TECHNICAL REPORT

Design of bonded fasteners in concrete under fire conditions

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1 INTRODUCTION

This Technical Report contains a fire design method for bonded fasteners in concrete having a European Technical Assessment (ETA) in accordance with EAD 330499-02-0601 [1] and later version of EAD without technical changes of fire assessment (applies throughout document).

2 SCOPE

2.1 General

This Technical Report provides a fire design method for bonded fasteners comprised of bonding material and an embedded metal part placed in pre-drilled holes perpendicular to the surface (maximum deviation 5°) in concrete and anchored therein primarily by means of bond. Bonded fasteners are often used to connect structural elements and non-structural elements to structural components.

The embedded metal part may be a threaded rod, deformed reinforcing bar, internal threaded sleeve or other shape made of carbon steel or stainless steel.

The design rules in this Technical Report are only valid for bonded fasteners with a European Technical Assessment (ETA) in accordance with EAD 330499-02-0601 [1], which can be used in cracked concrete.

This Technical Report covers fire design for bonded fasteners in normal weight concrete with a strength of at least C20/25 and at most C50/60. The determination of the fire resistance is according to the conditions given in EN 1363-1 [2] using the standard temperature/time curve (post flash-over fire, which is identical to the ISO 834-1 [5]).

In general, the duration of fire resistance of anchorages depends mainly on the configuration of the structure itself (base material, anchorage including the fixture). It is not possible to classify a bonded fastener for its fire resistance. The design concept includes the behaviour of the bonded fastener in concrete and the parts outside the concrete. The thermal influence of thin steel fixtures is considered negligible. In the calculations given in Annex A the fixture was neglected.

Bonded fasteners installed in reinforced concrete shall be designed for the required fire resistance duration of the base material.

Local spalling of concrete is possible under fire conditions. To avoid any influence of the spalling on the anchorage, the concrete member must be designed according to EN 1992-1-2 [3]. The members shall be protected from direct moisture until the fire event (i.e., e.g., fixing of sprinklers is covered), and the moisture content of the concrete has to be representative of dry internal conditions.

This Technical Report is intended for safety related applications in which the failure of bonded fasteners under fire conditions may result in collapse or partial collapse of the structure, cause risk to human life or lead to significant economic loss. In this context it also covers non-structural elements.

This Technical Report covers bonded fasteners for exposure to fire conditions from one or several sides, provided that the used model has been validated in accordance with Annex A. The temperature profiles given in Annex A shall be used only for one-sided exposure coming from the exposed extended part of the anchorage (see Figure A.1). For several sided exposure, the actual geometry of the fastener configuration shall be considered (i.e., embedment depth, diameter, edge distance, spacing…etc.). The design method complements EN 1992-4 [4], Annex D.

Bonded fasteners under fire conditions shall have a European Technical Assessment for use in cracked concrete. They shall also be assessed for fire conditions in accordance with EAD 330499-02-0601 [1]. In general, cracked concrete is assumed for fasteners under fire conditions.

This Technical Report covers bonded fasteners with the following dimensions:

- Minimum thread size of 6 mm (M6),
- Minimum embedment depth $h_{ef,min}$ larger than or equal to 40 mm and larger than or equal to $4 \cdot d$,
- Maximum embedment depth $h_{ef,max}$ smaller than or equal to $20 \cdot d$.

> *Note 1: The stated limit for the maximum embedment depth of* $20 \cdot d$ *is in accordance with EAD 330499-02-0601 [1] and EN 1992-4 [4].*

In general, the design under fire conditions is carried out according to the design method for normal ambient temperature given in EN 1992-4 [4]. However, partial factors and characteristic resistances under fire conditions are used instead of the corresponding values under normal ambient temperature. Normal ambient temperature is the temperature to which the anchorage is exposed before exposure to fire conditions. The characteristic resistances corresponding to normal ambient temperature shall be taken from the service temperature ranges given in the ETA.

In comparison to EOTA TR 082 (June 2023), the following clauses have been changed or added: 2.1, 3.2, 4, 7.2.1, 7.3.1, and A.1.

3 SYMBOLS AND ABBREVIATIONS

3.1 Indices

cr = cracked

fi = fire

k = characteristic value

max = maximum

min = minimum

p = pull-out

R = resistance

Rk = characteristic resistance

s = steel

t = test

3.2 Symbols

A_s = relevant stressed cross section of the metal part of the fastener

$c_{cr,N_p,fi}$ = characteristic edge distance for ensuring the transmission of the characteristic resistance of a single bonded fastener under tension load in case of combined concrete and pull-out failure under fire conditions

d = diameter of the embedded part

e_N = eccentricity of resultant tension force of tensioned fasteners in respect to the centre of gravity of the tensioned fasteners, see EN 1992 [4], Figure 6.3

h_{ef} = effective embedment depth, see EN 1992-4 [4], Figure 3.3

$k_{fi,p}(\theta)$ = temperature reduction factor for bond resistance under fire conditions

$k_{fi,p}\big(\theta(x)\big)$ = temperature reduction factor for considered segment length Δx determined using mean temperature along considered segment length Δx

$k_{fi,s}(\theta)$ = temperature reduction factor for steel failure under fire conditions

$M^0_{Rk,s,fi(t)}$ = characteristic shear resistance in case of shear load with lever arm at a given time t of exposure to fire conditions

$N^0_{Rk,p}$ = characteristic resistance of a single bonded fastener not influenced by adjacent bonded fasteners or edges of the concrete member in case of combined pull-out and concrete failure under tension load

$N^0_{Rk,p,fi(t)}$ = Characteristic tension resistance of a single bonded fastener not influenced by adjacent bonded fasteners or edges of the concrete member in case of combined pull-out and concrete failure under fire conditions at a given time t of exposure to fire conditions

$N_{Rk,s}$ = characteristic tension resistance in case of steel failure at normal ambient temperature taken from the ETA of the product

$N_{Rk,s,fi(t)}$ = characteristic tension resistance in case of steel failure at a given time t of exposure to fire conditions

$s_{cr,N_p,fi}$ = characteristic spacing to ensure the transmission of the characteristic resistance of a single bonded fastener under fire conditions

$V_{Rk,s,fi(t)}$ = characteristic shear resistance in case of steel failure at a given time t of exposure to fire conditions

$\alpha_{sus,fire}$ = ratio between the value of sustained actions (comprising permanent actions and permanent component of variable actions) and the value of total actions all considered at ULS under fire conditions

Δx = segment length considered in the Resistance Integration Method for calculation of the fire resistance to combined pull-out and concrete failure

θ = temperature in the tests for bond strength under fire conditions (tests according to EAD 330499-02-0601 [1], Table A.1, line F2)

θ_s = temperature of the steel element at the loaded section

θ_{max} = maximum temperature in the tests for bond strength under fire conditions, beyond which the bond resistance of the mortar is considered zero.

$\sigma_{Rk,s,fi(t)}$ = characteristic tension strength of a fastener in case of steel failure a given time t of exposure to fire conditions

$\tau_{Rk,cr}$ = characteristic bond resistance for cracked concrete at normal ambient temperature for concrete strength class C20/25 to be taken from the ETA of the product

$\tau_{Rk,fi}(\theta)$ = characteristic bond resistance for cracked concrete under fire conditions for a given temperature (θ)

$\tau_{Rk,fi,min}$ = minimum bond strength under fire conditions determined according to Equation (7.1) using the reduction factor $k_{fi,p}(\max\theta)$ for the maximum temperature $\max\theta$, along the embedment depth

$\tau_{Rk,ucr}$ = characteristic bond resistance for uncracked concrete at normal ambient temperature for concrete strength class C20/25 to be taken from the ETA of the product

ψ_{ce,N_p} = factor taking into account the group effect when different tension loads are acting on the individual fasteners of a group in case of combined pull-out and concrete failure of bonded fasteners at normal ambient temperature

$\psi_{ce,N_p,fi}$ = factor taking into account the group effect when different tension loads are acting on the individual fasteners of a group in case of combined pull-out and concrete failure of bonded fasteners under fire conditions

ψ_{g,N_p} = factor taking into account group effect for closely spaced bonded fasteners at normal ambient temperature

$\psi_{g,N_p,fi}$ = factor taking into account group effect for closely spaced bonded fasteners under fire conditions

$\psi_{re,N}$ = shell spalling factor

ψ_{s,N_p} = factor taking into account the disturbance of the distribution of stresses in the concrete due to the proximity of an edge in the concrete member in case of combined pull-out and concrete failure of bonded fasteners at normal ambient temperature

$\psi_{s,N_p,fi}$ = factor taking into account the disturbance of the distribution of stresses in the concrete due to the proximity of an edge in the concrete member in case of combined pull-out and concrete failure of bonded fasteners under fire conditions

$\psi_{sus,fire}$ = factor that takes account of the influence of sustained load on the bond strength under fire conditions, see 7.2.3

$\psi^0_{sus,fire}$ = product dependent factor that takes account of the influence of sustained load on the bond strength before a fire event, to be taken from the ETA of the product

4 BASIS OF DESIGN

EN 1992-4 [4], Section 4 applies. However, partial factors are addressed in Section 5.

5 PARTIAL FACTORS

EN 1992-4 [4], D.2 applies.

6 ACTIONS

EN 1992-4 [4], D.3 applies.

7 RESISTANCE

7.1 General

The characteristic resistances for steel failure and combined pull-out and concrete failure under fire conditions are given in the relevant European Technical Assessment (ETA). If the characteristic resistance under fire conditions for steel failure under tension or shear loading is not available in the ETA, the conservative values given in 7.2.1 or 7.3.1, respectively, may be used.

7.2 Tension load

7.2.1 Steel failure

Stress criterion

The characteristic steel resistance to tension load under fire conditions shall be taken from the ETA. If no performance is given in the ETA, the characteristic tension strength $\sigma_{Rk,s,fi}$ of a fastener in case of steel failure under fire conditions given in EN 1992-4 [4], Tables D.1 and D.2 for the covered steel materials is valid for the unprotected steel part of the fastener outside the concrete and may be used in the design. These values are conservative against values assessed according to EAD 330499-02-0601 [1].

The characteristic resistance $N_{Rk,s,fi}$ is obtained from EN 1992-4 [4], Equation (D.1).

Temperature-based reduction factor criterion

Alternatively, the characteristic resistance $N_{Rk,s,fi}$ may be determined based on the temperature of the steel at a given fire exposure time[1].

$$N_{Rk,s,fi(t)} = k_{fi,s}(\theta_s) \cdot N_{Rk,s} \tag{7.1}$$

The temperature reduction factor for steel failure $k_{fi,s}(\theta)$ shall be taken from Table 7.1 and Table 7.2, based on the type of steel element used for bonded fastener application.

Table 7.1: Temperature reduction factor for steel failure $k_{fi,s}(\theta_s)$ for threaded rods as anchor element

Threaded rods[2] with coarse pitch threads, with steel grades from 4.6 to 10.9 in accordance with EN ISO 898-1 [8], and steel grades A4 in accordance with EN ISO 3506 series [9]	
θ_s (°C)	$k_{fi,s}$
20	1,0
300	1,0
400	f_{yk}/f_{uk}
500	$0{,}78 \cdot f_{yk}/f_{uk}$
600	$0{,}47 \cdot f_{yk}/f_{uk}$
700	$0{,}23 \cdot f_{yk}/f_{uk}$
800	$0{,}11 \cdot f_{yk}/f_{uk}$
900	$0{,}06 \cdot f_{yk}/f_{uk}$
1000	$0{,}04 \cdot f_{yk}/f_{uk}$
1100	$0{,}02 \cdot f_{yk}/f_{uk}$
1200	0
For intermediate values of steel temperature, linear interpolation may be used.	

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[1] This approach covers threaded rods with coarse pitch threads, with steel grades from 4.6 to 10.9 in accordance with EN ISO 898-1 [5], and steel grade A4 in accordance with EN ISO 3506-1 [9] and reinforcing bars in accordance with the specifications of EN 1992-1-1:2004 [12], or later versions. Rebar tension anchors manufactured with friction welding between a rod and a reinforcing bar and steel elements other than regulated in the standards listed in these standards (e.g., internally threaded anchors) are not covered.

[2] The nut shall be in accordance with EN ISO 989-2 [10] for threaded rods made of carbon steel, and EN ISO 3506-2 [11] for threaded rods made of stainless steel, and shall have a steel grade at least equal to that of the threaded rod.

Table 7.2: Temperature reduction factor for steel failure $k_{fi,s}(\theta_s)$ for reinforcing bars as anchor element[3]

Reinforcing bars in accordance with EN 1992-1-1 [12]	
θ_s (°C)	$k_{fi,s}$
20	$1{,}0$
300	$1{,}0$
400	$0{,}90 \cdot f_{yk}/f_{uk}$
500	$0{,}70 \cdot f_{yk}/f_{uk}$
600	$0{,}47 \cdot f_{yk}/f_{uk}$
700	$0{,}23 \cdot f_{yk}/f_{uk}$
800	$0{,}11 \cdot f_{yk}/f_{uk}$
900	$0{,}06 \cdot f_{yk}/f_{uk}$
1000	$0{,}04 \cdot f_{yk}/f_{uk}$
1100	$0{,}02 \cdot f_{yk}/f_{uk}$
1200	0
For intermediate values of steel temperature, linear interpolation may be used.	

The application of rebar as anchor element is covered by this approach for the use of a rebar to sustain fixings attached to the steel of the rebar without using a nut or a coupler (concrete-to-concrete connections). This approach does not cover rebars with any type of welding.

> *Note 2: Haddadi and Al-Mansouri [6] [7] have confirmed the validity of the model in Equation (7.1) based on a database of over 300 fire tests resulting in steel failure (failure of the rod section, nut failure) on fasteners made of carbon steel and stainless steel of different types (torque-controlled expansion fasteners, wedge anchors, undercut fasteners, bonded fasteners, and headed studs) with steel grades from 5.8 to 12.9 in accordance with EN ISO 898-1 [8] and steel grade A4 in accordance with EN 3506 [9].*

Conservatively, for fasteners directly exposed to fire conditions (without fire protection), the values in Table B.1 to Table B.4 for $k_{fi,s}(\theta)$ may be adopted based on the required resistance to fire classification.

7.2.2 Concrete cone failure

EN 1992-4 [4], D4.2.2 applies.

7.2.3 Combined pull-out and concrete failure

The assessment according to EAD 330499-02-0601 [1] provides characteristic bond strengths τ_{Rk} for concrete strength classes C20/25 to C50/60 and reduction factors under fire conditions $k_{fi,p}(\theta)$ depending on the temperature θ, which are given in the corresponding ETA of the bonded fastener system. From these values, the characteristic bond resistance under fire conditions can be determined using Equation (7.2).

$$\tau_{Rk,fi}(\theta) = k_{fi,p}(\theta) \cdot \tau_{Rk,cr} \tag{7.2}$$

Where

$k_{fi,p}(20°C) = 1{,}0$. Therefore, $\tau_{Rk,fi}(20°C) = \tau_{Rk,cr}$

$k_{fi,p}(21°C \leq \theta \leq \theta_{max})$ is taken from the ETA of the product

$k_{fi,p}(\theta > \theta_{max}) = 0$

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[3] This approach is in accordance with EN 1992-1-2 [3] for consideration of the steel yield strength as the design limit of reinforcing bars under fire conditions.

$\tau_{Rk,cr}$ = characteristic bond resistance for cracked concrete at normal ambient temperature for concrete strength class C20/25 to be taken from the ETA of the product

Note 3: Eq. (7.2) may be used with Eq. (7.3) *(Simplified Method) or Eq. (7.6) (Resistance Integration Method) in this document. The first case is expected to lead to conservative (lower) fire resistance values.*

Temperature distribution

The determination of the characteristic resistance to combined pull-out and concrete failure of bonded fasteners requires the knowledge of the thermal distribution along the bond at a given time during the fire. Thermal fields shall be determined using the thermal and physical properties for concrete (EN 1992-1-2 [24]) and steel (EN 1993-1-2 [13]).

Simplified Method

In the simplified method the highest temperature of the temperature profile along the embedment depth of the bonded fastener is used for determination of the resistance to combined pull-out and concrete failure under fire conditions as given by Eq. (7.3), replacing EN 1992-4 [4], Eq. (7.14).

$$N^0_{Rk,p,fi} = \psi_{sus,fire} \cdot \tau_{Rk,fi,min} \cdot \pi \cdot d \cdot h_{ef} \tag{7.3}$$

Where

$$\psi_{sus,fire} = 1 \text{ for } \alpha_{sus,fire} \leq \psi^0_{sus,fire} \tag{7.4}$$

$$\psi_{sus,fire} = \psi^0_{sus,fire} + 1 - \alpha_{sus,fire} \text{ for } \alpha_{sus,fire} > \psi^0_{sus,fire} \tag{7.5}$$

The factor $\psi_{sus,fire}$ is included in Equations (7.3) and (7.6) to account for situations where the anchor is subjected to sustained load effect for a long period of time and a fire may occur afterwards. The sustained load effect may be evaluated according to EN 1992-4 and $\psi_{sus,fire}$ may be taken = 1,0 if proper justification is provided as detailed in Equations (7.4) and (7.5). If no value is given in the ETA of the product, a value of $\psi^0_{sus,fire} = \psi^0_{sus}$ according to EN 1992-4 [4], 7.2.1.6(2) shall be used.

As simplification and to keep the static and fire load cases separate, the actions considered for accidental design situations (fire conditions) shall be used. For the purposes of the determination of the ratio $\alpha_{sus,fire}$, the design actions to be considered shall be determined by the designer of the fastening according to EN 1990 [14], 6.4.3.3. Additional guidance may be given in national documents.

Conservatively, if the ratio between the value of sustained actions (comprising permanent actions and permanent component of variable actions) and the value of total actions all considered at ULS under fire conditions $\alpha_{sus,fire}$ is lower than 0,40, $\psi_{sus,fire}$ may be assumed equal to 1,0.

Resistance Integration Method

The resistance to combined pull-out and concrete of bonded fasteners under fire conditions can be determined using the Resistance Integration Method [15]. For the determination of the temperature profile along the embedment depth of the bonded fastener, the method requires the following entry data:

- Fire temperature-time relationship
- Exchange coefficients to determine the thermal boundary conditions (i.e., applied heat fluxes on the fire exposed and unexposed surfaces)
- Conductive properties of concrete
- Geometry of the structure

The standard temperature/time curve (ISO 834-1 [5]) is used to describe the gas temperature during exposure to fire conditions.

The emissivity and convection factor shall be taken from EN 1992-1-2 [3] for concrete, and EN 1993-1-2 [13] for steel. They shall be used to determine the radiative and convective heat fluxes applied to the fire exposed and unexposed surfaces.

The thermal and physical properties (specific heat $c_p(\theta)$, density $\rho(\theta)$ and thermal conductivity $\lambda(\theta)$) for concrete (EN 1992-1-2 [3]) and steel (EN 1993-1-2 [13]) shall be used. Concrete type and moisture content may influence the thermal distribution. Conservative thermal distribution can be obtained by considering the peak of the specific heat associated to a concrete moisture content of 1,5% (EN 1992-1-2 [3], 3.3.2).

The geometry of the structure influences the thermal distribution by the area and position of the fire exposed surfaces of concrete, in addition to the position of the fastener in the concrete element. The existence of a fixture on the extended metal part of the fastener yields lower temperatures along the bond. Therefore, the consideration of the fastener geometry (diameter × embedment depth) without the fixture (as unprotected) results in conservative (i.e., higher) temperature profiles.

The characteristic resistance to combined pull-out and concrete is calculated by integrating the bond resistances $\tau_{Rk,fi}(\theta(x))$ along the surface of the bonded fastener. The integration is carried out numerically and consists in adding the bond resistances on short segments of the fastener, each presenting a different temperature.

$$N^0_{Rk,p,fi} = \pi \cdot d \cdot \psi_{sus,fire} \cdot \int_0^{h_{ef}} \tau_{Rk,fi}\big(\theta(x)\big) \cdot dx \approx \pi \cdot d \cdot \psi_{sus,fire} \cdot \sum_0^{h_{ef}} k_{fi,p}\big(\theta(x)\big) \cdot \tau_{Rk,cr} \cdot \Delta x \qquad (7.6)$$

Where Eq. (7.4), Eq. (7.5) apply.

Further explication regarding $\psi_{sus,fire}$ can be found in the simplified method above.

For representativity, the segment length Δx shall be smaller than $2 \cdot d$ and is generally taken around 10 mm [16]. The temperature of each segment is considered as the mean temperature along the segment to represent the bond resistance along the segment.

> *Note 4: The Resistance Integration Method has been validated for bonded fasteners and post-installed rebar connections in uncracked concrete [15]-[22]. However, the method may also be applied to cracked concrete, which is the relevant concrete condition in this TR (see also EN 1992-4 [4], Annex D).*
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> *Note 5: The Resistance Integration Method does not take into account the displacement compatibility. The method assumes that at failure, all segments present the highest bond resistance (that can be reached at a certain temperature), regardless of the slip profile. However, in case of combined pull-out and concrete failure of the bonded fastener under fire conditions, the differential displacements between the segment of the fastener are considered negligible. This hypothesis appears sufficiently representative through experimental and theoretical support to predict bond failure at high temperatures [19].*
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> *Note 6: The temperature distribution along the fastener may be calculated neglecting the bond layer around the embedded metal part of the fastener as long as the thickness of the bond around the fastener does not exceed $0{,}25d$ [20]. This hypothesis results in negligible differences in temperature profiles. For cases where the thickness of the bond exceeds $0{,}25d$, the thermal and physical properties of the bond should be provided by the manufacturer to be taken into account in the calculation of the thermal distribution. Consequently, the thermal influence of the bond is reflected on the outcome of the Resistance Integration Method.*

In order to facilitate the applicability of the Resistance Integration Method, examples of temperature profiles are provided for common configurations of fastener diameter × embedment depth for bonded fasteners directly exposed to fire conditions in Annex A of this Technical Report.

Determination of characteristic bond resistance of a bonded fastener

The characteristic resistance of a fastener, a group of fasteners and the tensioned fasteners of a group of fasteners in case of combined pull-out and concrete failure under fire conditions $N_{Rk,p,fi}$ shall be obtained as given in EN 1992-4 [4], Eq. (7.13), by replacing $N^0_{Rk,p}$ by $N^0_{Rk,p,fi}$ as determined in equation (7.3) or (7.6) (see also Note 3) and the following stipulations concerning specific parameters:

Determine $\tau_{Rk,p,ucr,fi}$ as follows:

$$\tau_{Rk,ucr,fi} = \tau_{Rk,ucr} \cdot \frac{N^0_{Rk,p,fi}}{N^0_{Rk,p,cr}} \tag{7.7}$$

Replace τ_{Rk} by $\tau_{Rk,ucr,fi}$ in EN 1992-4 [4], Eq. (7.15) and (7.16), leading to:

$$s_{cr,N_p,fi} = 7{,}3d\left(\psi_{sus,fire} \cdot \tau_{Rk,ucr,fi}\right)^{0,5} \leq 4h_{ef} \tag{7.8}$$

$$c_{cr,N_p,fi} = \frac{s_{cr,N_p,fi}}{2} \tag{7.9}$$

Note 7: Equations (7.8) and (7.9) in this TR serve as entry data for the determination of the ψ factors under fire conditions as given below.

Replace ψ_{g,N_p} by $\psi_{g,N_p,fi} = 1{,}0$ in EN 1992-4 [4], Equations (7.13) and (7.17).

Replace ψ_{s,N_p} by $\psi_{s,N_p,fi}$ and c_{cr,N_p} by $c_{cr,N_p,fi}$ in EN 1992-4 [4], Eq. (7.20).

Where

$$\psi_{s,N_p,fi} = 0{,}7 + 0{,}3\left(\frac{c}{c_{cr,N_p,fi}}\right) \leq 1{,}0 \tag{7.10}$$

Determine the factor $\psi_{re,N}$ where EN 1992-4 [4], 7.2.1.6(6) applies.

Replace ψ_{ec,N_p} by $\psi_{ec,N_p,fi}$ and s_{cr,N_p} by $s_{cr,N_p,fi}$ in EN 1992-4 [4], Eq. (7.21).

Where

$$\psi_{ec,N_p,fi} = \frac{1}{1 + 2(e_N / s_{cr,N_p,fi})} \leq 1{,}0 \tag{7.11}$$

7.2.4 Concrete splitting failure

EN 1992-4 [4], D.4.2.4 applies.

7.3 Shear load

7.3.1 Steel failure

Stress criterion

The characteristic resistance to shear load under fire conditions shall be taken from the ETA.

If the characteristic shear resistance in case of steel failure under fire conditions $V_{Rk,s,fi}$ is not given in the ETA, the characteristic tension strength $\sigma_{Rk,s,fi}$ of a fastener in case of steel failure under fire conditions given in EN 1992-4 [4], Tables D.1 and D.2 for the covered steel materials are valid for the unprotected steel part of the fastener outside the concrete and may be used in the design. These values are conservative against values assessed according to EAD 330499-02-0601 [1].

Determine $V_{Rk,s,fi}$ where EN 1992-4 [4], Equation (D.6) applies.

Determine $M^0_{Rk,s,fi}$ where EN 1992-4 [4], Equation (D.7) applies.

Temperature-based reduction factor criterion

Alternatively, the characteristic resistance $V_{Rk,s,fi}$ may be determined based on the temperature of the steel at a given fire exposure time.

$$V_{Rk,s,fi}(\theta) = k_{fi,s}(\theta_s) \cdot V_{Rk,s} \tag{7.12}$$

The temperature reduction factor for steel failure $k_{fi,s}(\theta)$ shall be taken from Table 7.1 and Table 7.2.

7.3.2 Concrete pry-out failure

EN 1992-4 [4], D.4.3.2 applies. In addition, replace $N_{Rk,p}$ by $N_{Rk,p,fi}$ where EN 1992-4 [4], 7.2.2.4(3) applies.

7.3.3 Concrete edge failure

EN 1992-4 [4], D.4.3.3 applies.

7.4 Combined tension and shear load

The verifications according to EN 1992-4 [4], 7.2.3 for post-installed fasteners may be used. However, the design actions and design resistances used in these verifications shall correspond to fire conditions.

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ANNEX A TEMPERATURE PROFILE DETRMINATION USING NUMERICAL MODELS

This annex provides information about the determination of temperature profiles along the embedment depth of a fastener using numerical models. According to this Annex, two options are provided to the user:

1. Section A.1 provides temperature profiles for common geometries (diameter × embedment depth) assuming standard material thermal properties for concrete and steel (specific heat, density, and heat conductivity). Note that values given in Table A.1 are only valid for the considered input parameters.
2. Section A.2 provides information on development of numerical models and softwares for the calculation of temperature profiles considering different geometries (e.g., diameter, and/or embedment depth) than given in Section A.1, and /or different material thermal properties. In a first step, such models shall be benchmarked against results from Section A.1 (using the same geometry and thermal properties) and may later be modified considering user specific input parameters.

A.1 Examples of temperature profiles for common geometries of bonded fasteners

The temperature profiles provided in the following tables are calculated based on the hypotheses in this Technical Report.

Geometry

The bonded fastener is considered unprotected and directly exposed to fire conditions on the extended metal part of the fastener and fire exposed concrete surface surrounding the fastener (see Figure A.1). The existence of a fixture on the extended metal part of the fastener was not taken into account in the calculation of the temperature profiles. This results in conservative (higher) temperature profiles than the case where a fixture is considered.

Material properties and boundary conditions

The thermal and physical properties (specific heat $c_p(\theta)$, density $\rho(\theta)$ and thermal conductivity $\lambda(\theta)$) for concrete (EN 1992-1-2, Section 3.3 [24]) and carbon steel (EN 1993-1-2, Section 3.4 for c-steel and Section C.3 for stainless steel (informative) [13]) shall be used.

> *Note 9: The value of thermal conductivity $\lambda(\theta)$ for concrete may be set by the National Annex of EN 1992-1-2 [3] within the range of the lower and upper limit.*
>
> *Note 10: According to EN 1992-1-2, Annex A (informative) [3], temperature profiles can be determined with moisture content 1,5%.*

The emissivity shall be taken from EN 1992-1-2, Section 2.2 [3] for concrete, and EN 1993-1-2, Section 2.2 [13] for steel (i.e., equal to 0,7 unless otherwise stated by the National Annex of these standards). The convection factor shall be taken from EN 1991-1-2 [23], Section 3.1 (5) and Section 3.2.1 for the exposed surface [14]. They shall be used to determine the radiative and convective heat fluxes (i.e., thermal boundary conditions) applied to the fire exposed and unexposed surfaces.

In detail, the following geometry and material properties were used as basis for the determination of temperature profile results published in Table A.1:

- Extended part of the steel element outside the concrete member of $10 \cdot d$ (see Figure A.1).
- The surrounding concrete was considered with at least $1{,}5 \cdot h_{ef}$ around the fastener.
- density $\rho(\theta)$ = 25 kN/m³ (reinforced concrete).
- moisture content u = 1,5% (for specific heat).
- One-sided fire exposure (see Figure A.1).
- h_{fire} is the convective heat transfer coefficient for the fire exposed surface (25 W/m²·K).
- h_{air} is the convective heat transfer coefficient for the surface exposed to air at 20°C (4 W/m²·K).
- σ is surface emissivity (0,7).

- ε is the Boltzmann constant (5,667·10^{-8} W/m^2·K^4).
- Constant ambient air temperature = 20°C.

Table A.1 gives the temperature profiles of the embedded part[4] for common configurations of fastener diameter and embedment depth (e.g., MX × h_{ef}) for fire exposure times of 30, 60, 90 and 120 min. These temperature profiles shall be used as a basis for validating the calculation method of temperature profiles of other bonded fastener configurations.

Temperature profiles given in Table A.1 are presented as a third-degree polynomial relationship between the temperature of the fastener θ and the position along the embedment depth of the fastener (x). The principle is shown by equation (8.1)[5]:

$$\theta(x) = a \cdot x^3 + b \cdot x^2 + c \cdot x + d \tag{8.1}$$

Where

$\theta(x)$ is the temperature (°C) at the position x (mm) along the embedment depth.

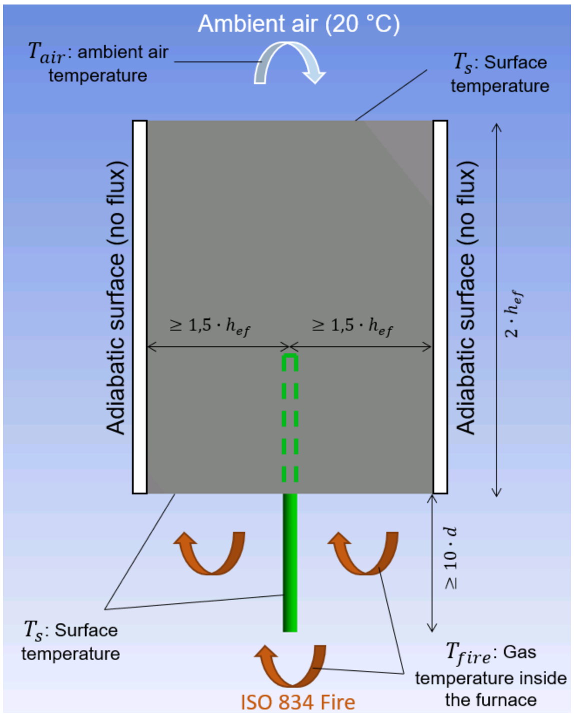

Figure A.1: Geometry of the model representing the bonded fastener configuration

A.2 Requirements and details for numerical modelling

The following guidance provides requirements and details for numerical modelling. The temperature profiles provided in Table A.1[6] shall be used for benchmarking following the provisions described below.

Geometry

---

[4] The temperature profiles in Table A.1 shall be used for the purposes of determining the characteristic combined concrete and pull-out under fire conditions. They shall not be extrapolated for bigger fastener diameters or deeper embedment depths. They shall not be interpolated for intermediate fastener diameters or embedment depths. They shall not be extrapolated over the extended part outside the concrete element for the determination of the temperature of the steel part.

[5] This polynomial form of fitting works only for the examples of temperature profiles given in Table A.1 and cannot be automatically applied for other geometries.

[6] The fitting curves used to represent the temperature profiles in this Annex shall be only usable for the purpose of verifying the validity of the numerical model used by the designer. Once validated, the model can be used for determination of the temperature profiles used for the calculation of the resistance to combined concrete and pull-out failure.

For model benchmarking, the same geometry as described above in Section A.1 shall be used.

3D or axisymmetric modelling are accepted. 2D plane modelling is prohibited.

Material properties and boundary conditions

Specific heat $c_p(\theta)$, density $\rho(\theta)$ and thermal conductivity $\lambda(\theta)$ of concrete and steel shall be taken from EN 1992-1-2 [24] and EN 1993-1-2 [13] respectively. For model benchmarking, the same material properties and boundary conditions described in section A.1 shall be used.

Mesh size and time-step

Numerical models are sensitive to mesh size and time-step choices. A sensitivity analysis shall be conducted prior to adopting the results of the developed model.

Additional requirements for model benchmarking

The determined temperature profiles shall show a steady decrease with increasing embedment depth. A maximum acceptable temperature difference of ± 10% shall be permitted. Furthermore, the resistances using the Resistance Integration Method (as per Eq. (7.6) in [kN]) shall be calculated based on the determined temperature profile and for the corresponding benchmark models given in Section A.1. In comparison with the corresponding benchmark model given in Section A.1, an acceptable difference between both models of ± 0,05 kN shall be permitted.

Table A.1: Examples of temperature profiles along the embedment depth of common bonded fastener configurations (for c-steel threaded rods and rebars[7]) directly exposed to ISO 834-1 fire conditions [5] (without fire protection)

Nominal diameter	Embedment depth h_{ef}	Fire exposure time t	a	b	c	d
[mm]	[mm]	[min]				
8	60	30	0,000076	0,0939	-13,371	621,87
		60	0,000257	0,0716	-13,136	783,67
		90	0,000341	0,0585	-12,625	876,57
		120	0,000527	0,0348	-11,680	940,27
	90	30	-0,000317	0,1194	-14,185	620,13
		60	-0,000147	0,0920	-14,082	774,05
		90	-0,000084	0,0801	-13,800	866,92
		120	-0,000018	0,0680	-13,297	930,99
	120	30	-0,000379	0,1247	-14,336	619,96
		60	-0,000232	0,0994	-14,364	774,11
		90	-0,000166	0,0847	-14,026	864,45
		120	-0,000133	0,0760	-13,683	928,61
10	60	30	0,000099	0,0794	-11,957	613,52
		60	0,000239	0,0626	-11,826	777,30
		90	0,000299	0,0528	-11,429	871,92
		120	0,000485	0,0297	-10,524	936,37
	90	30	-0,000218	0,0977	-12,750	608,45
		60	-0,000104	0,0791	-12,871	763,74
		90	-0,000054	0,0702	-12,697	858,29
		120	0,000001	0,0603	-12,284	922,10
	120	30	-0,000296	0,1050	-13,011	609,24
		60	-0,000176	0,0842	-13,145	762,57
		90	-0,000135	0,0744	-13,000	852,83
		120	-0,000107	0,0675	-12,762	917,70
12	70	30	-0,000012	0,0740	-11,189	602,55
		60	0,000089	0,0608	-11,255	766,21
		90	0,000123	0,0544	-11,035	861,19
		120	0,000234	0,0389	-10,406	926,99
	90	30	-0,000155	0,0827	-11,641	600,15
		60	-0,000073	0,0697	-11,888	757,29
		90	-0,000037	0,0630	-11,773	851,12
		120	0,000010	0,0544	-11,421	916,49
	110	30	-0,000225	0,0892	-11,902	599,93
		60	-0,000126	0,0723	-12,108	753,64
		90	-0,000099	0,0662	-12,094	846,38
		120	-0,000068	0,0596	-11,858	911,27
	130	30	-0,000239	0,0902	-11,937	599,03
		60	-0,000152	0,0747	-12,245	753,16
		90	-0,000119	0,0668	-12,187	843,40
		120	-0,000099	0,0616	-12,045	908,76

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[7] This is valid for c-steel threaded rods and rebars with a constant cross-section along the steel element (embedded and extended parts).

Nominal diameter	**Embedment depth h_{ef}**	**Fire exposure time t**	a	b	c	d
[mm]	**[mm]**	**[min]**				
16	80	30	-0,000065	0,0637	-9,871	588,26
		60	-0,000002	0,0554	-10,097	752,53
		90	0,000018	0,0513	-10,024	851,18
		120	0,000080	0,0414	-9,599	917,29
	110	30	-0,000150	0,0694	-10,276	582,73
		60	-0,000093	0,0599	-10,681	740,90
		90	-0,000071	0,0555	-10,718	835,41
		120	-0,000048	0,0507	-10,564	902,80
	140	30	-0,000170	0,0710	-10,389	583,49
		60	-0,000114	0,0606	-10,838	738,86
		90	-0,000095	0,0559	-10,919	829,84
		120	-0,000081	0,0523	-10,870	895,82
20	90	30	-0,000072	0,0551	-8,987	579,36
		60	-0,000029	0,0490	-9,285	747,24
		90	-0,000027	0,0477	-9,312	842,51
		120	0,000020	0,0403	-9,027	910,87
	120	30	-0,000125	0,0596	-9,360	574,56
		60	-0,000089	0,0531	-9,848	735,28
		90	-0,000080	0,0513	-9,999	829,70
		120	-0,000064	0,0477	-9,908	896,82
	150	30	-0,000139	0,0611	-9,513	575,50
		60	-0,000095	0,0527	-9,986	734,90
		90	-0,000085	0,0501	-10,163	826,25
		120	-0,000078	0,0480	-10,199	892,36
24	90	30	-0,000074	0,0505	-8,255	571,42
		60	-0,000061	0,0485	-8,627	740,93
		90	-0,000050	0,0465	-8,651	841,46
		120	-0,000012	0,0399	-8,372	911,62
	120	30	-0,000102	0,0514	-8,468	560,62
		60	-0,000077	0,0474	-9,006	725,74
		90	-0,000070	0,0460	-9,181	825,14
		120	-0,000055	0,0429	-9,109	895,15
	150	30	-0,000113	0,0525	-8,623	560,25
		60	-0,000080	0,0465	-9,182	723,78
		90	-0,000074	0,0449	-9,409	820,26
		120	-0,000068	0,0432	-9,444	887,43

ANNEX B TEMPERATIRE REDUCTION FACTORS FOR STEEL FAILURE AT A GIVEN RESISTANCE TO FIRE CLASSIFICATION

This Annex gives tabulated reduction factors for threaded rods with steel grades from 4.6 to 10.9 in accordance with EN ISO 898-1 [8], and steel grades A4 in accordance with EN ISO 3506 series [9] (Table B.1, and Table B.3), and reinforcing bars in accordance with EN 1992-1-1 [23] (Table B.2, and Table B.4), at a given resistance to fire classification.

The reduction factor values are conservative. They are based on bonded fasteners configurations with the longest embedment depth allowed by EN 1992-4 [4] (i.e., leading to a higher temperature along the steel member) directly exposed to fire conditions. They also adopt the maximum temperature reached along the steel element for the determination of the reduction factor based on Table 7.1, and Table 7.2 where applicable.

Table B.1: $k_{fi,s}$ values for threaded rods (made of c-steel) as anchor elements under tension load directly exposed to ISO 834-1 fire conditions [5] (without fire protection)

Fastener size	R15	R30	R45	R60	R90	R120	R180
M6	$0{,}212 \cdot f_{yk}/f_{uk}$	$0{,}092 \cdot f_{yk}/f_{uk}$	$0{,}060 \cdot f_{yk}/f_{uk}$	$0{,}051 \cdot f_{yk}/f_{uk}$	$0{,}039 \cdot f_{yk}/f_{uk}$	$0{,}030 \cdot f_{yk}/f_{uk}$	$0{,}018 \cdot f_{yk}/f_{uk}$
M7							
M8							
M10	$0{,}216 \cdot f_{yk}/f_{uk}$						
M12	$0{,}219 \cdot f_{yk}/f_{uk}$						
M14	$0{,}227 \cdot f_{yk}/f_{uk}$	$0{,}093 \cdot f_{yk}/f_{uk}$					
M16	$0{,}232 \cdot f_{yk}/f_{uk}$		$0{,}061 \cdot f_{yk}/f_{uk}$				
M18	$0{,}247 \cdot f_{yk}/f_{uk}$	$0{,}095 \cdot f_{yk}/f_{uk}$					
M20	$0{,}263 \cdot f_{yk}/f_{uk}$						
M22	$0{,}281 \cdot f_{yk}/f_{uk}$	$0{,}097 \cdot f_{yk}/f_{uk}$					
M24	$0{,}321 \cdot f_{yk}/f_{uk}$	$0{,}099 \cdot f_{yk}/f_{uk}$					
M27	$0{,}351 \cdot f_{yk}/f_{uk}$	$0{,}102 \cdot f_{yk}/f_{uk}$	$0{,}062 \cdot f_{yk}/f_{uk}$				
M30	$0{,}369 \cdot f_{yk}/f_{uk}$	$0{,}106 \cdot f_{yk}/f_{uk}$					
M33	$0{,}402 \cdot f_{yk}/f_{uk}$	$0{,}112 \cdot f_{yk}/f_{uk}$					
M36	$0{,}437 \cdot f_{yk}/f_{uk}$	$0{,}120 \cdot f_{yk}/f_{uk}$	$0{,}063 \cdot f_{yk}/f_{uk}$				
M39	$0{,}466 \cdot f_{yk}/f_{uk}$	$0{,}134 \cdot f_{yk}/f_{uk}$	$0{,}064 \cdot f_{yk}/f_{uk}$	$0{,}052 \cdot f_{yk}/f_{uk}$			

Table B.2: $k_{fi,s}$ values for reinforcing bars (made of c-steel) as anchor elements under tension load directly exposed to ISO 834-1 fire conditions [5] (without fire protection)

Reinforcing bar size	R15	R30	R45	R60	R90	R120	R180
$\phi 8$	$0{,}212 \cdot f_{yk}/f_{uk}$	$0{,}092 \cdot f_{yk}/f_{uk}$	$0{,}060 \cdot f_{yk}/f_{uk}$	$0{,}051 \cdot f_{yk}/f_{uk}$	$0{,}039 \cdot f_{yk}/f_{uk}$	$0{,}030 \cdot f_{yk}/f_{uk}$	$0{,}018 \cdot f_{yk}/f_{uk}$
$\phi 10$	$0{,}216 \cdot f_{yk}/f_{uk}$						
$\phi 12$	$0{,}219 \cdot f_{yk}/f_{uk}$						
$\phi 14$	$0{,}227 \cdot f_{yk}/f_{uk}$	$0{,}093 \cdot f_{yk}/f_{uk}$					
$\phi 16$	$0{,}232 \cdot f_{yk}/f_{uk}$						
$\phi 18$	$0{,}247 \cdot f_{yk}/f_{uk}$	$0{,}095 \cdot f_{yk}/f_{uk}$	$0{,}061 \cdot f_{yk}/f_{uk}$				
$\phi 20$	$0{,}263 \cdot f_{yk}/f_{uk}$						
$\phi 22$	$0{,}281 \cdot f_{yk}/f_{uk}$	$0{,}097 \cdot f_{yk}/f_{uk}$					
$\phi 24$	$0{,}321 \cdot f_{yk}/f_{uk}$	$0{,}099 \cdot f_{yk}/f_{uk}$					
$\phi 25$	$0{,}331 \cdot f_{yk}/f_{uk}$	$0{,}100 \cdot f_{yk}/f_{uk}$					
$\phi 26$	$0{,}340 \cdot f_{yk}/f_{uk}$	$0{,}101 \cdot f_{yk}/f_{uk}$					
$\phi 28$	$0{,}360 \cdot f_{yk}/f_{uk}$	$0{,}104 \cdot f_{yk}/f_{uk}$	$0{,}062 \cdot f_{yk}/f_{uk}$				
$\phi 30$	$0{,}369 \cdot f_{yk}/f_{uk}$	$0{,}106 \cdot f_{yk}/f_{uk}$					
$\phi 32$	$0{,}391 \cdot f_{yk}/f_{uk}$	$0{,}109 \cdot f_{yk}/f_{uk}$					
$\phi 36$	$0{,}437 \cdot f_{yk}/f_{uk}$	$0{,}120 \cdot f_{yk}/f_{uk}$	$0{,}063 \cdot f_{yk}/f_{uk}$				
$\phi 40$	$0{,}478 \cdot f_{yk}/f_{uk}$	$0{,}136 \cdot f_{yk}/f_{uk}$	$0{,}064 \cdot f_{yk}/f_{uk}$	$0{,}052 \cdot f_{yk}/f_{uk}$			

Table B.3: $k_{fi,s}$ values for threaded rods (made of stainless-steel) as anchor elements under tension load directly exposed to ISO 834-1 fire conditions [5] (without fire protection)

Fastener size	R15	R30	R45	R60	R90	R120	R180
M6	$0{,}196 \cdot f_{yk}/f_{uk}$	$0{,}091 \cdot f_{yk}/f_{uk}$	$0{,}059 \cdot f_{yk}/f_{uk}$	$0{,}051 \cdot f_{yk}/f_{uk}$	$0{,}039 \cdot f_{yk}/f_{uk}$	$0{,}030 \cdot f_{yk}/f_{uk}$	$0{,}018 \cdot f_{yk}/f_{uk}$
M7							
M8							
M10	$0{,}197 \cdot f_{yk}/f_{uk}$						
M12	$0{,}200 \cdot f_{yk}/f_{uk}$						
M14	$0{,}203 \cdot f_{yk}/f_{uk}$						
M16	$0{,}206 \cdot f_{yk}/f_{uk}$		$0{,}060 \cdot f_{yk}/f_{uk}$				
M18	$0{,}211 \cdot f_{yk}/f_{uk}$	$0{,}092 \cdot f_{yk}/f_{uk}$					
M20	$0{,}216 \cdot f_{yk}/f_{uk}$						
M22	$0{,}223 \cdot f_{yk}/f_{uk}$						
M24	$0{,}235 \cdot f_{yk}/f_{uk}$	$0{,}093 \cdot f_{yk}/f_{uk}$	$0{,}061 \cdot f_{yk}/f_{uk}$				
M27	$0{,}259 \cdot f_{yk}/f_{uk}$						
M30	$0{,}284 \cdot f_{yk}/f_{uk}$	$0{,}094 \cdot f_{yk}/f_{uk}$					
M33	$0{,}311 \cdot f_{yk}/f_{uk}$	$0{,}095 \cdot f_{yk}/f_{uk}$					
M36	$0{,}339 \cdot f_{yk}/f_{uk}$		$0{,}062 \cdot f_{yk}/f_{uk}$				
M39	$0{,}367 \cdot f_{yk}/f_{uk}$	$0{,}096 \cdot f_{yk}/f_{uk}$					

Table B.4: $k_{fi,s}$ values for reinforcing bars (made of stainless-steel) as anchor elements under tension load directly exposed to ISO 834-1 fire conditions [5] (without fire protection)

Reinforcing bar size	R15	R30	R45	R60	R90	R120	R180
$\phi 8$	$0{,}196 \cdot f_{yk}/f_{uk}$	$0{,}091 \cdot f_{yk}/f_{uk}$	$0{,}059 \cdot f_{yk}/f_{uk}$	$0{,}051 \cdot f_{yk}/f_{uk}$	$0{,}039 \cdot f_{yk}/f_{uk}$	$0{,}030 \cdot f_{yk}/f_{uk}$	$0{,}018 \cdot f_{yk}/f_{uk}$
$\phi 10$	$0{,}197 \cdot f_{yk}/f_{uk}$						
$\phi 12$	$0{,}200 \cdot f_{yk}/f_{uk}$		$0{,}060 \cdot f_{yk}/f_{uk}$				
$\phi 14$	$0{,}203 \cdot f_{yk}/f_{uk}$						
$\phi 16$	$0{,}206 \cdot f_{yk}/f_{uk}$	$0{,}092 \cdot f_{yk}/f_{uk}$					
$\phi 18$	$0{,}211 \cdot f_{yk}/f_{uk}$						
$\phi 20$	$0{,}216 \cdot f_{yk}/f_{uk}$						
$\phi 22$	$0{,}223 \cdot f_{yk}/f_{uk}$	$0{,}093 \cdot f_{yk}/f_{uk}$					
$\phi 24$	$0{,}235 \cdot f_{yk}/f_{uk}$		$0{,}061 \cdot f_{yk}/f_{uk}$				
$\phi 25$	$0{,}244 \cdot f_{yk}/f_{uk}$						
$\phi 26$	$0{,}252 \cdot f_{yk}/f_{uk}$						
$\phi 28$	$0{,}279 \cdot f_{yk}/f_{uk}$						
$\phi 30$	$0{,}284 \cdot f_{yk}/f_{uk}$	$0{,}094 \cdot f_{yk}/f_{uk}$					
$\phi 32$	$0{,}302 \cdot f_{yk}/f_{uk}$						
$\phi 36$	$0{,}339 \cdot f_{yk}/f_{uk}$	$0{,}095 \cdot f_{yk}/f_{uk}$	$0{,}062 \cdot f_{yk}/f_{uk}$				
$\phi 40$	$0{,}380 \cdot f_{yk}/f_{uk}$	$0{,}096 \cdot f_{yk}/f_{uk}$					