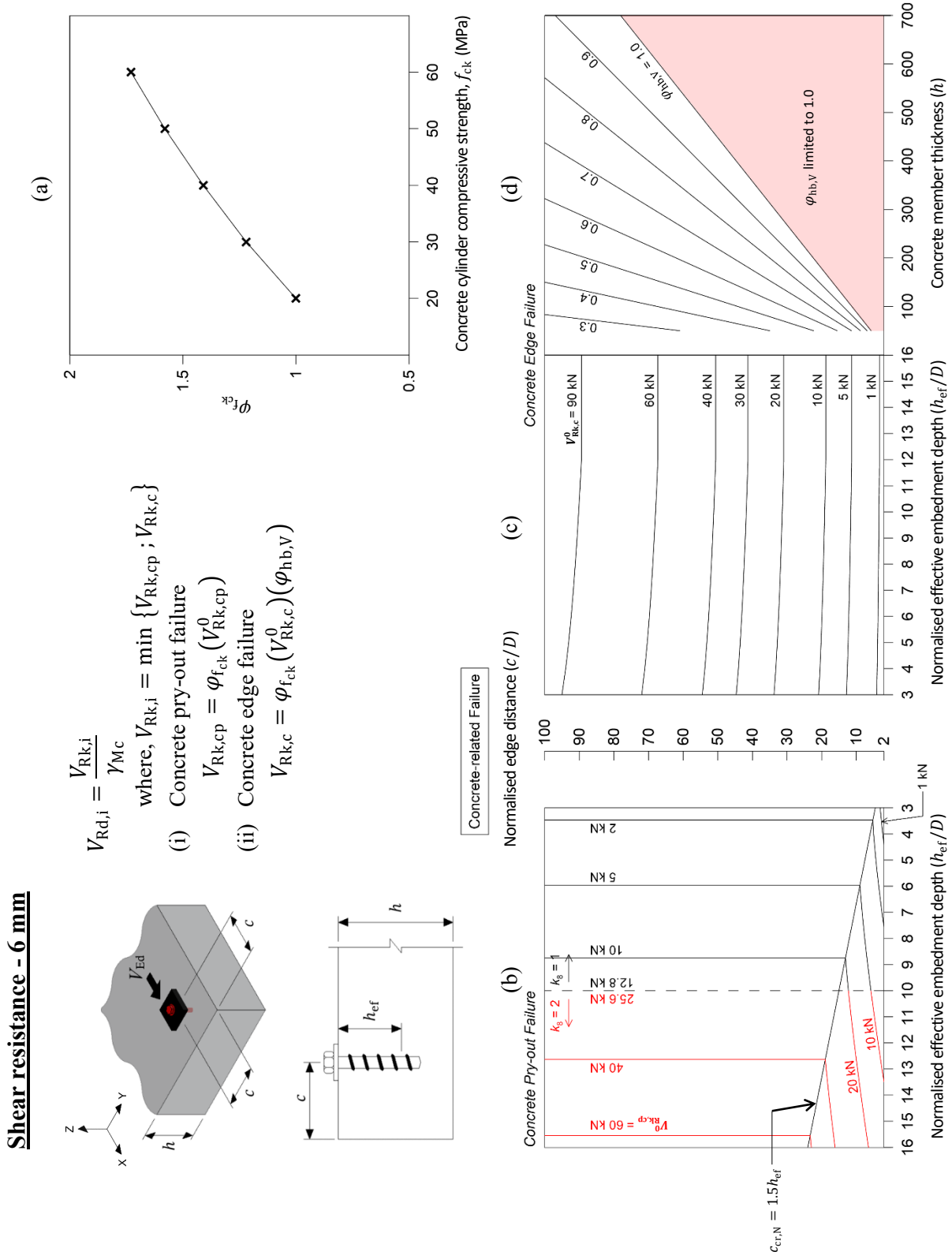


Fig. B1 Nomogram for shear resistance for anchor size M6

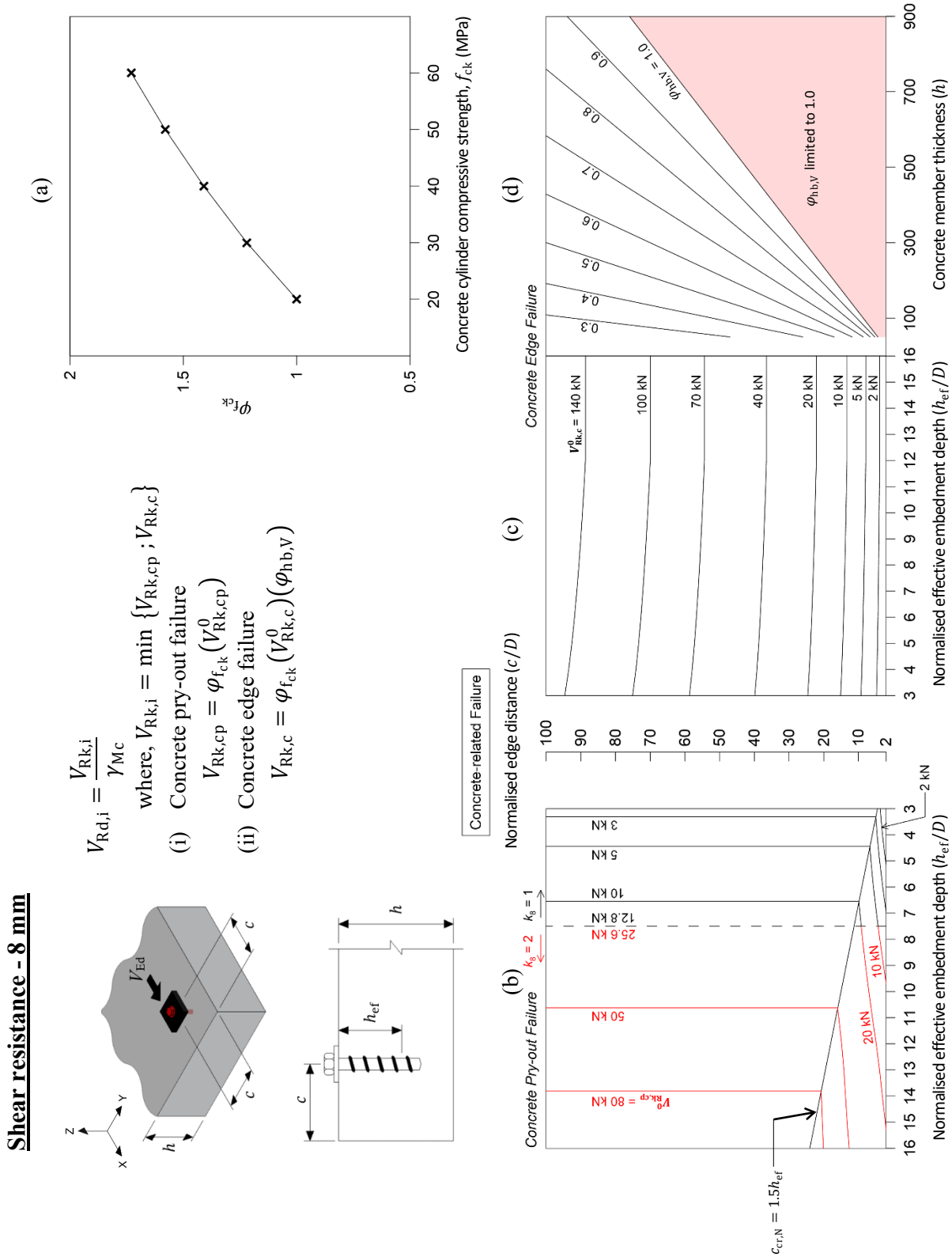


Fig. B2 Nomogram for shear resistance for anchor size M8

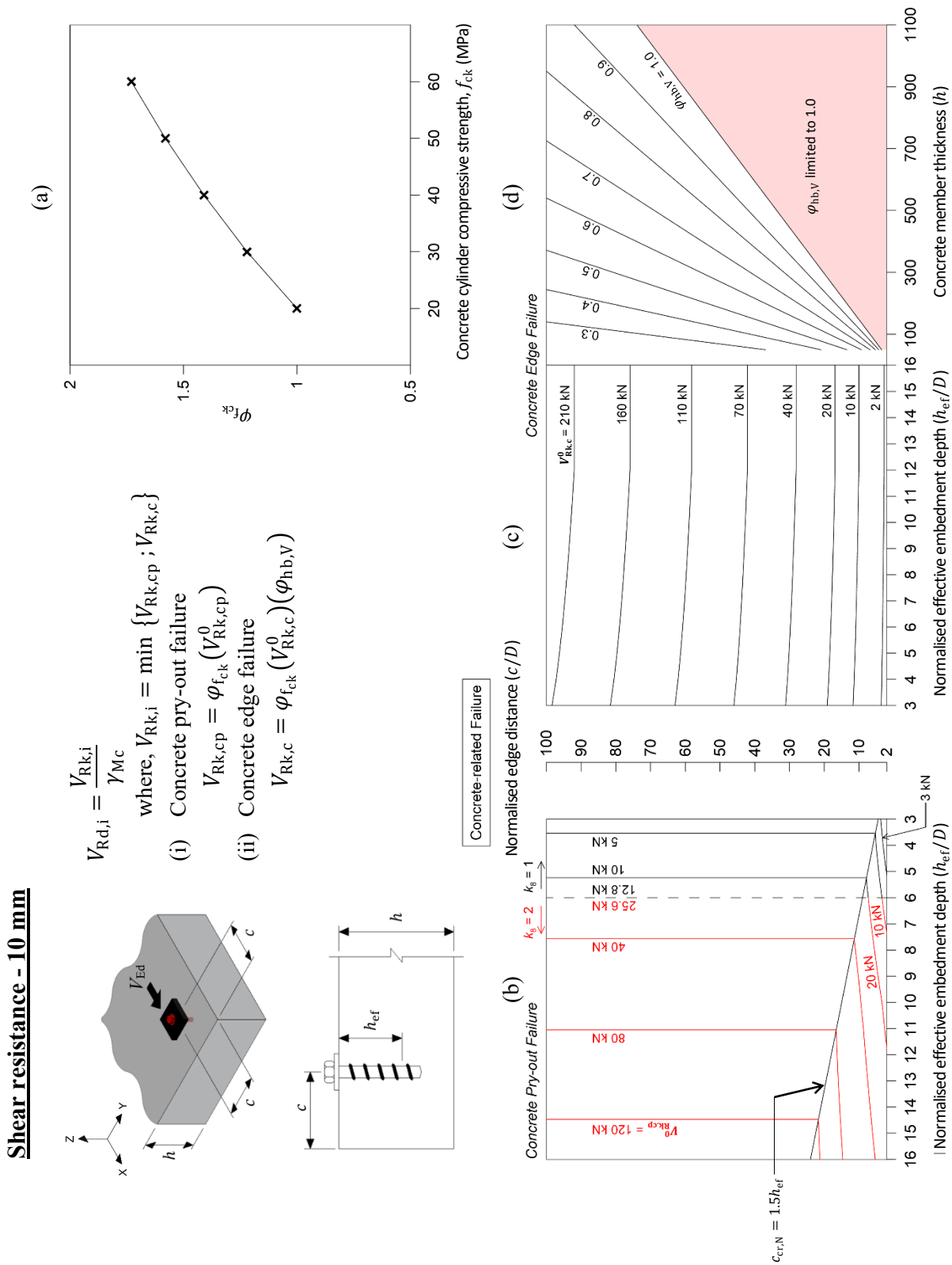


Fig. B3 Nomogram for shear resistance for anchor size M10

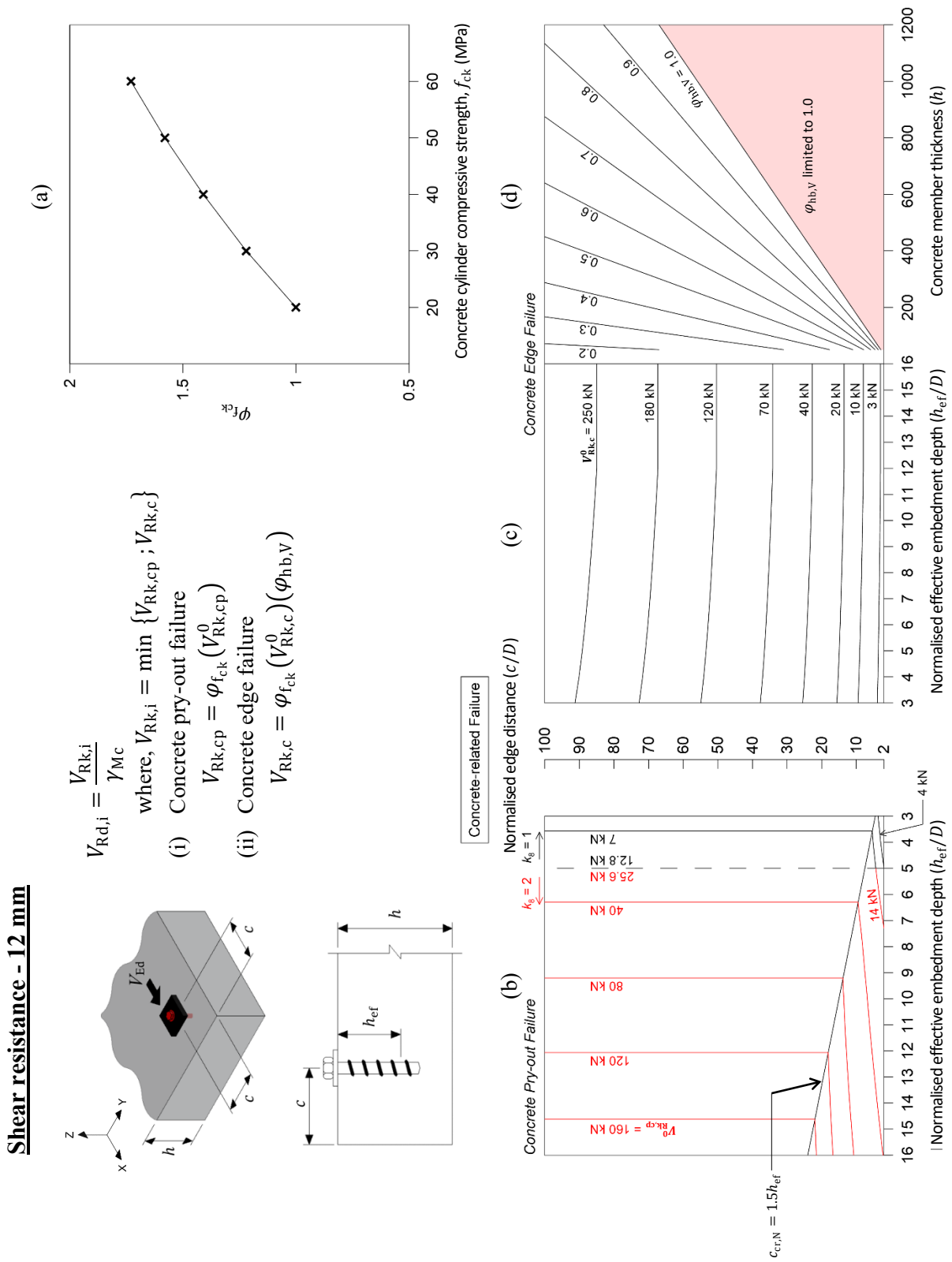


Fig. B4 Nomogram for shear resistance for anchor size M12

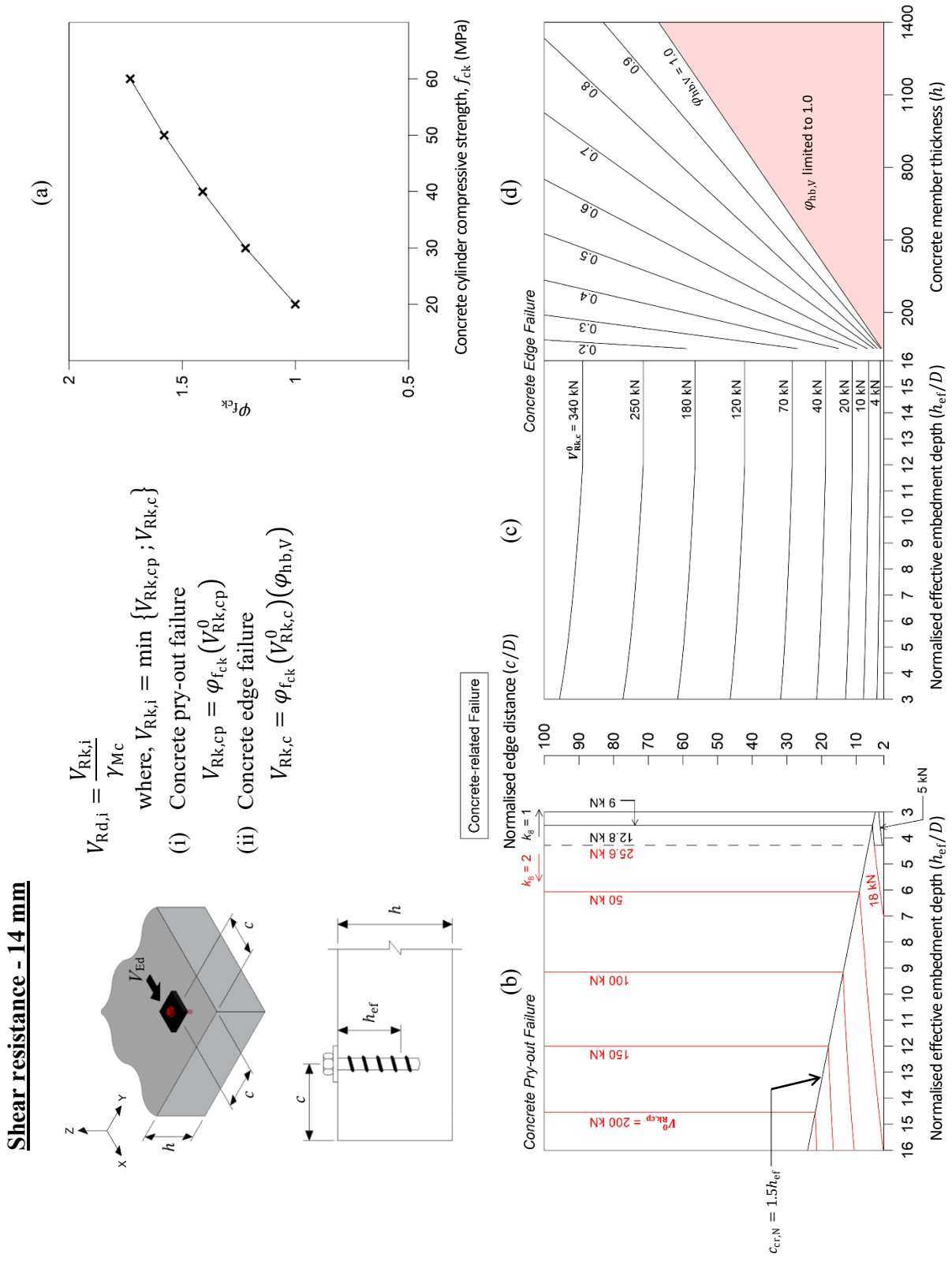


Fig. B5 Nomogram for shear resistance for anchor size M14

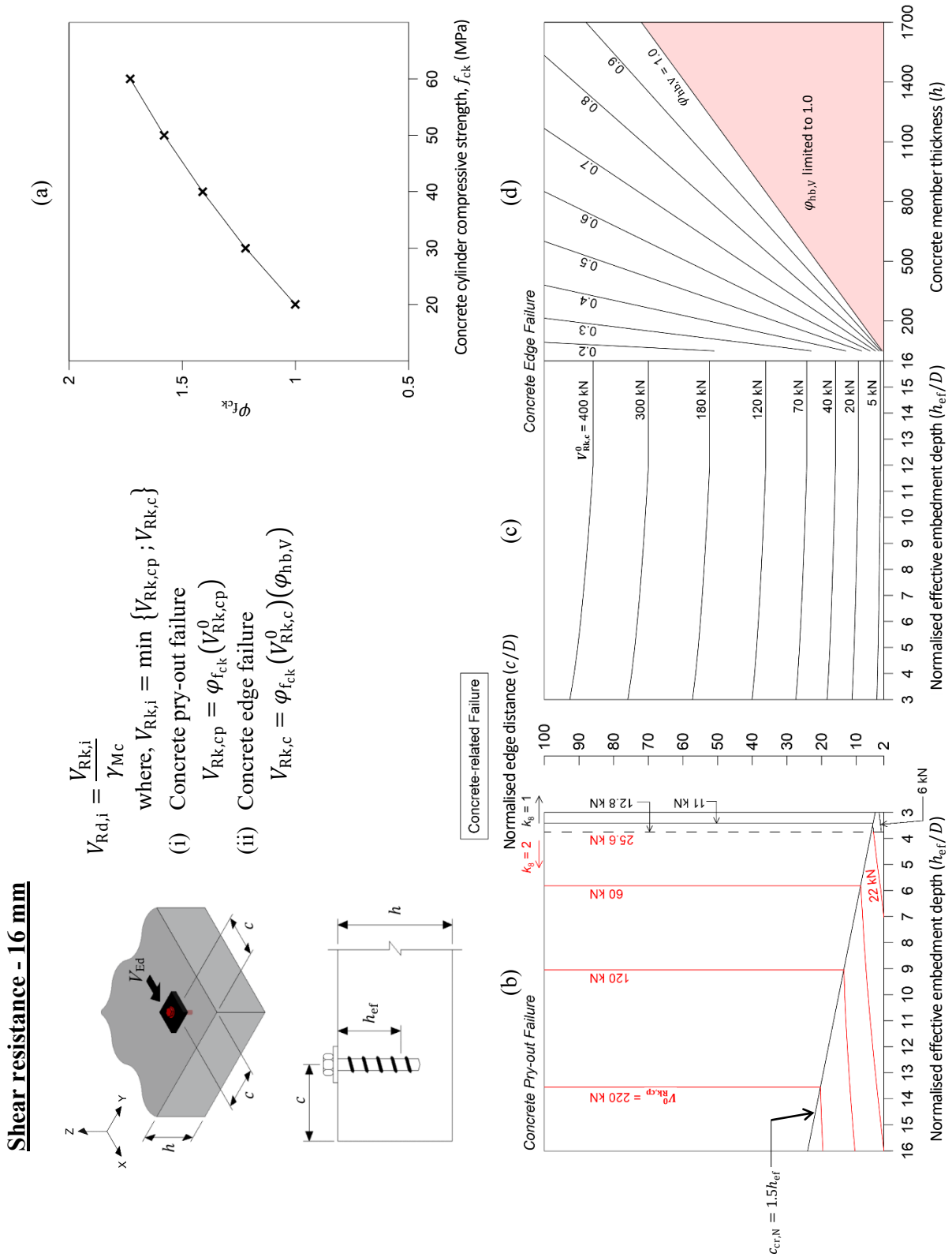


Fig. B6 Nomogram for shear resistance for anchor size M16

Appendix C

An example of calculating the tensile and shear resistances using the proposed nomogram is presented here. The example refers to the details of Model 1, as shown in Table 2.

Dimensions and details

Anchor size = M8 (D = 8 mm); f_{ck} = 30 MPa; h_{ef} = 56.1 mm; c = 50 mm; and h = 150 mm

Tensile resistance of screw anchor

Step 1: Product A prequalified as per EAD 330232 [25] and designed to EN 1992-4:2018 [11] is selected as an example.

Step 2: D = 8 mm; f_{ck} = 30 MPa; h_{ef} = 56.1 mm; c = 50 mm; h = 150 mm

Step 3a: From the ETA of Product A, $N_{Rk,s}$ = 36.0 kN; $\gamma_{Ms,N}$ = 1.5

Step 3b: $N_{Rd,s} = \frac{N_{Rk,s}}{\gamma_{Ms,N}} = \frac{36.0}{1.5} =$ 24.0 kN

Step 4a: From the ETA of Product A, $N_{Rk,p\,(C20/25)} \geq N^0_{Rk,c}$, so it is conservatively taken as equal to $N^0_{Rk,c}$ = 14.5 kN; γ_{inst} = 1.0

$N_{Rk,p} = \varphi_{f_{ck}}\left(N_{Rk,p\,(C20/25)}\right) = 1.22(14.5) =$ 17.7 kN

Step 4b: $N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}} = \frac{17.7}{1.5(1.0)} =$ 11.8 kN

Note: For Steps 5a to 5d, an example of using the nomogram is shown in Fig. C1.

Step 5a: $\varphi_{f_{ck}}$ = 1.22

Step 5b: h_{ef}/D = 7; c/D = 6.3, $N^0_{Rk,i}$ = 6.5 kN

Step 5c: $N^0_{Rk,sp\,(C20/25)}$ = 14.5 kN, φ_M = 1.0

Step 5d:

For h_{ef}/D = 7; c/D = 6.3, $\varphi_{hb,N}$ = 1.09

For h_{ef}/D = 7; h = 150 mm, $\varphi_{hb,N}$ = 1.20

Hence, $\varphi_{hb,N}$ = 1.09 (lowest value is chosen)

Step 5e(i): $N_{Rk,c} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right) = 1.22(6.5) =$ 7.9 kN

Step 5e(ii): $N_{Rk,sp} = \varphi_{f_{ck}}\left(N^0_{Rk,i}\right)(\varphi_M)(\varphi_{hb,N}) = 1.22(6.5)(1.0)(1.09) =$ 8.6 kN

Step 5f: $N_{Rk,i} = \min\left\{N_{Rk,c}\,;N_{Rk,sp}\right\} = \min\{7.9\,;8.6\} =$ 7.9 kN (Governed by concrete cone failure)

Step 5g: $N_{Rd,i} = \frac{N_{Rk,i}}{\gamma_{Mc}} = \frac{7.9}{1.5(1.0)} =$ 5.3 kN

Step 6: The tensile resistance of the screw anchor $= \min\left\{N_{Rd,s}\,;N_{Rd,p}\,;N_{Rd,i}\right\} = \min\{24.0\,;11.8\,;5.3\} =$ 5.3 kN (Governed by concrete cone failure)

Shear resistance of screw anchor

Step 1: Product A prequalified as per EAD 330232 [25] and designed to EN 1992-4:2018 [11] is selected as an example.

Step 2: D = 8 mm; f_{ck} = 30 MPa; h_{ef} = 56.1 mm; c = 50 mm; h = 150 mm

Step 3a: From the ETA of Product A, $V^0_{Rk,s}$ = 21.9 kN, hence $V_{Rk,s}$ = 21.9 kN; $\gamma_{Ms,V}$ = 1.25

Step 3b: $V_{Rd,s} = \frac{V_{Rk,s}}{\gamma_{Ms,V}} = \frac{21.9}{1.25} =$ 17.5 kN

Note: For Steps 4a to 4d, an example of using the nomogram is shown in Fig. C2.

Step 4a: $\varphi_{f_{ck}}$ = 1.22

Step 4b: h_{ef}/D = 7; c/D = 6.3; $V^0_{Rk,cp}$ = 6.7 kN

Step 4c: $V^0_{Rk,c}$ = 3.4 kN

Step 4d: $\varphi_{hb,V}$ = 1.0

Step 4e(i): $V_{Rk,cp} = \varphi_{f_{ck}}\left(V^0_{Rk,cp}\right) = 1.22(6.7) =$ 8.2 kN

Step 4e(ii): $V_{Rk,c} = \varphi_{f_{ck}}\left(V^0_{Rk,c}\right)\left(\varphi_{hb,V}\right) = 1.22(3.4)(1.0) =$ 4.1 kN

Step 4f: $V_{Rk,i} = \min\left\{V_{Rk,cp}\,;V_{Rk,c}\right\} = \min\{8.2\,;4.1\} =$ 4.1 kN (Governed by concrete edge failure)

Step 4g: $V_{Rd,i} = \frac{V_{Rk,i}}{\gamma_{Mc}} = \frac{4.1}{1.5(1.0)} =$ 2.7 kN

Step 5: The shear resistance of the screw anchor $= \min\left\{V_{Rd,s}\,;V_{Rd,i}\right\} = \min\{17.5\,;2.7\} =$ 2.7 kN (Governed by concrete edge failure)

Summary of screw anchor design

The design tensile resistance = 5.3 kN (Governed by concrete cone failure)

The design shear resistance = 2.7 kN (Governed by concrete edge failure)

Tensile resistance - 8 mm

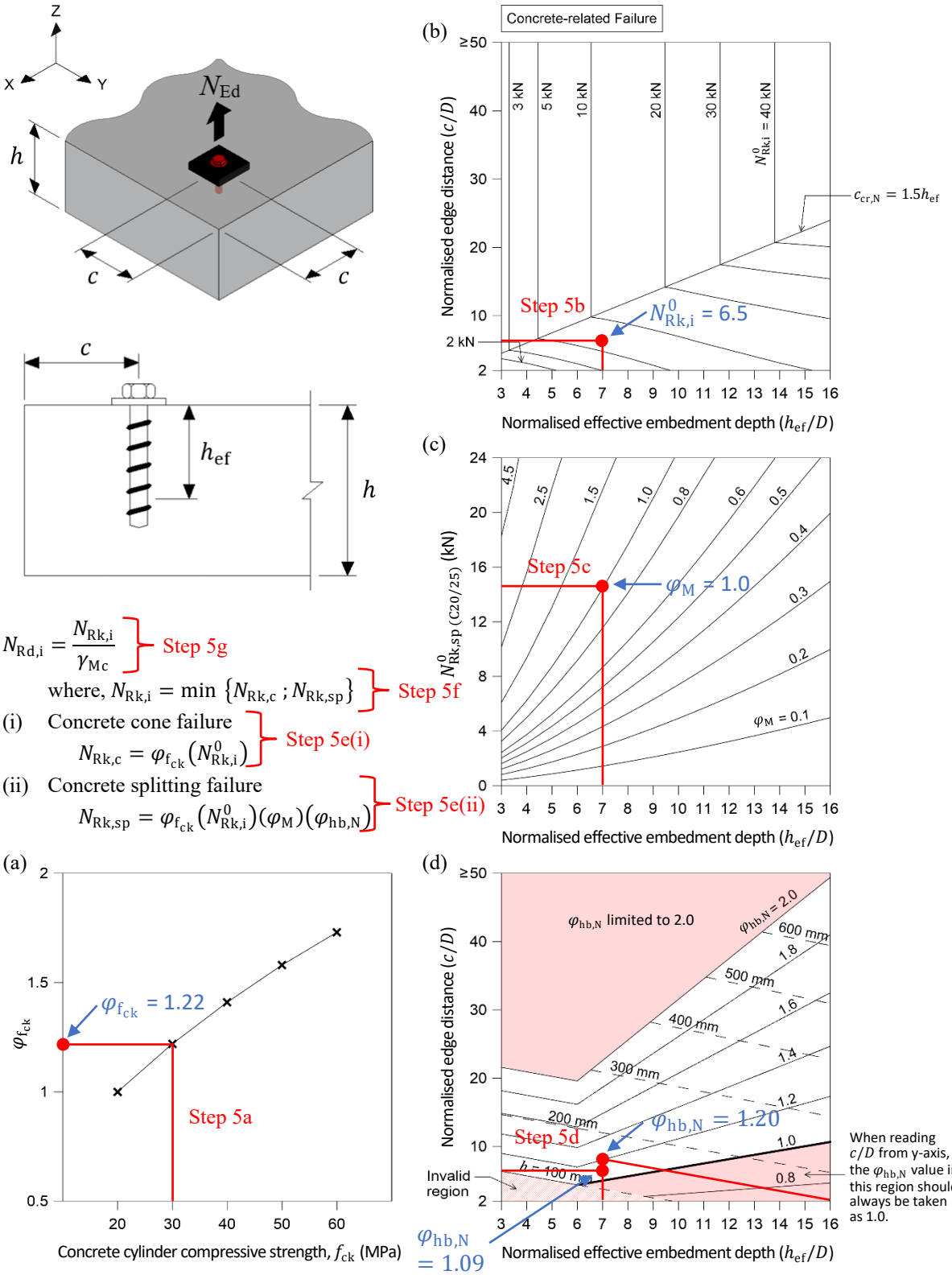


Fig. C1 An example of using the nomogram under tensile load

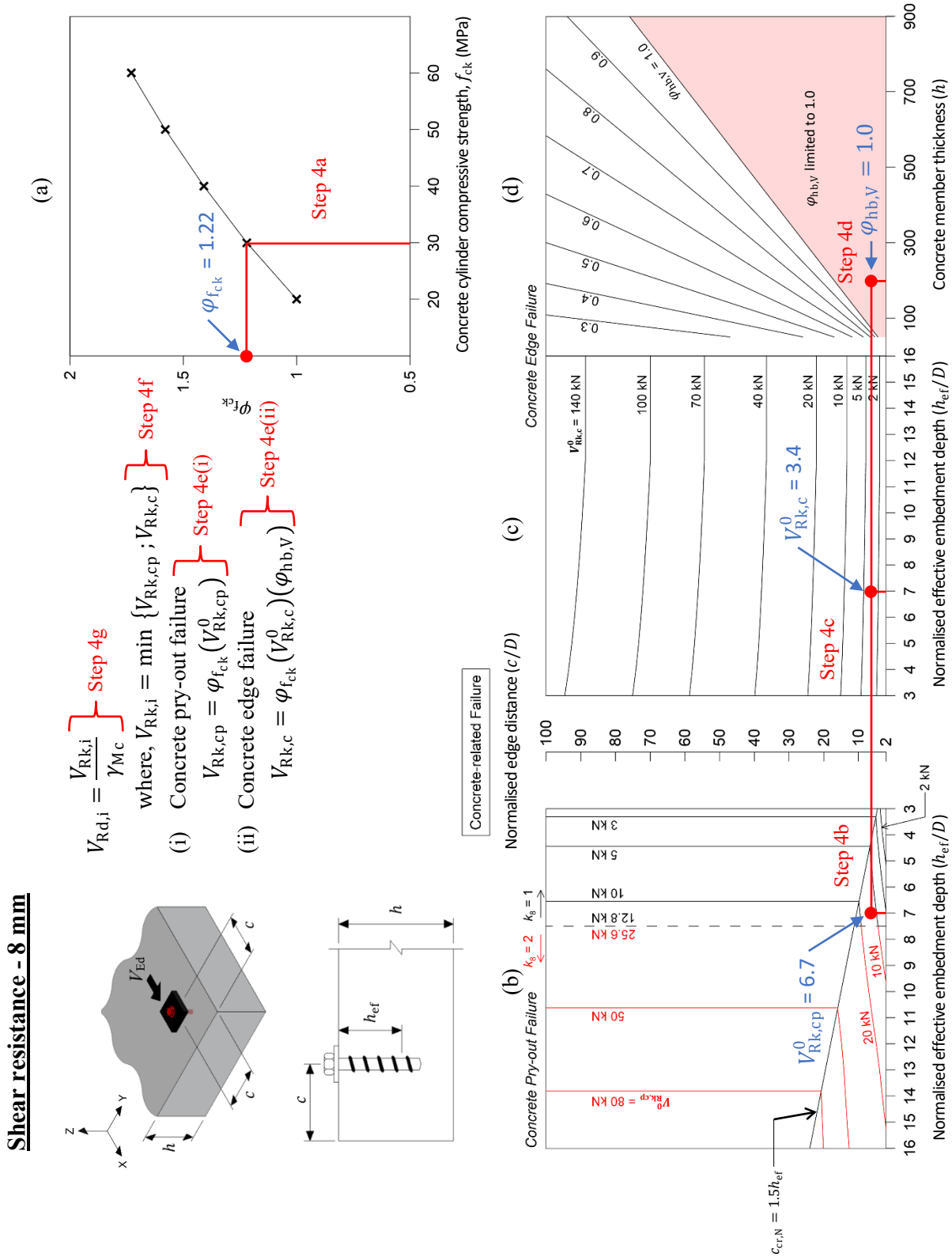


Fig. C2 An example of using the nomogram under shear load