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Design of reinforced concrete T-sections according to the second generation of Eurocode

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Research Paper

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Design of reinforced concrete T-sections according to the second generation of Eurocode

The design procedure for reinforced concrete T-sections according to the standard HRN EN 1992-1-1:2023 (second generation of Eurocode 2) is described in this paper. Rectangular stress-strain diagram was used for concrete, while bilinear stress-strain diagram with a horizontal post-elastic branch without strain limit was applied for the reinforcing steel. Due to the use of such stress-strain diagrams, while designing reinforced concrete T-sections, it is necessary to reach and limit strain in the compressive zone of the concrete, so that the cross-section is in the ultimate limit state. Hence, by using rectangular stress-strain diagram for concrete, it is possible to apply direct analytical procedure for the design of reinforced concrete T-sections, in which, by solving the quadratic equation, the depth of the neutral axis is obtained, and subsequently, the required cross-sectional area of tensile reinforcement and possibly compressive reinforcement. Tables for the design of reinforced concrete T-sections are also provided, which were obtained based on derived equations by direct analytical procedure.

Key words:

reinforced concrete T-section, standard HRN EN 1992-1-1:2023, the second generation of Eurocode 2, bending, design

Prethodno priopćenje

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Dimenzioniranje armiranobetonskih T-presjeka prema drugoj generaciji Eurokoda

U radu opisan je postupak dimenzioniranja armiranobetonskih T-presjeka prema normi HRN EN 1992-1-1:2023 (druga generacija Eurokoda 2). Za beton primijenjena je pravokutna raspodjela naprezanja, dok je za čelik za armiranje primijenjen bilinearni proračunski dijagram naprezanje – deformacija s horizontalnom gornjom granom bez ograničenja deformacije. Zbog primjene takvih proračunskih dijagrama naprezanje – deformacija pri dimenzioniranju armiranobetonskog T-presjeka potrebno je dostići i ograničiti deformaciju u tlačnoj zoni betona kako bi presjek bio u graničnome stanju nosivosti. Korištenjem pravokutne raspodjele naprezanja moguće je primijeniti direktni analitički postupak dimenzioniranja armiranobetonskog T-presjeka, pri kojemu se rješavanjem kvadratne jednadžbe dobiva visina neutralne osi, a nakon toga potrebna ploština vlačne i eventualno ploština tlačne armature. Dane su i tablice za dimenzioniranje armiranobetonskih T-presjeka, dobivene na temelju izvedenih izraza dobivenih izravnim analitičkim postupkom.

Ključne riječi:

armiranobetonski T-presjek, norma HRN EN 1992-1-1:2023, druga generacija Eurokoda 2, savijanje, dimenzioniranje

1. Introduction

According to the currently valid Standard HRN EN 1992-1-1:2013 [1] (first generation of Eurocode 2) three different stress-strain diagrams for concrete are intended for use: in the form of a second-degree parabola and a rectangle, a bilinear diagram or a diagram in the form of a rectangle. Standard HRN EN 1992-1-1:2023 [2] (second generation of Eurocode 2) allows to use the stress-strain diagram of concrete in the form of a second degree parabola and a rectangle or in the form of a rectangle.

In this paper rectangular stress block distribution is used for the design of T-sections according to the Standard HRN EN 1992-1-1:2023 [2]. This form of stress distribution within the compression zone was selected so that a direct analytical procedure for the design of T-sections could be applied. Using the direct analytical procedure the depth of the neutral axis x is obtained by solving the quadratic equation, by which the required cross-sectional area of tensile reinforcement in singly reinforced concrete cross-section or required cross-sectional area of both tensile and compressive reinforcement in case of doubly reinforced cross-section is obtained.

Both HRN EN 1992-1-1:2013 [1] and HRN EN 1992-1-1:2023 [2] intend to use a bilinear stress-strain diagram for reinforcing steel with either inclined branch (with strain limitation) or horizontal post-elastic branch (without strain limitation). In this paper for the design of T-sections according to HRN EN 1992-1-1:2023 [2] a bilinear stress-strain diagram for reinforcing steel with horizontal post-elastic branch without strain limit is applied. The use of stress-strain diagram for concrete in the form of a parabola and a rectangle is traditionally prevalent in most of Europe [3-7], while in the UK the use of the rectangular stress block distribution is preferred [8, 9]. The result of using stress-strain diagram for concrete in the form of a parabola and a rectangle in the design of T-section is that it is difficult to get an exact solution - approximate procedures are used, which are usually on the safe side. Since the use of rectangular stress distribution is preferred in the UK it is possible to obtain an exact solution in the design of T-section [8, 9]. This is the main reason why rectangular stress distribution for concrete is used in this paper, which allows the application of direct analytical procedure for the design of T-sections.

The design of T-section, when using the parabola-rectangle stress-strain diagram for concrete, is usually divided into two cases depending on the position of the neutral axis: "case 1" and "case 2" (in which two cases are again distinguished: "2a" and "2b") [3-7]. In "case 1" the neutral axis is located in the flange, therefore the T-section is designed as a rectangular cross-section of width b_{eff} (effective flange width) and depth h , using tables for the design of reinforced concrete rectangular cross-sections, which are an approximate solution to the problem. In "case 2" neutral axis is located in the web, where two cases exist. "Case 2a" refers to the case where $b_{\text{eff}}/b_w > 5$ (b_w is the web width) in which a rectangular stress distribution in the flange is assumed, while the compressive part of the flange is neglected. The solution obtained by this procedure is also an approximate

solution. "Case 2b" refers to the case where $b_{\text{eff}}/b_w \leq 5$, in which the T-section is replaced by an equivalent rectangular cross-section and using iterative procedure for the solution via tables in which ratios h_f/d and b_{eff}/b_w are related to ξ , where h_f is the flange thickness, d is the effective depth of the cross-section, while ξ is the coefficient of the depth of the compression zone. Also, like the previous methods this method is also an approximate method.

In [6, 7] tables for design of T-sections are provided, in which ratios h_f/d , b_{eff}/b_w and μ_{Ed} (dimensionless design bending moment) are related to the mechanical reinforcement ratio ω_1 . These tables were obtained using the stress-strain diagram of concrete in the form of parabola-rectangle. The solution obtained in this way is only an approximate solution.

In [10,11] it was demonstrated that by using the stress-strain diagram for concrete in the form of a parabola and a rectangle in design of the T-section, an equation may be obtained that is a fourth-degree polynomial, whose roots are the solution for the coefficient of the depth of the compression zone ξ . The solution obtained in this way, although numerically correct, is too complex for the design of T-sections in engineering practice. In the design of the T-section using the rectangular stress distribution [8, 9], the problem is reduced to solving a quadratic equation. However, in [8, 9] expressions for the design of T-section in a general form are not provided, instead it is necessary to derive and solve the quadratic equation each time. From the available literature [3-11] it is clear that a relatively simple and accurate solution for the design of T-section may be obtained only in case when rectangular stress distribution is applied. In that case a direct analytical procedure for the design of T-section may be applied, in a way that formulas for the design are derived in a general form.

Expressions for the design of T-section derived in this work are similar to the expressions in [12, 13], in which the rectangular stress distribution is used, but according to Standard BS 8110 [14].

In [15] a direct analytical procedure for the design of rectangular cross-sections has already been successfully applied. An exact solution in case of rectangular cross-sections is obtained using the stress-strain diagram of concrete in the form of a second-degree parabola or the rectangular stress distribution.

A program for the design of T-sections was created in Mathcad [16] using the general expressions obtained in this paper. The results were verified using the computer program Gala [17], a program which is used for the design of reinforced concrete cross-sections of general shape.

In addition to the derived expressions for the direct analytical procedure, tables for design of reinforced concrete T-sections are also provided in this paper. They can be used for simple and fast design in engineering practice.

The aim of this paper is to derive general expressions for the design of T-sections by applying a direct analytical procedure, in order to obtain a simple and numerically exact solution for the design of T-sections. To achieve this, the rectangular stress distribution is used and the problem is reduced to solving a

quadratic equation, in which the unknown quantity is the depth of the neutral axis x , and subsequently the exact solution for the required cross-sectional area of tensile reinforcement and if needed cross-sectional area of compressive reinforcement is obtained. All derived expressions are in accordance with the provisions of HRN EN 1992-1-1:2023 [2].

2. Stress-strain design diagrams

2.1. Stress-strain design diagram for concrete

According to HRN EN 1992-1-1:2023 [2, 15] the value of the design concrete compressive strength f_{cd} is evaluated as:

$$f_{cd} = \eta_{cc} \cdot k_{tc} \cdot \frac{f_{ck}}{\gamma_c} \quad (1)$$

where f_{ck} is the characteristic concrete cylinder compressive strength, γ_c is the partial factor for concrete ($\gamma_c = 1.50$ for persistent and transient design situations), η_{cc} is a factor to account for the difference between the undisturbed compressive strength of a cylinder and the effective compressive strength that can be developed in the structural member:

$$\eta_{cc} = \left(\frac{f_{ck,ref}}{f_{ck}} \right)^{1/3} \leq 1.0 \quad (2)$$

while k_{tc} is a factor accounting for the effect of high sustained loads and of time of loading on concrete compressive strength.

In HRN EN 1992-1-1:2023 [2] the following recommended values are provided:

- $f_{ck,ref} = 40$ MPa
- $k_{tc} = 1.00$ for $t_{ref} \leq 28$ days for concretes with strength development classes CR and CN (rapid and normal strength development, respectively) and $t_{ref} \leq 56$ days for concretes with strength development class CS (slow strength development) where the design loading is not expected for at least three months after casting, with t_{ref} as the age of concrete at which the concrete strength is determined
- $k_{tc} = 0.85$ for other cases, including when f_{ck} is replaced by $f_{ck}(t)$.

In the National Annex, according to HRN EN 1992-1-1:2023 [2] different values may be given (Croatian National Annex is still in the development phase).

According to HRN EN 1992-1-1:2023 [2] a rectangular stress distribution, in which the ultimate compressive stress in concrete is equal to $\varepsilon_{cu} = 3.5 \text{ ‰}$, may be used for the design of cross-sections (Figure 1). Rectangular stress distribution was selected so that the direct analytical procedure for the design could be applied, in which the design procedure is reduced to solving a quadratic equation.

In the direct analytical procedure the depth of the neutral axis x is obtained by solving the quadratic equation, then the required

cross-sectional area of tensile reinforcement A_{s1} in singly reinforced sections is obtained, and in case of doubly reinforced sections also the required cross-sectional area of compression reinforcement A_{s2} is obtained.

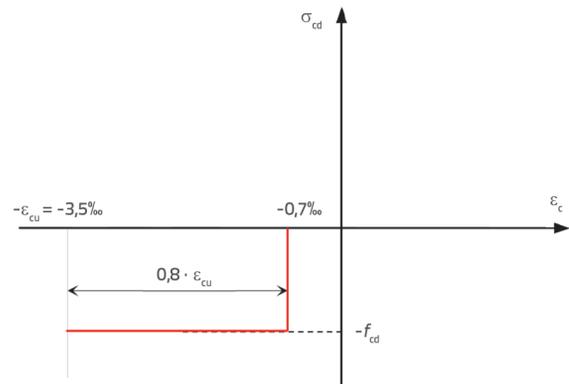


Figure 1. Rectangular stress distribution for concrete

2.2. Stress-strain design diagram for reinforcing steel

According to HRN EN 1992-1-1:2023 [2, 15], the bilinear stress-strain diagram for reinforcing steel with horizontal post-elastic branch without strain limit may be used for the design (Figure 2).

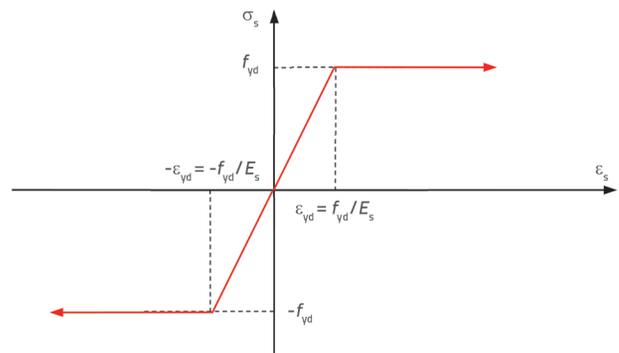


Figure 2. Stress-strain diagram for reinforcing steel

The design yield strength of reinforcing steel f_{yd} is obtained as, expression (3):

$$f_{yd} = \frac{f_{yk}}{\gamma_s} \quad (3)$$

where f_{yk} is the characteristic yield strength of the reinforcing steel and γ_s is the partial factor for reinforcing steel ($\gamma_s = 1.15$ for persistent and transient design situations).

The stress in reinforcing steel σ_s (Figure 2) may be evaluated using the following expression (4):

$$\sigma_s = \frac{|\varepsilon_s| \cdot E_s}{1000} \leq f_{yd} \quad (4)$$

where ε_s is the strain in the reinforcing steel in [‰], while $E_s = 200$ GPa is the modulus of elasticity of reinforcing steel.

3. Design of T-sections

3.1. Limit values for pure bending

Limit values for the case of pure bending (Table 1), required to distinguish between singly and doubly reinforced cross-sections, are adopted from [15] where $\epsilon_{c,ed2,lim}$ is the limit value of the strain in concrete at the top edge and $\epsilon_{s1,lim}$ is the limit value of the strain in the tensile reinforcement.

Table 1. Limit values for the case of pure bending ($E_s = 200$ GPa, $\gamma_s = 1.15$) [15]

f_{yk} [MPa]	f_{yd} [MPa]	$\epsilon_{c,ed2,lim}$ [‰]	$\epsilon_{s1,lim}$ [‰]	ξ_{lim}
400	347.83	-3.5	2.484	0.585
450	391.30	-3.5	2.795	0.556
500	434.78	-3.5	3.106	0.530
550	478.26	-3.5	3.416	0.506
600	521.74	-3.5	3.727	0.484
700	608.70	-3.5	4.348	0.446

The limit value of the coefficient of the depth of the compression zone $\xi_{lim} = x_{lim} / d$ is obtained by setting δ_M to 1, where δ_M is the ratio of the bending moment after redistribution (linear analysis with redistribution) to the elastic bending moment, while x_{lim} is the limit value of the depth of the neutral axis.

More information on the procedure for determining the limit coefficient of the depth of the compression zone ξ_{lim} is given in [15]. According to Table 1, this limit values are determined depending on the characteristic yield strength of reinforcing steel f_{yk} , namely 400 MPa, 450 MPa, 500 MPa, 550 MPa, 600 MPa and 700 MPa.

3.2. Strain distribution in a reinforced concrete cross-section

In the design of reinforced concrete cross-sections according to HRN EN 1992-1-1:2023 [2], the following assumptions are used:

- plain sections remain plane,

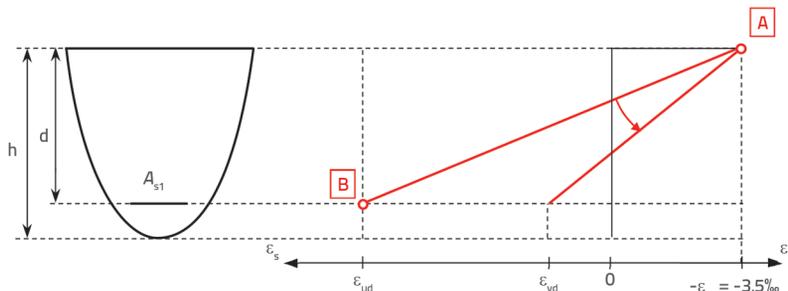


Figure 3. Strain distribution in a reinforced concrete cross-section of general shape for the case of pure bending

- the change in strain in bonded reinforcement, both in tension and in compression, is the same as the change in strain in the surrounding concrete,
- the tensile strength of concrete is ignored,
- the stresses in the concrete in compression are derived from the rectangular stress distribution (see Figure 1)
- the stresses in the reinforcing steel are derived from the design stress-strain relationship given in Figure 2.

Figure 3 presents the possible range of strain distribution in a reinforced concrete cross-section of general shape for the case of pure bending.

A reinforced concrete cross-section will be in the ultimate limit state when at least one strain limit is reached, either in the concrete ($-\epsilon_{cu}$) or in the reinforcing steel (ϵ_{ud}) (see Figure 3). The ultimate strain in the reinforcing steel will never be reached since the design stress-strain diagram for the reinforcing steel with a horizontal upper branch without strain limit (Figure 2) is used. Therefore, for a reinforced concrete cross-section to be in the ultimate limit state, the strain in the compression zone of concrete must be reached and limited to $\epsilon_{c,ed2} = -\epsilon_{cu} = -3.5$ ‰ (Figure 3).

3.3. Singly reinforced T-section for $0.8 \cdot x \leq h_f$

Singly reinforced T-section for $0.8 \cdot x \leq h_f$ is presented in Figure 4. Note that the length of the rectangular stress block $0.8 \cdot x$ is not equal to the depth of the neutral axis x (see Figure 1 for the description of the rectangular stress distribution).

The design compressive force in concrete F_{cd} is defined as:

$$F_{cd} = b_{eff} \cdot (0.8 \cdot x) \cdot f_{cd} \tag{5}$$

The design force in tensile reinforcement F_{s1d} is obtained from:

$$F_{s1d} = \sigma_{s1d} \cdot A_{s1} \tag{6}$$

where σ_{s1d} is the design stress in tensile reinforcement and A_{s1} is the cross-sectional area of tensile reinforcement.

The level arm of internal forces equals to (Figure 4):

$$z = d - 0.4 \cdot x \tag{7}$$

where d is the effective depth of the cross section (distance between the center of gravity of the tensile reinforcement and the top edge of the cross-section).

The load bearing moment M_{Rd} by which the cross-section withstands the bending action, calculated with respect to the center of gravity of the tensile reinforcement amounts to:

$$M_{Rd} = F_{cd} \cdot z = [b_{eff} \cdot (0.8 \cdot x) \cdot f_{cd}] \cdot (d - 0.4 \cdot x) \tag{8}$$

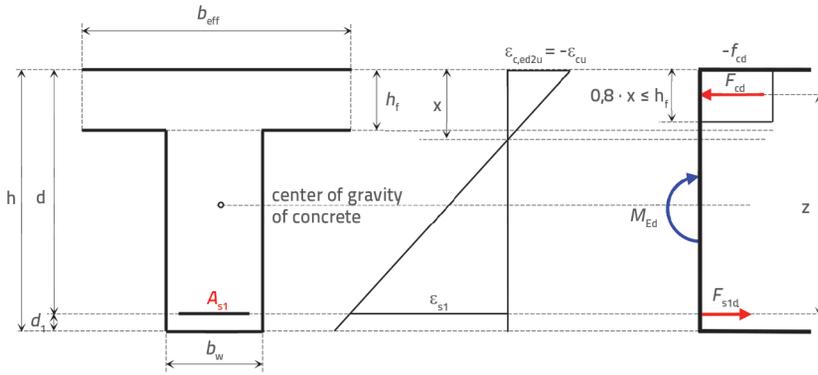


Figure 4. Singly reinforced T-section for $0.8 \cdot x \leq h_f$

In cross-sections subjected to bending moment, the following condition should be satisfied:

$$M_{Ed} \leq M_{Rd} \tag{9}$$

where M_{Ed} is the design acting bending moment, while M_{Rd} is the moment of resistance of the cross-section.

The equilibrium equation is used for the design of the cross-section:

$$M_{Ed} = M_{Rd} = b_{eff} \cdot 0.8 \cdot f_{cd} \cdot d \cdot x - b_{eff} \cdot 0.32 f_{cd} \cdot x^2 \tag{10}$$

By arranging expression (10) the following quadratic equation is obtained:

$$\frac{0.4}{d} x^2 - x + \frac{M_{Ed}}{0.8 \cdot b_{eff} \cdot d \cdot f_{cd}} = 0 \tag{11}$$

which has two solutions:

$$x_{1,2} = 1.25 \cdot d \left[1 \pm \sqrt{1 - \frac{2 \cdot M_{Ed}}{b_{eff} \cdot d^2 \cdot f_{cd}}} \right] \tag{12}$$

The first solution x_1 has no physical meaning since $x_1 > d$, therefore the second solution x_2 gives the depth of the neutral axis $x = x_2$:

$$x = 1.25 \cdot d \left[1 - \sqrt{1 - \frac{2 \cdot M_{Ed}}{b_{eff} \cdot d^2 \cdot f_{cd}}} \right] \tag{13}$$

Based on the triangle similarity theorem from Figure 4 we obtain:

$$\frac{|\epsilon_{c,ed2}|}{x} = \frac{\epsilon_{s1}}{d-x} \tag{14}$$

from which we derive the strain in the tensile reinforcement ϵ_{s1} (strain in concrete at the top edge is set to $\epsilon_{c,ed2} = -\epsilon_{cu} = -3.5\%$):

$$\epsilon_{s1} = \frac{|-3.5\%|(d-x)}{x} \tag{15}$$

If the strain in the tensile reinforcement ϵ_{s1} is greater than the design yield strain ϵ_{yd} (see Figure 2), then the tensile reinforcement yielded, therefore the design stress in the tensile reinforcement equals to $\sigma_{s1d} = f_{yd}$.

From the sum of horizontal forces in the cross-section (Figure 4) we obtain:

$$\Sigma H = 0 \tag{16}$$

$$F_{s1d} - F_{cd} = 0 \tag{17}$$

Finally, when expressions (5) and (6) are inserted into (17), and assuming that the tensile reinforcement yielded (i.e. $\sigma_{s1d} = f_{yd}$), we obtain the required cross-sectional area of the tensile reinforcement:

$$A_{s1} = \frac{b_{eff} \cdot 0.8 \cdot x \cdot f_{cd}}{f_{yd}} \tag{18}$$

The maximum load bearing moment $M_{Rd,f}$ which the cross-section withstands when the rectangular stress block length $0.8 \cdot x$ is equal to the flange depth h_f is obtained by inserting $0.8 \cdot x = h_f$ into expression (8):

$$M_{Rd,f} = (b_{eff} \cdot h_f \cdot f_{cd}) \cdot \left(d - \frac{h_f}{2} \right) \tag{19}$$

Expressions derived in this section are valid for the design of simply reinforced T-sections for $0.8 \cdot x \leq h_f$, what can be presented as $M_{Ed} \leq M_{Rd,f}$

3.4 Singly reinforced T-section for $h_f < 0.8 \cdot x < 0.8 \cdot x_{lim}$

Singly reinforced T-section for $h_f < 0.8 \cdot x < 0.8 \cdot x_{lim}$ is shown in Figure 5.

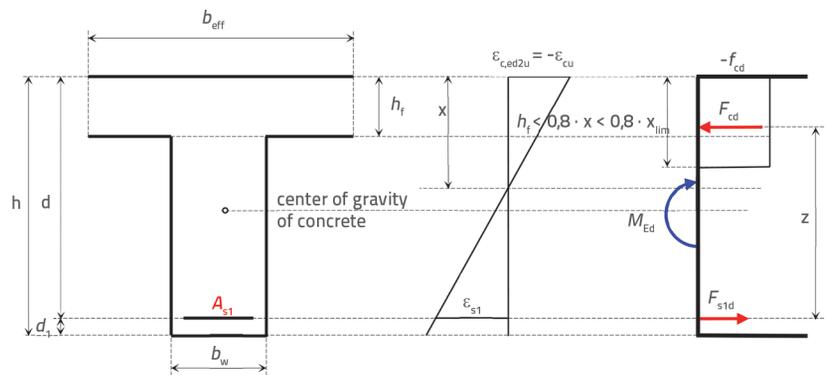


Figure 5. Singly reinforced T-section for $h_f < 0.8 \cdot x < 0.8 \cdot x_{lim}$

The design compressive force in concrete F_{cd} is defined as:

$$F_{cd} = (b_{eff} - b_w) \cdot h_f \cdot f_{cd} + b_w \cdot (0.8 \cdot x) \cdot f_{cd} \quad (20)$$

The design force in tensile reinforcement F_{s1d} is obtained from expression (6).

The load bearing moment M_{Rd} by which the cross-section withstands the bending action, calculated with respect to the center of gravity of the tensile reinforcement amounts to:

$$M_{Rd} = F_{cd} \cdot z = [(b_{eff} - b_w)h_f \cdot f_{cd}] \cdot \left(d - \frac{h_f}{2}\right) + [b_w (0.8 \cdot x) \cdot f_{cd}] (d - 0.4 \cdot x) \quad (21)$$

The equilibrium equation is used for the design of the cross-section:

$$M_{Ed} = M_{Rd} = [(b_{eff} - b_w)h_f \cdot f_{cd}] \cdot \left(d - \frac{h_f}{2}\right) + [(b_w (0.8 \cdot x) \cdot f_{cd}) (d - 0.4 \cdot x)] \quad (22)$$

By arranging expression (22) the following quadratic equation is obtained:

$$\frac{0.4}{d} x^2 - x + \frac{\frac{b_{eff}}{b_w} \left[M_{Ed} - (b_{eff} - b_w)h_f \cdot f_{cd} \cdot \left(d - \frac{h_f}{2}\right) \right]}{0.8 \cdot b_{eff} \cdot d \cdot f_{cd}} = 0 \quad (23)$$

which has two solutions:

$$x_{1,2} = 1.25 \cdot d \left[1 \pm \sqrt{1 - \frac{2 \cdot \frac{b_{eff}}{b_w} \left[M_{Ed} - (b_{eff} - b_w)h_f \cdot f_{cd} \cdot \left(d - \frac{h_f}{2}\right) \right]}{b_{eff} \cdot d^2 \cdot f_{cd}}} \right] \quad (24)$$

The first solution of the quadratic equation x_1 has no physical meaning since $x_1 > d$, hence the second solution x_2 gives the depth of the neutral axis $x = x_2$:

$$x = 1.25 \cdot d \left[1 - \sqrt{1 - \frac{2 \cdot \frac{b_{eff}}{b_w} \left[M_{Ed} - (b_{eff} - b_w)h_f \cdot f_{cd} \cdot \left(d - \frac{h_f}{2}\right) \right]}{b_{eff} \cdot d^2 \cdot f_{cd}}} \right] \quad (25)$$

Strain in the tensile reinforcement ϵ_{s1} may be determined using expression (15). If the strain in the tensile reinforcement ϵ_{s1} is greater than the design yield strain ϵ_{yd} (see Figure 2) then the tensile reinforcement yielded, therefore the design stress in the tensile reinforcement equals to $\sigma_{s1d} = f_{yd}$. Finally, if expressions (20) and (6) are inserted into (17), and assuming that the tensile reinforcement yielded ($\sigma_{s1d} = f_{yd}$), we obtain the required cross-sectional area of the tensile reinforcement:

$$A_{s1} = \frac{f_{cd} [(b_{eff} - b_w) \cdot h_f + b_w \cdot 0.8 \cdot x]}{f_{yd}} \quad (26)$$

The limiting bending moment for a singly reinforced T-section $M_{Rd,lim}$ which the cross-section withstands when the depth of the neutral axis x is equal to the limit value x_{lim} , is obtained by inserting $x = x_{lim}$ into expression (21):

$$M_{Rd,lim} = [(b_{eff} - b_w)h_f \cdot f_{cd}] \cdot \left(d - \frac{h_f}{2}\right) + [b_w (0.8 \cdot x_{lim}) \cdot f_{cd}] (d - 0.4 \cdot x_{lim}) \quad (27)$$

Expressions derived in this section are valid for design of simply reinforced T-sections for $h_f < 0.8 \cdot x < 0.8 \cdot x_{lim}$, what can be presented as $M_{Rd,f} < M_{Ed} < M_{Rd,lim}$.

3.5. Doubly reinforced T-section ($x = x_{lim}$)

Figure 6 presents a doubly reinforced T-section valid for the case $x = x_{lim}$.

This case occurs when the design acting bending moment M_{Ed} is greater than or equal to the limiting bending moment for singly reinforced T-section $M_{Rd,lim}$ (27). In this case, the obtained depth of the neutral axis x would be greater than the limit value x_{lim} . Therefore, the depth of the neutral axis x must be made equal to the limit neutral axis depth x_{lim} . The consequence of this condition is that beside tensile reinforcement, compression reinforcement must also be determined.

Therefore, the condition for design of doubly reinforced T-section may be presented as:

$$M_{Ed} \geq M_{Rd,lim} \quad (28)$$

The design compressive force in concrete F_{cd} is obtained using expression (20), by inserting $x = x_{lim}$:

$$F_{cd} = (b_{eff} - b_w) \cdot h_f \cdot f_{cd} + b_w \cdot (0.8 \cdot x_{lim}) \cdot f_{cd} \quad (29)$$

Based on the triangle similarity theorem from Figure 6 we obtain:

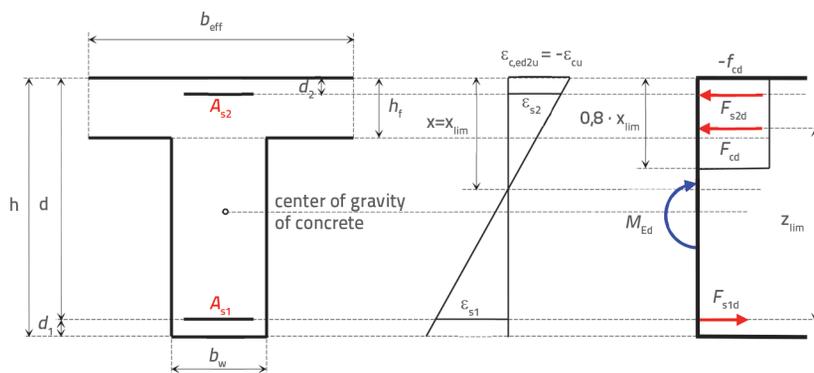


Figure 6. Doubly reinforced T-section ($x = x_{lim}$)

$$\frac{|\varepsilon_{c,ed2}|}{x_{lim}} = \frac{|\varepsilon_{s2}|}{x_{lim} - d_2} \quad (30)$$

By arranging expression (30) the strain in the compressive reinforcement ε_{s2} may be derived:

$$|\varepsilon_{s2}| = \frac{|\varepsilon_{c,ed2}|(x_{lim} - d_2)}{x_{lim}} \quad (31)$$

The design stress in compressive reinforcement is then evaluated using expression (4):

$$\sigma_{s2d} = \frac{|\varepsilon_{s2}| \cdot E_s}{1000} \leq f_{yd} \quad (32)$$

Finally, the design force in compressive reinforcement is obtained as:

$$F_{s2d} = \sigma_{s2d} A_{s2} \quad (33)$$

The load bearing moment by which the cross-section withstands the bending action, calculated with respect to the center of gravity of the tensile reinforcement, according to Figure 6 amounts to:

$$M_{Rd} = M_{Rd,lim} + F_{s2d}(d - d_2) = M_{Rd,lim} + (\sigma_{s2d} \cdot A_{s2})(d - d_2) \quad (34)$$

The equilibrium equation is used for the design:

$$M_{Ed} = M_{Rd} = M_{Rd,lim} + (\sigma_{s2d} \cdot A_{s2})(d - d_2) \quad (35)$$

By arranging expression (35) the required cross-sectional area of compressive reinforcement may be obtained:

$$A_{s2} = \frac{M_{Ed} - M_{Rd,lim}}{\sigma_{s2d}(d - d_2)} \quad (36)$$

Strain in the tensile reinforcement ε_{s1} may be evaluated using expression (15), if the strain in the tensile reinforcement ε_{s1} is greater than the design yield strain ε_{yd} (see Figure 2) then the tensile reinforcement yielded, hence the design stress in the tensile reinforcement equals to $\sigma_{s1d} = f_{yd}$.

From the sum of horizontal forces in the cross-section, using expression (16) and Figure 6 we derive:

$$F_{s1d} - F_{cd} - F_{s2d} = 0 \quad (37)$$

Finally, when expressions (6), (29) and (33) are inserted into (37) the required cross-sectional area of tensile reinforcement is obtained:

$$A_{s1} = \frac{f_{cd}[(b_{eff} - b_w) \cdot h_f + b_w \cdot 0.8 \cdot x_{lim}] + \sigma_{s2d} \cdot A_{s2}}{f_{yd}} \quad (38)$$

Expressions derived in this section are valid for $x_{lim} \geq d_2$, i.e. the compressive reinforcement must be in the compression zone of the cross-section, which is a regular case that occurs in practice in doubly reinforced cross-sections.

3.6. Tables for design of T-sections

Besides the expression derived for the design of T-section by direct analytical procedure presented above, in this section we provide tables for the design of reinforced concrete T-sections. In singly reinforced T-section for $0.8 \cdot x \leq h_f$, expression (13) used to determine the depth of the neutral axis x may be also presented as:

$$\xi = 1.25 \left[1 - \sqrt{1 - 2 \cdot \mu_{Ed}} \right] \quad (39)$$

where ξ is the coefficient of the depth of the compression zone:

$$\xi = \frac{x}{d} \quad (40)$$

while μ_{Ed} is the dimensionless design bending moment defined as:

$$\mu_{Ed} = \frac{M_{Ed}}{b_{eff} \cdot d^2 \cdot f_{cd}} \quad (41)$$

Expression (18) for the required cross-sectional area of tensile reinforcement A_{s1} may be also presented as:

$$\omega_1 = 1 - \sqrt{1 - 2 \cdot \mu_{Ed}} \quad (42)$$

where ω_1 is the mechanical reinforcement ratio defined as:

$$\omega_1 = \frac{A_{s1} \cdot f_{yd}}{f_{cd} \cdot b_{eff} \cdot d} \quad (43)$$

In singly reinforced T-section for $h_f < 0.8 \cdot x < 0.8 \cdot x_{lim}$, expression (25) used to determine the depth of the neutral axis x may be also presented as:

$$\xi = 1.25 \left[1 - \sqrt{1 - 2 \cdot \frac{b_{eff}}{b_w} \cdot \mu_{Ed} + 2 \cdot \left(\frac{b_{eff}}{b_w} - 1 \right) \frac{h_f}{d} \left(1 - \frac{h_f}{2 \cdot d} \right)} \right] \quad (44)$$

Finally, expression (26) for the required cross-sectional area of tensile reinforcement A_{s1} may be presented via mechanical reinforcement ratio:

$$\omega_1 = \left(1 - \frac{b_w}{b_{eff}} \right) \frac{h_f}{d} + \frac{b_w}{b_{eff}} \left[1 - \sqrt{1 - 2 \cdot \frac{b_{eff}}{b_w} \cdot \mu_{Ed} + 2 \cdot \left(\frac{b_{eff}}{b_w} - 1 \right) \frac{h_f}{d} \left(1 - \frac{h_f}{2 \cdot d} \right)} \right] \quad (45)$$

Tables for design of T-sections were obtained using expressions (39), (42), (44) and (45) for width ratios $b_{eff}/b_w = 2, 3, 5$ and 10 and for depth ratios h_f/d from 0.05 to 0.5 with a

step of 0.05, and are shown in Tables 2, 3, 4 and 5. Tables for design of T-sections are also provided in [6, 7, 18], in this paper we applied the display type according to [18] since this type of display is the most comprehensive.

The procedure for using the tables for design of T-section is as follows: first the dimensionless design bending moment μ_{Ed} should be obtained using expression (41), then for the calculated b_{eff}/b_w ratio the corresponding Table 2, 3, 4 or 5 is selected. In the selected table, for the corresponding h_f/d ratio the first greater or equal value for the dimensionless design

bending moment μ_{Ed} is selected, for which the corresponding mechanical reinforcement ratio ω_1 and coefficient of the depth of the compression zone ξ are selected. In addition, it is necessary to verify whether the obtained coefficient of the depth of the compression zone ξ is less than or equal to the limit value ξ_{lim} from Table 1. If this condition is fulfilled, the required cross-sectional area of tensile reinforcement is obtained using:

$$A_{s1} = \frac{\omega_1 \cdot f_{cd} \cdot b_{eff} \cdot d}{f_{yd}} \tag{46}$$

Table 2. Table for design of reinforced concrete T-sections, $b_{eff}/b_w = 2$

μ_{Ed}	$h/d=0.05$		$h/d=0.10$		$h/d=0.15$		$h/d=0.20$		$h/d=0.25$		$h/d=0.30$		$h/d=0.35$		$h/d=0.40$		$h/d=0.45$		$h/d=0.50$	
	ω_1	ξ																		
0.010	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013
0.020	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025
0.030	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038
0.040	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051
0.050	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066
0.060	0.062	0.092	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077
0.070	0.073	0.120	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091
0.080	0.084	0.148	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104
0.090	0.096	0.177	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118
0.100	0.107	0.206	0.106	0.139	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132
0.110	0.120	0.236	0.117	0.167	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146
0.120	0.132	0.268	0.129	0.197	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160
0.130	0.145	0.300	0.141	0.227	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175
0.140	0.158	0.334	0.153	0.258	0.151	0.191	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189
0.150	0.172	0.368	0.166	0.290	0.163	0.221	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204
0.160	0.187	0.405	0.179	0.323	0.176	0.252	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219
0.170	0.202	0.442	0.193	0.357	0.189	0.284	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234
0.180	0.218	0.482	0.207	0.393	0.202	0.317	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250
0.190	0.235	0.524	0.222	0.430	0.215	0.351	0.213	0.282	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266
0.200	0.252	0.568	0.238	0.469	0.229	0.386	0.226	0.315	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282
0.210	0.271	0.616	0.254	0.510	0.244	0.423	0.239	0.349	0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298
0.220			0.272	0.554	0.260	0.462	0.254	0.384	0.252	0.317	0.252	0.315	0.252	0.315	0.252	0.315	0.252	0.315	0.252	0.315
0.230			0.290	0.600	0.276	0.503	0.268	0.421	0.265	0.351	0.265	0.331	0.265	0.331	0.265	0.331	0.265	0.331	0.265	0.331
0.240					0.293	0.546	0.284	0.459	0.279	0.386	0.279	0.349	0.279	0.349	0.279	0.349	0.279	0.349	0.279	0.349
0.250					0.312	0.592	0.300	0.500	0.294	0.423	0.293	0.366	0.293	0.366	0.293	0.366	0.293	0.366	0.293	0.366
0.260							0.317	0.543	0.310	0.462	0.307	0.393	0.307	0.384	0.307	0.384	0.307	0.384	0.307	0.384
0.270							0.335	0.589	0.326	0.503	0.322	0.430	0.322	0.402	0.322	0.402	0.322	0.402	0.322	0.402
0.280									0.343	0.546	0.338	0.469	0.337	0.421	0.337	0.421	0.337	0.421	0.337	0.421
0.290									0.362	0.592	0.354	0.510	0.352	0.442	0.352	0.440	0.352	0.440	0.352	0.440
0.300											0.372	0.554	0.368	0.482	0.368	0.459	0.368	0.459	0.368	0.459
0.310											0.390	0.600	0.385	0.524	0.384	0.479	0.384	0.479	0.384	0.479
0.320													0.402	0.568	0.400	0.500	0.400	0.500	0.400	0.500
0.330													0.421	0.616	0.417	0.543	0.417	0.521	0.417	0.521
0.340															0.435	0.589	0.434	0.543	0.434	0.543
0.350																	0.452	0.568	0.452	0.565
0.360																	0.471	0.616	0.471	0.589

Table 3. Table for design of reinforced concrete T-sections, $b_{eff}/b_w = 3$

μ_{Ed}	$h/d=0.05$		$h/d=0.10$		$h/d=0.15$		$h/d=0.20$		$h/d=0.25$		$h/d=0.30$		$h/d=0.35$		$h/d=0.40$		$h/d=0.45$		$h/d=0.50$	
	ω_1	ξ																		
0.010	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013
0.020	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025
0.030	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038
0.040	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051
0.050	0.051	0.067	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066	0.051	0.066
0.060	0.062	0.108	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077
0.070	0.073	0.150	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091
0.080	0.085	0.193	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104
0.090	0.097	0.238	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118
0.100	0.110	0.286	0.106	0.146	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132
0.110	0.123	0.336	0.117	0.189	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146
0.120	0.137	0.388	0.129	0.234	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160
0.130	0.152	0.445	0.142	0.282	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175
0.140	0.168	0.505	0.155	0.331	0.151	0.193	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189
0.150	0.186	0.571	0.169	0.384	0.164	0.238	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204
0.160	0.205	0.644	0.184	0.440	0.176	0.286	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219
0.170			0.200	0.500	0.190	0.336	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234
0.180			0.217	0.565																

Table 4. Table for design of reinforced concrete T-sections, $b_{eff}/b_w = 5$

μ_{Ed}	$h/d=0.05$		$h/d=0.10$		$h/d=0.15$		$h/d=0.20$		$h/d=0.25$		$h/d=0.30$		$h/d=0.35$		$h/d=0.40$		$h/d=0.45$		$h/d=0.50$		
	ω_1	ξ																			
0.010	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	
0.020	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	
0.030	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	
0.040	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	
0.050	0.051	0.071	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	
0.060	0.062	0.139	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	
0.070	0.074	0.212	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	
0.080	0.086	0.290	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	
0.090	0.100	0.375	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	
0.100	0.115	0.469	0.106	0.160	0.106	0.160	0.106	0.160	0.106	0.160	0.106	0.160	0.106	0.160	0.106	0.160	0.106	0.160	0.106	0.160	
0.110	0.132	0.577	0.118	0.234	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	
0.120	0.153	0.705	0.130	0.315	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	
0.130			0.144	0.402	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	
0.140			0.160	0.500	0.151	0.197	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	
0.150			0.178	0.613	0.164	0.274	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	
0.160					0.177	0.357	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	
0.170					0.192	0.450	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	
0.180					0.209	0.554	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	
0.190					0.228	0.677	0.213	0.331	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266	
0.200							0.227	0.421	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282	
0.210							0.243	0.521	0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298	
0.220							0.262	0.638	0.252	0.323	0.252	0.315	0.252	0.315	0.252	0.315	0.252	0.315	0.252	0.315	
0.230									0.266	0.411	0.265	0.331	0.265	0.331	0.265	0.331	0.265	0.331	0.265	0.331	
0.240									0.282	0.510	0.279	0.349	0.279	0.349	0.279	0.349	0.279	0.349	0.279	0.349	
0.250									0.300	0.625	0.293	0.366	0.293	0.366	0.293	0.366	0.293	0.366	0.293	0.366	
0.260											0.307	0.421	0.307	0.384	0.307	0.384	0.307	0.384	0.307	0.384	
0.270											0.323	0.521	0.322	0.402	0.322	0.402	0.322	0.402	0.322	0.402	
0.280											0.342	0.638	0.337	0.421	0.337	0.421	0.337	0.421	0.337	0.421	
0.290													0.352	0.450	0.352	0.440	0.352	0.440	0.352	0.440	
0.300													0.369	0.554	0.368	0.459	0.368	0.459	0.368	0.459	
0.310													0.388	0.677	0.384	0.479	0.384	0.479	0.384	0.479	
0.320														0.400	0.500	0.400	0.500	0.400	0.500	0.400	0.500
0.330														0.418	0.613	0.417	0.521	0.417	0.521	0.417	0.521
0.340															0.434	0.543	0.434	0.543	0.434	0.543	
0.350															0.452	0.577	0.452	0.565	0.452	0.565	
0.360															0.473	0.705	0.471	0.589	0.471	0.589	

Table 5. Table for design of reinforced concrete T-sections, $b_{eff}/b_w = 10$

μ_{Ed}	$h/d=0.05$		$h/d=0.10$		$h/d=0.15$		$h/d=0.20$		$h/d=0.25$		$h/d=0.30$		$h/d=0.35$		$h/d=0.40$		$h/d=0.45$		$h/d=0.50$	
	ω_1	ξ																		
0.010	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013	0.010	0.013
0.020	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025	0.020	0.025
0.030	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038	0.030	0.038
0.040	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051	0.041	0.051
0.050	0.051	0.079	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064	0.051	0.064
0.060	0.063	0.221	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077	0.062	0.077
0.070	0.076	0.386	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091	0.073	0.091
0.080	0.092	0.592	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104	0.083	0.104
0.090			0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118	0.094	0.118
0.100			0.106	0.197	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132	0.106	0.132
0.110			0.119	0.357	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146	0.117	0.146
0.120			0.134	0.554	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160	0.128	0.160
0.130			0.157	0.835	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175	0.140	0.175
0.140					0.151	0.206	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189	0.151	0.189
0.150					0.164	0.368	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204	0.163	0.204
0.160					0.180	0.568	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219	0.175	0.219
0.170					0.204	0.860	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234	0.188	0.234
0.180							0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250	0.200	0.250
0.190							0.214	0.421	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266	0.213	0.266
0.200							0.231	0.638	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282	0.225	0.282
0.210									0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298	0.238	0.298
0.220									0.252	0.334	0.252	0.315	0.252	0.315	0.252	0.315	0.252	0.315	0.252	0.315
0.230									0.267	0.524	0.265	0.331	0.265	0.331	0.265	0.331	0.265	0.331	0.265	0.331
0.240</																				

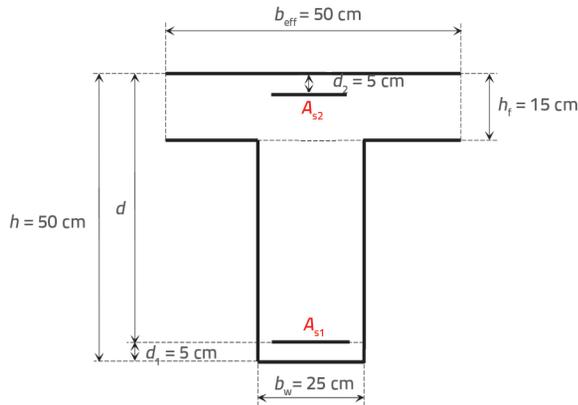


Figure 7. T-section

Factor η_{cc} is evaluated using expression (2):

$$\eta_{cc} = \left(\frac{f_{ck,ref}}{f_{ck}} \right)^{\frac{1}{3}} \leq 1.0$$

$$\eta_{cc} = \left(\frac{40}{30} \right)^{\frac{1}{3}} = 1.01 \leq 1.0$$

$$\eta_{tc} = 1.0$$

Factor k_{tc} accounting for the age of concrete at which the compressive strength is determined $t_{ref} = 28$ days and cement class CN (normal strength development) equals to:

$$k_{tc} = 1.0$$

Design value of concrete compressive strength f_{cd} using expression (1) is:

$$f_{cd} = \eta_{cc} \cdot k_{tc} \cdot \frac{f_{ck}}{\gamma_C} = 1.0 \cdot 1.0 \cdot \frac{30}{1.5} = 20 \text{ MPa}$$

Design yield strength of reinforcing steel f_{yd} using (3) gives:

$$f_{yd} = \frac{f_{yk}}{\gamma_s} = \frac{500}{1.15} = 434.78 \text{ MPa}$$

Design yield strain of reinforcing steel (Figure 2) is:

$$\epsilon_{yd} = \frac{f_{yd}}{E_s} = \frac{434.78}{200000} = 2.17 \text{ ‰}$$

Effective depth of the cross-section (Figure 7):

$$d = h - d_f = 50 - 5 = 45 \text{ cm}$$

The maximum load bearing moment $M_{Rd,f}$ which the T-section withstands when the rectangular stress block length $0.8 \cdot x$ is equal to the flange depth h_f using expression (19) equals to:

$$M_{Rd,f} = (b_{eff} \cdot h_f \cdot f_{cd}) \cdot \left(d - \frac{h_f}{2} \right) =$$

$$= (0.5 \cdot 0.15 \cdot 20000) \cdot \left(0.45 - \frac{0.15}{2} \right) = 562.5 \text{ kNm}$$

Limit value for singly reinforced cross-section for B500 is selected from Table 1:

$$\xi_{lim} = \frac{x_{lim}}{d} = 0.530$$

$$x_{lim} = \xi_{lim} \cdot d = 0.530 \cdot 45 = 23.85 \text{ cm}$$

Limiting bending moment for a singly reinforced T-section, which the cross-section withstands when the depth of the neutral axis x is equal to the limit value x_{lim} using expression (27) yields:

$$M_{Rd,lim} = [(b_{eff} - b_w) h_f \cdot f_{cd}] \cdot \left(d - \frac{h_f}{2} \right) + [b_w \cdot 0.8 \cdot x_{lim} \cdot f_{cd}] \cdot$$

$$\cdot (d - 0.4 \cdot x_{lim}) = [(0.5 - 0.25) 0.15 \cdot 20000] \cdot \left(0.45 - \frac{0.15}{2} \right) +$$

$$+ [0.25 \cdot 0.8 \cdot 0.2385 \cdot 20000] (0.45 - 0.4 \cdot 0.2385) = 619.54 \text{ kNm}$$

Since $M_{Ed} = 100 \text{ kNm} < M_{Rd,f} = 562.5 \text{ kNm}$, this is the case $0.8 \cdot x \leq h_f$ which means that expressions derived in section 3.3 should be used. This is the case of singly reinforced T-section since $M_{Ed} = 100 \text{ kNm} < M_{Rd,lim} = 619.54 \text{ kNm}$.

Depth of the neutral axis x may be evaluated using (13):

$$x = 1.25 \cdot d \left[1 - \sqrt{1 - \frac{2 \cdot M_{Ed}}{b_{eff} \cdot d^2 \cdot f_{cd}}} \right] =$$

$$= 1.25 \cdot 45 \left[1 - \sqrt{1 - \frac{2 \cdot 100000}{50 \cdot 45^2 \cdot 2}} \right] = 2.85 \text{ cm}$$

Strain in the tensile reinforcement is determined using (15):

$$\epsilon_{s1} = \frac{-3.5\% (d - x)}{x} = \frac{-3.5\% (45 - 2.85)}{2.85} = 51.76 \text{ ‰}$$

Since the strain in the tensile reinforcement $\epsilon_{s1} = 51.76 \text{ ‰} > \epsilon_{yd} = 2.17 \text{ ‰}$, the tensile reinforcement yielded, therefore the design stress in the tensile reinforcement equals to $\sigma_{s1d} = f_{yd}$. Finally, the required cross-sectional area of tensile reinforcement is obtained using expression (18):

$$A_{s1} = \frac{b_{eff} \cdot 0.8 \cdot x \cdot f_{cd}}{f_{yd}} = \frac{50 \cdot 0.8 \cdot 2.85 \cdot 2}{43.478} = 5.24 \text{ cm}^2$$

4.2. Example 2

Design the T-section subjected to design acting bending moment $M_{Ed} = 600 \text{ kNm}$ (Figure 7). Other parameters are the same as in Example 1.

Since $M_{Ed} = 600 \text{ kNm} > M_{Rd,f} = 562.5 \text{ kNm}$, this is the case

$h_f < 0.8 \cdot x < 0.8 \cdot x_{lim}$ which means that expressions derived in section 3.4 should be used. This is the case of singly reinforced T-section since $M_{Ed} = 600 \text{ kNm} < M_{Rd,lim} = 619.54 \text{ kNm}$.

Depth of the neutral axis is evaluated using expression (25):

$$x = 1.25 \cdot d \left[1 - \sqrt{1 - \frac{2 \cdot \frac{b_{eff}}{b_w} \left[M_{Ed} - (b_{eff} - b_w) h_f \cdot f_{cd} \cdot \left(d - \frac{h_f}{2} \right) \right]}{b_{eff} \cdot d^2 \cdot f_{cd}}} \right]$$

$$= 1.25 \cdot 45 \left[1 - \sqrt{1 - \frac{2 \cdot \frac{50}{25} \left[60000 - (50 - 25) 15 \cdot 2 \cdot \left(45 - \frac{15}{2} \right) \right]}{50 \cdot 45^2 \cdot 2}} \right] = 22.02 \text{ cm}$$

Strain in the tensile reinforcement is determined using expression (15):

$$\varepsilon_{s1} = \frac{|-3.5\%|(d-x)}{x} = \frac{|-3.5\%|(45-22.02)}{22.02} = 3.65 \text{ ‰}$$

Since the strain in the tensile reinforcement $\varepsilon_{s1} = 3.65 \text{ ‰} > \varepsilon_{yd} = 2.17 \text{ ‰}$, the tensile reinforcement yielded, therefore the design stress in the tensile reinforcement equals to $\sigma_{s1d} = f_{yd}$. Finally, the required cross-sectional area of tensile reinforcement is obtained using expression (26):

$$A_{s1} = \frac{f_{cd} \left[(b_{eff} - b_w) \cdot h_f + b_w \cdot 0.8 \cdot x \right]}{f_{yd}} =$$

$$= \frac{2 \left[(50 - 25) \cdot 15 + 25 \cdot 0.8 \cdot 22.02 \right]}{43.478} = 37.51 \text{ cm}^2$$

4.3. Example 3

Design the T-section subjected to design acting bending moment $M_{Ed} = 700 \text{ kNm}$ (Figure 7). Other parameters are the same as in Example 1.

Since the condition (28) is satisfied: $M_{Ed} = 700 \text{ kNm} > M_{Rd,lim} = 619.54 \text{ kNm}$, this case is a doubly reinforced cross-section, therefore expressions derived in section 3.5 should be used (i.e. $x = x_{lim}$).

Strain in the compressive reinforcement using (31), expressed as an absolute value equals to:

$$|\varepsilon_{s2}| = \frac{|\varepsilon_{c,ed2}|(x_{lim} - d_2)}{x_{lim}} = \frac{|-3.5\%|(23.85 - 5)}{23.85} = 2.77 \text{ ‰}$$

Design stress in compressive reinforcement σ_{s2d} using (32), expressed as an absolute value is:

$$\sigma_{s2d} = \frac{|\varepsilon_{s2}| \cdot E_s}{1000} \leq f_{yd}$$

$$\sigma_{s2d} = \frac{|2.77\%| \cdot 200000}{1000} \leq 434.78 \text{ MPa}$$

$$\sigma_{s2d} = 554 \text{ MPa} \leq 434.78 \text{ MPa}$$

$$\sigma_{s2d} = 434.78 \text{ MPa}$$

Required cross-sectional area of compressive reinforcement using expression (36) gives:

$$A_{s2} = \frac{M_{Ed} - M_{Rd,lim}}{\sigma_{s2d} (d - d_2)} = \frac{70000 - 61954}{43.478 (45 - 5)} = 4.63 \text{ cm}^2$$

Using expression (15) and applying the condition $x = x_{lim}$, strain in the tensile reinforcement is obtained:

$$\varepsilon_{s1} = \frac{|-3.5\%|(d-x)}{x} = \frac{|-3.5\%|(45-23.85)}{23.85} = 3.10 \text{ ‰}$$

Since the strain in the tensile reinforcement $\varepsilon_{s1} = 3.10 \text{ ‰} > \varepsilon_{yd} = 2.17 \text{ ‰}$, the tensile reinforcement yielded therefore the design stress in the tensile reinforcement equals to $\sigma_{s1d} = f_{yd}$. Finally, the required cross-sectional area of tensile reinforcement is obtained using expression (38):

$$A_{s1} = \frac{f_{cd} \left[(b_{eff} - b_w) \cdot h_f + b_w \cdot 0.8 \cdot x_{lim} \right] + \sigma_{s2d} \cdot A_{s2}}{f_{yd}} =$$

$$= \frac{2 \left[(50 - 25) \cdot 15 + 25 \cdot 0.8 \cdot 23.85 \right] + 43.478 \cdot 4.63}{43.478} = 43.82 \text{ cm}^2$$

4.4. Comparison of results

In this section, a comparison of results obtained in Examples 1 and 2 with the computer program Gala [17], which is used for the design of reinforced concrete cross-sections of general shape, is made. Example 3 was not verified using the computer program Gala since doubly reinforced T-section cannot be specified in the Gala. Table 6 shows the most important results obtained using analytical expressions (rectangular stress distribution) and the Gala computer program applying both the rectangular stress distribution and the parabola-rectangle diagram for concrete. A bilinear stress-strain diagram for reinforcing steel with horizontal post-elastic branch (without strain limitation) is used in all cases.

It is evident that the results obtained in Examples 1 and 2 via analytical expressions (rectangular stress distribution) are identical to the results obtained with the Gala program (rectangular stress distribution) because the same rectangular stress distribution was used. This verification proved the accuracy of the derived expressions.

When comparing the results from analytical expressions (rectangular stress distribution) with the results obtained with the Gala program (parabola-rectangle stress-strain diagram), it is evident that the Gala program yielded slightly larger cross-

Table 6. Comparison of results

Parameter	Example 1			Example 2		
	Analytical expression	Gala (rectangular stress distribution)	Gala (parabola-rectangle diagram)	Analytical expression	Gala (rectangular stress distribution)	Gala (parabola-rectangle diagram)
ε_{ced2} [‰]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5
x [cm]	2.85	2.85	2.82	22.02	22.02	22.42
ε_{s1} [‰]	51.76	51.763	52.383	3.65	3.653	3.525
A_{s1} [cm ²]	5.24	5.24	5.25	37.51	37.51	37.76

sectional areas of tensile reinforcement, but this difference is smaller than 1 %, and is a consequence of using different stress-strain diagrams for concrete.

5. Conclusion

T-section is, along with the rectangular cross-section, the most common cross-section used in reinforced concrete structures. Due to the use of stress-strain diagram of concrete in the form of a second-degree parabola and a rectangle, so far we have been forced to use approximate solutions for the design of T-sections.

Nowadays, various computer programs are mostly used for the design of reinforced concrete sections subjected to bending moment, which use an iterative process to solve the problem, i.e. determine the required cross-sectional area of tensile reinforcement and possibly cross-sectional area of compressive reinforcement.

Regardless of the existence of computer programs for the design of reinforced concrete members, it is desirable to make a control of the obtained results in a simple way, using ready-made analytical expressions or tables.

This paper presents relatively simple and accurate analytical expressions for the design of T-sections, obtained by applying the direct analytical procedure, which result in solving a quadratic equation in which the unknown is the depth of the

neutral axis x . When the depth of the neutral axis x is known, the required cross-sectional area of tensile reinforcement and in some cases compressive reinforcement is obtained.

In order to obtain these relatively simple expressions, rectangular stress distribution for concrete should be used. A bilinear stress-strain diagram with horizontal post-elastic branch without strain limit was applied for the reinforcing steel. Based on the derived analytical expressions, a program for design of T-sections was created in *Mathcad*, which enables simple design of T-sections in engineering practice. The accuracy of the obtained results was verified by the computer program Gala, a program used for the design of reinforced concrete cross-sections of general shape.

In addition, the obtained analytical expressions can be used to create aids for the design of T-sections using, for example, Excel or a similar spreadsheet calculator, and in this way the design procedure may be automated.

Tables for the design of T-sections can find their application in engineering practice for simple and fast approximate design of reinforced-concrete T-sections.

Although the Standard HRN EN 1992-1-1:2013 is still valid, the Standard HRN EN 1992-1-1:2023 is used in this paper in order to help the professional community to get used to the changes that will come with the new Standard. This paper thus represents a contribution to a simple, fast and accurate solution to the problem of design of reinforced-concrete T-sections.

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