Simplified Design of Composite Columns, Based on a Comparative Study of the Development of Building Regulations in Germany and the United States

Holger Eggemann

INTRODUCTION

This paper refers to composite columns of structural steel, concrete and reinforcing steel. Three basic types of composite columns can be distinguished, completely encased sections, partially encased sections, and concrete filled hollow sections. The paper presents a simplified method for dimensioning and design of composite columns, based on a comparative study on historic building regulations in Germany and the United States. The method can be used for approximate determination of load resistance in early design stages or to make proof of computer calculations. Construction History plays an important role in the development of the proposed method, as several ideas from ancient authors were taken into account to make it as easy as possible. The simplified design method and the study on historic building regulations are part of the author´s doctoral thesis (Eggemann 2003b).

CONSTRUCTION HISTORY OF COMPOSITE COLUMNS

The construction history of composite columns can be divided into four periods:

1 Research started early in the beginning of the 20th century
2 A first climax of application about 1930, followed by
3 A period of oblivion, until
4 A revival of research and application from the 1950s until today.

Although composite columns of concrete and steel were rarely used from the end of World War II until the early 1970s (Viest et al. 1997, 1.13), research had started a long time before, at the beginning of the 20th century. Combining of these materials had a number of motivations, steel columns were often encased in concrete to protect them from fire, while concrete columns were combined with structural steel as a reinforcement.

Until 1932, more than 1 500 tested specimen in Europe and North America were reported by Emperger at the first IABSE Congress in Paris (1932), among those were 138 tests done by himself. Emperger complained about the lack of design rules for composite columns in Europe and mentioned the American “Standard Specifications for Concrete and Reinforced Concrete” of 1924, which gave explicit formulas for both composite columns and steel columns encased in concrete, a vital advantage for the application of composite columns during the 1920s and 1930s in tall buildings in Chicago. In Germany, it took until 1943 to apply composite columns in the German concrete regulations DIN 1045. Emperger´s efforts in the development of composite columns are described in (Eggemann 2003a).

After a period of oblivion, research in the field of composite construction was intensified during the 1950s and several design methods were developed. As a consequence, Klöppel´s proposal for concrete filled steel columns - first published (1935) - were taken into account for German steel regulations DIN 1050 in 1954. For today’s Eurocode 4, the design method of Roik and his team was considered, developed in the 1970s (Roik, Bergmann, Bode and Wagenknecht 1975; 1976). This was taken as a basis for the proposed simplified design method.

EARLY EXAMPLES

United States

This paragraph refers to engineers who tried to find design formulas for columns combining structural steel and concrete and applied it in buildings. First documented design attempts in the United States were given by Talbot and Lord (1912) for steel columns reinforced with concrete and by Swain and Holmes (1915) for concrete filled steel pipes. Both teams tested more than 30 columns and used a straight line formula as common for steel columns at the time. While Talbot and Lord determined only the allowable stress of the steel section by a straight line formula, Swain and Holmes used this for both the steel and the concrete area, with a ratio of elasticity of steel to concrete of 9.6.

Also in 1912, William H. Burr made tests with steel columns filled with concrete, but gave no design formula, for tests were too few in number. Several years before, in 1908, he had applied such columns successfully in the construction of the Mc Graw Building in New York **(fig.1, 2)**, allowing an increased working load on the inner concrete:

> The use of the steel, in load-supporting condition, as a long column independent of the concrete, and at the same time forming a rigid banding member for the latter, with the consequent increase of permissible working load on the concrete, reduced the size of the columns in the basement and lower stories to dimensions quite consistent with the desired convenient and economical use of the clear floor space.
>
> (Burr 1908, p.446)

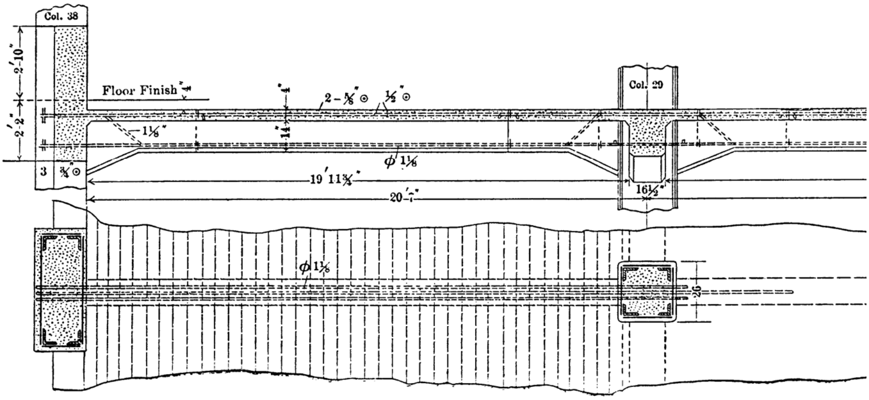


Figure 1. Mc Graw Building, column and floor section (Burr 1908, Plate LVI)

Figure 2. Mc Graw Building, 39th Street, New York, 1908 (Burr 1908, Plate LII)

Germany and Austria

In Germany, the first design formula for composite columns was given by Emperger (1913a, 32). The column type examined was a concrete column with a core of cast-iron and a strong horizontal reinforcement (Hohle Gußeisensäule mit einem Mantel aus umschnürtem Beton), the later so called Emperger column **(fig.3)**.

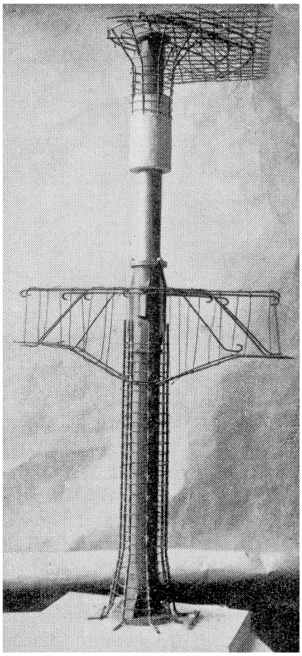


Figure 3. Emperger column, presented at Leipzig fair in 1912 (Emperger 1913b, fig. 7)

Emperger developed this column inspired by Melan arch bridges with embedded steel sections, called after its inventor Josef Melan, of which he had constructed the first ones in the United States during the 1890s. Emperger had this type of column patented in the German Reich in 1911 (Emperger 1911) and applied it in the construction of the Ericsson factory building in Vienna in 1913 **(fig.4, 5)**.

Emperger calculated the ultimate load P of a column as the sum of the strength of the materials (addition law - Additionsgesetz):

$$P = F_b\sigma_b + F_e\sigma_e + F_g\sigma_g \qquad (1)$$

where F is area, σ is stress, b is the index for concrete (Beton), e is the index for mild-steel reinforcement (Eisen) and g is the index for cast-iron (Gußeisen). This addition law is still valid today and used in the design of both concrete and composite columns.

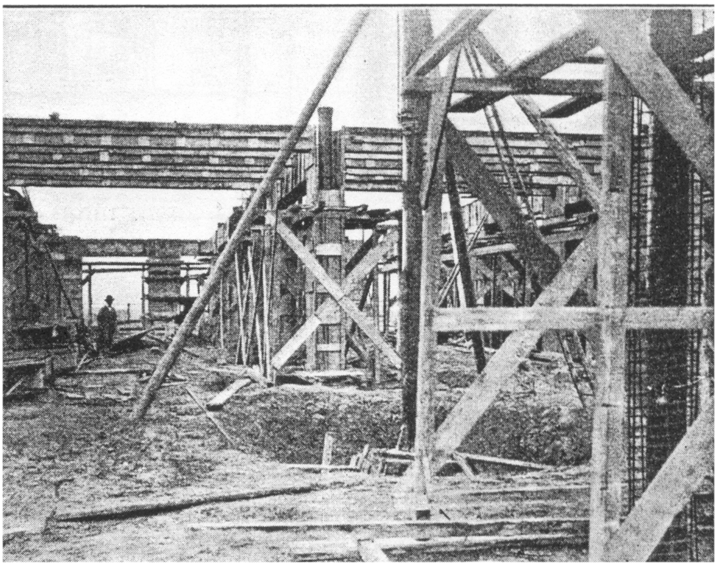


Figure 4. Ericsson Building, Vienna, 1913 (Emperger 1913b, fig. 5)

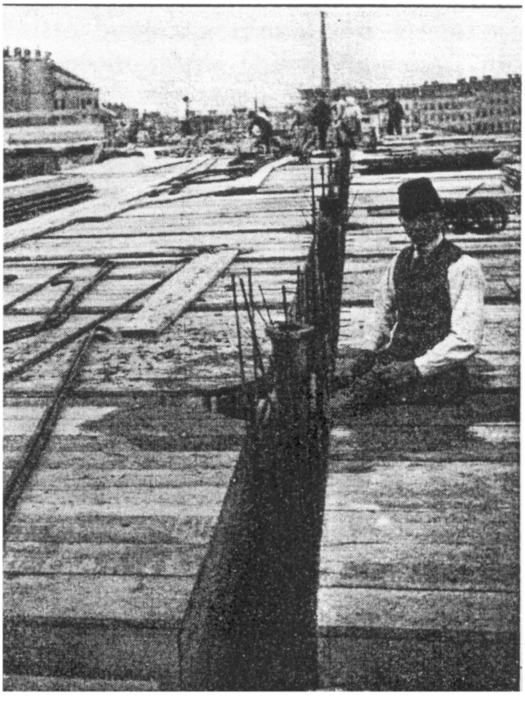


Figure 5. Column-joint, Ericsson Building, Vienna (Emperger 1913b, fig. 6)

BUILDING REGULATIONS

ASCE Progress Reports 1910 - 1917

At the annual convention of the American Society of Civil Engineers on June 11th, 1903, a special committee was appointed:

> to take up the question of concrete and steel-concrete, and that such committee co-operate with the American Society for Testing Materials, and the American Railway Engineering and Maintenance of Way Association.
>
> (ASCE 1910, p.431)

In 1904, the name of the committee was changed to "Special Committee on Concrete and Reinforced Concrete". In its First Progress Report, recommendations were given for both concrete and reinforced concrete construction. In paragraph 9 concerning columns, it was said that:

> columns may be reinforced by means of longitudinal rods, by bands or hoops, by bands or hoops together with longitudinal bars, or by structural forms which in themselves are sufficiently rigid to act as columns.
>
> (ASCE 1910, p.450)

For columns reinforced with structural steel, stresses were allowed 45% higher than for columns with longitudinal reinforcement only. In the discussion of the paper, several engineers remarked that the report had been written to fast and that allowed stresses had not been verified by test results. In the Second Progress Report, it was said that:

> Composite columns of structural steel and concrete in which the steel forms a column by itself, should be designed with caution. To classify this type as a concrete column reinforced with structural steel is hardly permissible, as the steel will generally take the greater part of the load. When this type of column is used, the concrete should not be relied on to tie the steel units together or to transmit stresses from one unit to another. The units should be adequately tied together by tie-plates or lattice bars, which, together with other details, such as splices, etc., should be designed in conformity with standard practice for structural steel.
>
> (ASCE 1914, p.421)

This paragraph can be seen as an attempt to reject composite columns from concrete construction and to pass it to the steel side of structural engineering. This paragraph was kept up in the Final Report (ASCE 1917), but concerning reinforced concrete columns, a vital improvement was made; only columns with horizontal reinforcement were allowed and:

> It is recommended that the minimum size of columns to which the working stresses may be applied be 12 in. out to out. … Hooping is to be circular and the ends of bands must be united in such way as to develop their full strength.
>
> (ASCE 1917, p.1133)

Nevertheless, composite columns were adopted again in the first American Standard Specifications No. 23 in 1920.

ACI Standard Specifications No. 23 - 1920

Design rules for two types of composite columns were given in the ACI Standard Specifications No. 23, “Standard Building Regulations for the Use of Reinforced Concrete”. First type were steel columns filled with concrete and encased in a shell of concrete, as used in the Mc Graw Building in New York, and second type were:

> Composite columns having a cast iron core or centre surrounded by concrete which is enclosed in a spiral of not less than one-half of 1 per cent of the core area, and with a pitch of not more than three inches, may be figured for a stress of 12,000 – 60 L/R, but not over 10,000 lb. per sq. in. on the cast iron section and not more than 25 per cent of the compressive strength specified in Section 40 on the concrete within the spiral or core. The diameter of the cast iron core shall not exceed one-half of the diameter of the spiral.
>
> (ACI 23 1920, p.301)

Obviously, the latter one was the Emperger type of column, and was in common use until the 1930s in the construction of tall buildings in Chicago (ENR 1930, p.278). This can be considered the first climax of composite column application. At the same time in Europe, few buildings were constructed with composite columns, due to the lack of design rules, as explained by Emperger (1932, p.595).

German Standard DIN 1045 - 1943

During the 1930s, tests in Germany were made by Memmler, Bierett and Grüning (1934) on steel columns filled with conrete and by Gehler and Amos (1936) on concrete columns reinforced with structural steel. The latter ones led to the first German building regulations on composite columns. DIN 1045-1943, §27 d) treated concrete columns reinforced with structural steel **(fig.6)**. Column resistance was calculated by the addition law and a factor □ considering buckling. This paragraph existed until 1972, when the design of reinforced concrete columns was changed to ultimate load theory and officials decided that structural steel members encased in concrete should be designed to carry the loads alone without considering the strength of the concrete (Bonzel, Bub and Funk 1972, 49).

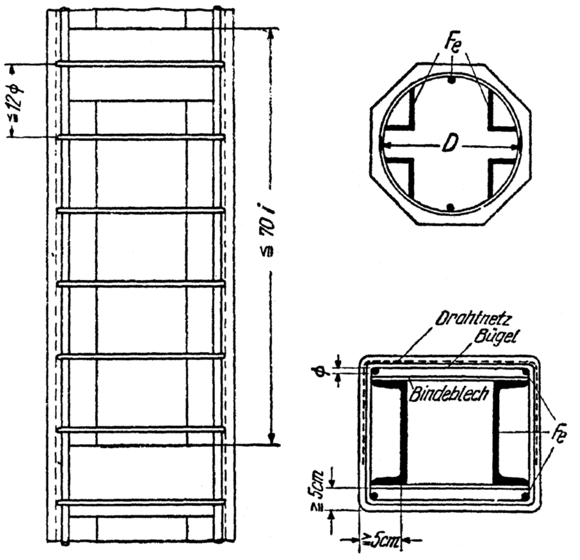


Figure 6. Columns reinforced with Structural Steel (DIN 1045-1943, Fig. 23)

German Standard VDE 0210 - 1953

This paragraph explains the post-war development of concrete filled hollow sections beginning with its use in overhead transmission line masts, e.g. in the construction of the Nufenen pass line in Switzerland, built in 1947 **(fig.7, 8)**. This system by “Motor-Columbus” was patented in Switzerland and several European countries (Girkmann and Königshofer 1952, p.320). The concrete filling allowed a notable saving of steel in post-war economy. In 1953, a paragraph on the design of such sections was added to German standard VDE 0210, “Vorschriften für den Bau von Starkstrom-Freileitungen” (Regulations for the construction of high-voltage overhead transmission lines).

For the first time, the term of an ideal or effective slenderness was used in the design of composite columns, considering the stiffness of both the concrete and the steel section together. The ideal or effective radius of gyration was calculated by:

$$i_{id} = \sqrt{J_{id} / F_{id}}\ ,\ J_{id} = J_e + J_b / n; \qquad (2)$$

where
J_e is the moment of inertia of the steel pipe
J_b is the moment of inertia of the concrete filling and
n is the relation of the moduli of elasticity of steel to concrete with a default value of 10.

This term, the ideal radius of gyration, explains the problem of buckling much more graphically to students than the modern non-dimensional slenderness. Therefore, the objective was to reintroduce it within the developed simplified design method.

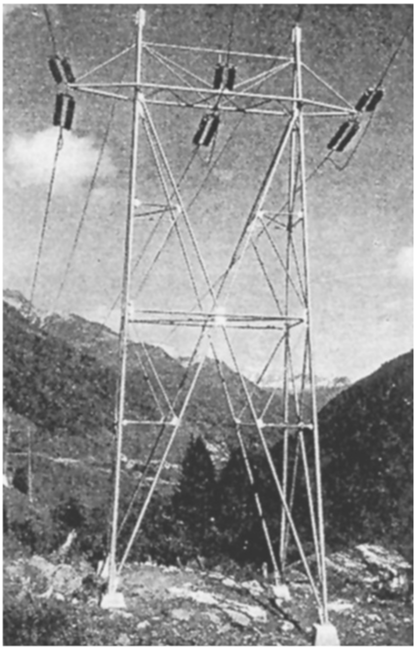


Figure 7. Transmission line mast, Switzerland, 1947 (Girkmann and Königshofer 1952, p.320)

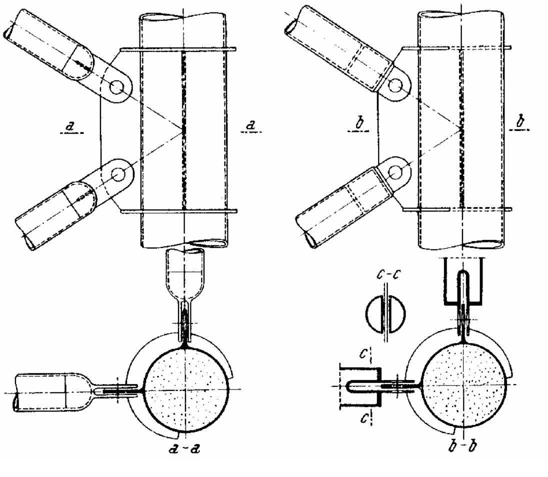


Figure 8. Transmission line mast, section and detail (Girkmann and Königshofer 1952, p.321)

Since construction was restricted to columns with a slenderness bigger than 50, Klöppel and Goder made tests with concrete filled sections in 1957 to extent the practicability of this design method to usual column sizes. They tested 54 filled and 45 pure steel pipes. In their abstract (Klöppel and Goder 1957, p.47) they compared the radius of gyration of the composite section with that of the bare steel section, and showed the relation in a diagram **(fig.9)**. This type of diagram turned out as a practical means in the developed simple design method.

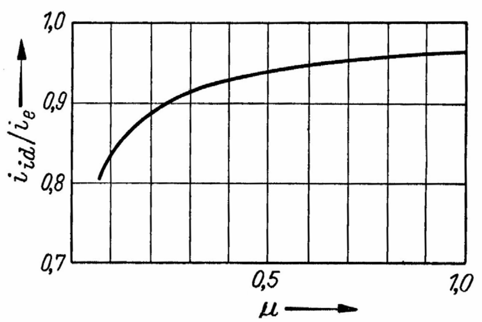


Figure 9. Relation of radii of gyration of composite to steel section (Klöppel and Goder 1957, p.47)

German Standard DIN 18806 - 1984

German Standard 18806 was the first building regulation in Germany dedicated exclusively to composite columns, for the first time covering three different types of composite columns **(fig. 10)** with one design concept. Its design rules were based on the work of Roik, Bergmann, Bode and Wagenknecht (1975, 1976). The basic principles were kept up in Eurocode 4 method, see next paragraph.

Eurocode 4 - 1994

The simplified design method of Eurocode 4 is also based on the method developed at Bochum University by Roik and his team. The ultimate load of a composite column is given similar to Emperger´s Addition-Law by:

$$N_{pl,Rd} = A_a f_{yd} + A_c \square_c f_{cd} + A_s f_{sd} \qquad (3)$$

with f_{yd} the yield strength of structural steel, f_{cd} the compressive strength of concrete and f_{sd} the yield strength of reinforcement steel. Buckling safety is provided by a factor k, by which the ultimate load has to be multiplied. The factor k is given by European buckling curves of Eurocode 3. It has to be calculated as a function of the non-dimensional slenderness $\square\tilde{\square}$ Roik based the design of composite columns on the design of steel columns, using the European buckling curves and the non-dimensional slenderness.

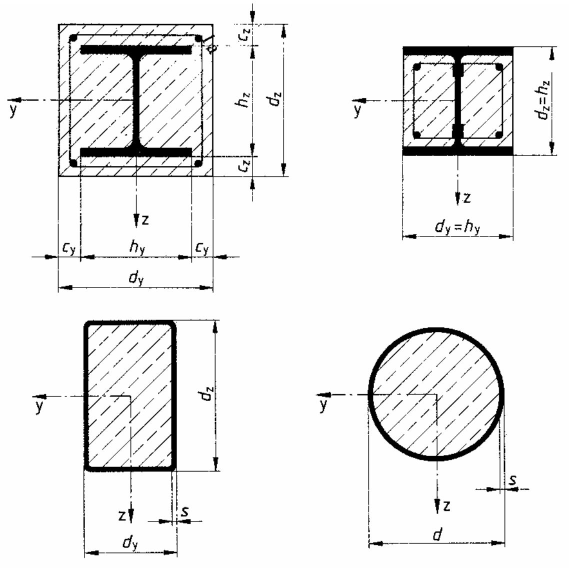


Figure 10. Composite Columns, DIN 18806

Table 1. Design of Composite Columns, Germany (Eggemann 2003b, p.54)

Emperger 1913	Hooped column with a core of cast-iron	$P = (F_b □_b + F_e □_e + F_g □_g) / (4 □)$ [kp] Addition-law
DIN 1045, 1943 Regulations for reinforced concrete construction	Columns reinforced with structural steel	$P_{zul} = (K_b F_b + □_S F_e) / (3 □)$ [kp] Addition-law
DIN 1050, 1954 Riveted and bolted steel construction based on: Klöppel 1935	Steel columns with a core of concrete	$S \leq \frac{\sigma_{zul}}{\omega_x}\left(F_e + 0{,}5 \frac{W_{b28}}{\sigma_k} F_b\right) \leq 1{,}33\, F_e \frac{\sigma_{zul}}{\omega_x}$ [kp] Strength of concrete W_{b28} valued only 50%
VDE 0210, 1953 Regulations for the construction of high-voltage transmission lines	Concrete filled steel pipes	$□ = □\, S / F_{id} \leq □_{zul}$ [kp/cm²] Effective slenderness
DIN 18806 T1, 1984 Composite construction - Composite columns based on: Roik et al. 1975, 1976	Composite Columns	$N_{kr} = □ \cdot N_{pl}$ [kN] □ function of □□
DIN 18800-5, 1990 Eurocode 4, 1994 Composite construction based on: Roik et al. 1975, 1976	Composite Columns	$N_{Rd} = (A_a f_{yd} + A_c □_c f_{cd} + A_s f_{sd}) \cdot □$ [kN] □ function of □□

Table 2. Design of Composite Columns, United States of America (Eggemann 2003b, p.55)

Talbot and Lord 1912	Concrete as reinforcement for structural steel columns	$P = A (36500 - 155\ l/r)$ [lb] Tetmajer-formula
Swain and Holmes 1915	Concrete-filled pipe columns	$P = 1100 (A_c + 9{,}6A_s)$ $P = (A_c + 9{,}6A_s) (1600 – 7\ L/r)$ [lb] Tetmajer-formula
ASCE Reports 1910-1917	Columns reinforced with structural steel	$P = f_c (A_C + nA_S)$ [lb] Total safe load
ACI 23, 1920 Standard building regulations for the use of reinforced concrete	Steel columns filled with concrete and encased in a shell of concrete Composite columns with cast iron core -Emperger type	$f = 18.000 – 70\ L/R < 16.000$ [lb/in.²] allowable stress on steel section $f = 12.000 – 60\ L/R < 10.000$ [lb/in.²] allowable stress on cast iron section
ACI E-1A-28T, 1928 Tentative building regulations for reinforced concrete	Composite columns with cast iron or steel core Combination columns	allowable stress as in ACI 23 Structural steel columns of any rolled or built up section ... encased in concrete
ACI 501-36-T, 1936 Building regulations for reinforced concrete	Composite columns Combination Columns	with cast iron or steel core $P = 0{,}225\ A_c f_c' + f_s A_s + f_r A_r$ [lb] a) Steel columns encased in concrete b) Pipe columns
ACI 318, 1947 Building code requirements for reinforced concrete	Composite columns Combination columns	as in ACI 500-36-T as in ACI 500-36-T
ACI 318, 1977 Building code requirements for reinforced concrete	Composite columns	$r = \sqrt{\frac{(E_c I_g / 5) + E_s I_t}{(E_c A_g / 5) + E_s A_t}}$ Effective radius of gyration

SIMPLIFIED DESIGN METHOD

The proposed simplified design method is based on the simplified method given in Eurocode 4. The design normal force including load factors has to be smaller than the column resistance to normal force:

$$N_{Sd} \leq N_{Rd} \tag{4}$$

As proposed by Führer (1980) for concrete columns, the resistance of a composite column is calculated as the product of only three terms:

$$N_{Rd} = A \cdot \square_{Ri} \cdot k \qquad (5)$$

where

A is the total cross sectional area of the column
$\square_{Ri}$ is the ideal allowed stress, including all safety factors and
k is the buckling factor according to European buckling curves.

The total cross sectional area can be calculated easily, the ideal allowed stress can be tabled exactly considering the column section, the used concrete and the percentage of additional reinforcement, see figure 14. For determination of buckling factor k, the ideal slenderness $\square$ of the column is used instead of the relative slenderness $\square\square$.

For steel columns, the relative slenderness $\square\square$ can be calculated as the product of the “old” slenderness $\square$ and the reciprocal of $\square_a$, thus considering the material properties of steel.

$$\overline{\lambda} = \sqrt{\frac{N_{pl,\,Rk}}{N_{cr}}} = \frac{s_k}{i_{id}} \frac{1}{\lambda_a} \qquad (6)$$

where

s_k is the buckling length of the column
i_{id} is the radius of gyration and
$\square_a$ is a factor considering the material properties of steel

$$\lambda_a = \pi \sqrt{\frac{E}{f_{yk}}} \qquad (7)$$

If we apply this principle to composite columns and solve equation (6) to the radius of gyration i_{id}, we can determine an “ideal” radius of gyration of a composite column:

$$i_{id} = \sqrt{\frac{I_a + \frac{I_c}{n_E} + I_s}{A_a + \frac{A_c}{n_c} + \frac{A_s}{n_s}}} \qquad (8)$$

To avoid by-hand analysis of equation (8), the ideal radius of gyration of a composite column is now calculated as the product of the radius of the steel section and a factor called a:

$$i_{id} = i_a \cdot a \qquad (9)$$

The factor a can be read out of a diagram considering the steel section and the used concrete. Approximately, the influence of additional reinforcement is neglected. For usual column length of 3 to 5 metres (slenderness smaller than 70), the fault of this procedure is limited to 3%. In many cases, results calculated by this simplified method are equal to those calculated by Eurocode 4 method. With the ideal radius of gyration, the ideal slenderness of the column can be calculated:

$$\square_{id} = s_k / i_{id} \qquad (10)$$

The complete procedure for concrete filled hollow sections fits on one page **(fig.11)**, the diagram to determine factor a is inspired by the work of Klöppel and Goder (1957). The European buckling curves are transformed by multiplying the domain values by $\square_a$, thus reintroducing the material properties of steel.

The limitations of the proposed simplified design method are the same as in Eurocode 4. The most important is the composite condition:

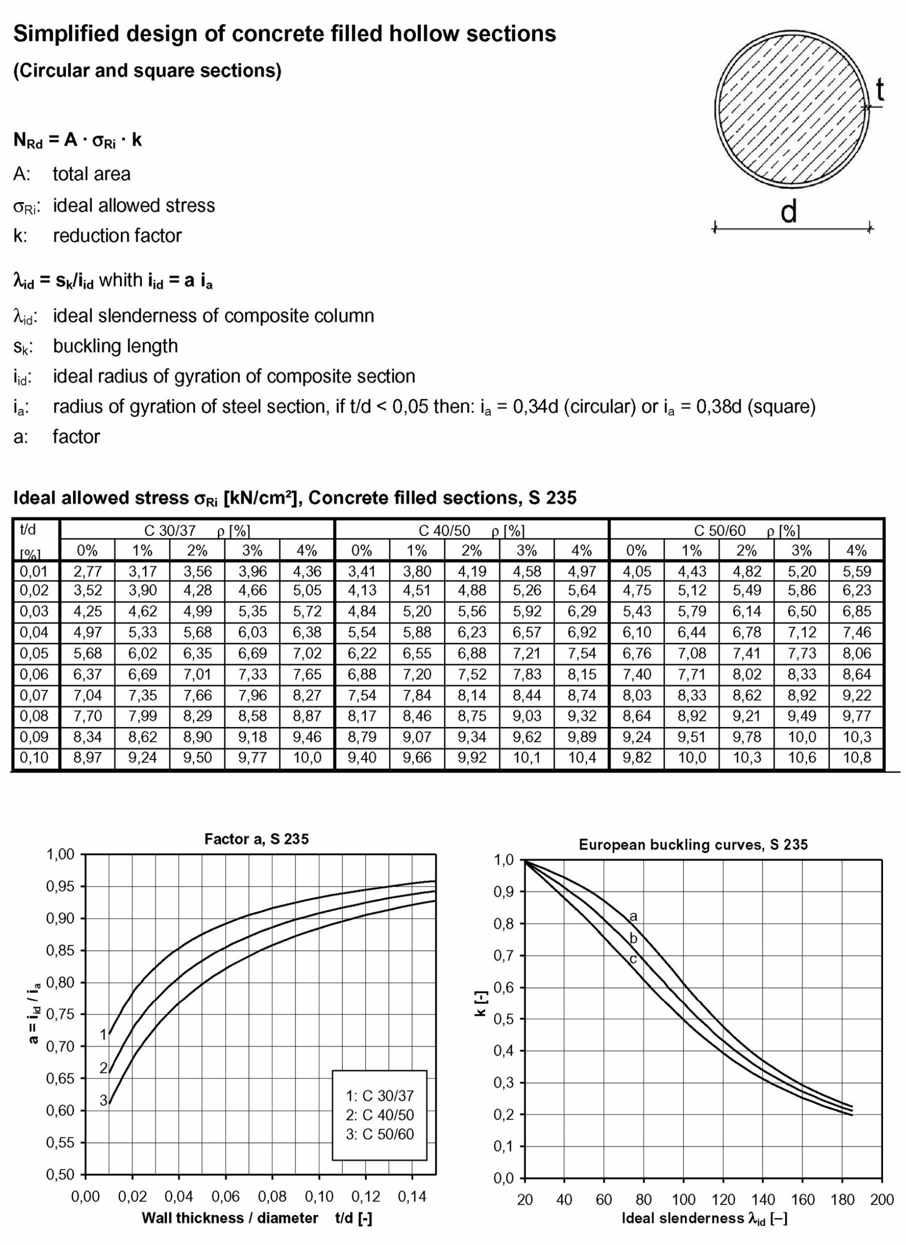
$$0.2 \leq \square \leq 0.9 \qquad (11)$$

which means that a composite column is a composite column if the steel section carries more than 20% and less than 90% of the column load.

RÉSUMÉ

An overview of the construction history of composite columns was given, with a special focus on first applications in buildings and a comparative analysis of building regulations. For the proposed approximation procedure, ideas from Emperger, Klöppel and Roik were taken into account, demonstrating the importance of construction history for today.

The ultimate load of a composite column is determined as the product of the total area with an effective stress. Buckling safety is provided by using the former slenderness ratio s_k/i_{id} (L/r), where s_k (L) is the length of the column and i_{id} (r) its effective (or ideal) radius of gyration. Furthermore, numerous means are provided to calculate the ideal radius of gyration of a composite column by multiplying the radius of the steel section with a correction factor. The procedure for concrete filled steel pipes fits on one page of paper **(fig.11)** and can be used both in university education of architecture and by structural engineers for dimensioning and design of composite columns. In many cases, approximately calculated ultimate column loads are equal to those calculated by Eurocode 4 method. The procedure was successfully presented to students at RWTH Aachen University.



Simplified design of concrete filled hollow sections

(Circular and square sections)

$\mathbf{N_{Rd} = A \cdot \sigma_{Ri} \cdot k}$

A: total area

σ_{Ri}: ideal allowed stress

k: reduction factor

$\boldsymbol{\lambda_{id} = s_k / i_{id}}$ whith $\mathbf{i_{id} = a\ i_a}$

λ_{id}: ideal slenderness of composite column

s_k: buckling length

i_{id}: ideal radius of gyration of composite section

i_a: radius of gyration of steel section, if $t/d < 0{,}05$ then: $i_a = 0{,}34d$ (circular) or $i_a = 0{,}38d$ (square)

a: factor

Ideal allowed stress σ_{Ri} [kN/cm²], Concrete filled sections, S 235

t/d	C 30/37 ρ [%]					C 40/50 ρ [%]					C 50/60 ρ [%]				
[%]	0%	1%	2%	3%	4%	0%	1%	2%	3%	4%	0%	1%	2%	3%	4%
0,01	2,77	3,17	3,56	3,96	4,36	3,41	3,80	4,19	4,58	4,97	4,05	4,43	4,82	5,20	5,59
0,02	3,52	3,90	4,28	4,66	5,05	4,13	4,51	4,88	5,26	5,64	4,75	5,12	5,49	5,86	6,23
0,03	4,25	4,62	4,99	5,35	5,72	4,84	5,20	5,56	5,92	6,29	5,43	5,79	6,14	6,50	6,85
0,04	4,97	5,33	5,68	6,03	6,38	5,54	5,88	6,23	6,57	6,92	6,10	6,44	6,78	7,12	7,46
0,05	5,68	6,02	6,35	6,69	7,02	6,22	6,55	6,88	7,21	7,54	6,76	7,08	7,41	7,73	8,06
0,06	6,37	6,69	7,01	7,33	7,65	6,88	7,20	7,52	7,83	8,15	7,40	7,71	8,02	8,33	8,64
0,07	7,04	7,35	7,66	7,96	8,27	7,54	7,84	8,14	8,44	8,74	8,03	8,33	8,62	8,92	9,22
0,08	7,70	7,99	8,29	8,58	8,87	8,17	8,46	8,75	9,03	9,32	8,64	8,92	9,21	9,49	9,77
0,09	8,34	8,62	8,90	9,18	9,46	8,79	9,07	9,34	9,62	9,89	9,24	9,51	9,78	10,0	10,3
0,10	8,97	9,24	9,50	9,77	10,0	9,40	9,66	9,92	10,1	10,4	9,82	10,0	10,3	10,6	10,8

Figure 11. Simplified Design of Composite Columns (Eggemann 2003b, p.85)

PROSPECTS

Beyond the given example of composite columns, Construction History could play a more important role in the education of both architects and engineers. Former design methods could be studied in all materials, e.g. wood, steel and concrete construction, as they are more graphical to students of architecture. Furthermore, elder methods and procedures to determine the inner forces of statical systems could be studied, to gain the capacity of simple control of computer calculations.

A concept for historic and genetic education of the Theory of Structures was presented by Kurrer (2002, p.455). According to his concept, the presented study represents a historical-logical longitudinal section. Other ways are the historical-logical cross section and the historical-logical comparison of construction.

REFERENCES

ACI 23, 1920. “Standard Specifications No. 23, Standard Building Regulations for the Use of Reinforced Concrete”. *Proceedings*, ACI, vol. 16, pp.283-302.

ACI 318-47, 1947. “Building Code Requirements for Reinforced Concrete”. In: Betonkalender 1951, Teil II, Berlin: Ernst & Sohn, pp.386-396.

ACI 318-77, 1977. “Building Code Requirements for Reinforced Concrete”. In: Betonkalender 1980, Teil I, Berlin: Ernst & Sohn, pp.1087-1178.

ACI 501-36-T, 1936. “Building Regulations for Reinforced Concrete”. *Proceedings*, American Concrete Institute, vol. 32, pp.407-.

ACI E-1A-28T, 1928. “Tentative Building Regulations for Reinforced Concrete”. *Proceedings*, American Concrete Institue, vol. 24, 1928, pp.791-828.

ASCE, 1910. “Progress Report of Special Committee on Concrete and Reinforced Concrete”. *Transactions*, ASCE, vol. 66, pp.431-93.

ASCE, 1914. “Progress Report of the Special Committee on Concrete and Reinforced Concrete”. *Transactions*, ASCE, vol. 77, pp.385-437.

ASCE, 1917. “Final Report of the Special Committee on Concrete and Reinforced Concrete”. *Transactions*, ASCE, vol. 81, pp.1101-1206.

Bonzel, J., Bub, H. and Funk, P., 1972. *Erläuterungen zu den Stahlbetonbestimmungen*. Band. I, 7. Auflage. Berlin, München, Düsseldorf: Ernst & Sohn.

Burr, W. H., 1908. "The reinforced concrete work of the McGraw Building". *Transactions*, ASCE, vol. 60, pp.443-457.

Burr, W. H., 1912. "Composite Columns of Concrete and Steel". *Minutes of the Proceedings,* ICE, vol. 188, London, pp.114-126.

DIN 1045, 1943. "A. Bestimmungen für die Ausführung von Bauwerken aus Stahlbeton". 4. Ausg. 1943. Berlin: Beuth.

DIN 1050, 1954. "Genietete und geschraubte Stahlbauten außer Eisenbahn- und Straßenbrücken, Berechnung und bauliche Durchbildung". *Stahlbau,* vol. 23, pp.273-278.

DIN 18800-5, 1999. "DIN 18800: Teil 5 Verbundtragwerke aus Stahl und Beton, Bemessung und Konstruktion, Ausgabe Januar 1999". Berlin: Beuth.

DIN 18806, 1984. "DIN 18806: Teil 1 Verbundkonstruktionen, Verbundstützen, Ausgabe März 1984". Berlin: Beuth.

Eggemann, H., 2003a. "Development of Composite Columns – Emperger´s Effort". *Proceedings of the First International Congress on Construction History*. Ed. S. Huerta. 20.-24. Januar 2003. Madrid: Instituto Juan de Herrera, ETSA. pp.787-798.

Eggemann, H., 2003b. "Vereinfachte Bemessung von Verbundstützen im Hochbau: Entwicklung, historische Bemessung und Herleitung eines Näherungsverfahrens" Dissertation, RWTH Aachen University, published online: www.bth.rwth-aachen.de.

Emperger, F., 1911. *Hohle Gußeisensäule mit einem Mantel aus umschnürtem Beton*. German Reich Patent no. 291068.

Emperger, F., 1913a. "Weitere Versuche mit umschnürten Gußeisen". *Beton und Eisen,* vol. 12, pp.30-37; 137-139.

Emperger, F., 1913b. "Säulen aus umschnürtem Gußeisen". *Beton und Eisen,* vol. 12, pp.365-367.

Emperger, F., 1932. "Verbundsäulen". IABSE, First Congress Paris 1932, *Preliminary Publication*, Vol. 1, pp.595-616.

ENR, 1930. “Reinforced-Concrete Columns with Cast-Iron Cores”. *Engineering News-Record*, Feb. 13, pp.241-245.

Eurocode 4, 1994. “Bemessung und Konstruktion von Verbundtragwerken aus Stahl und Beton, Teil 1-1 Allgemeine Bemessungsregeln – Bemessungsregeln für den Hochbau”, Berlin: Beuth.

Führer, W., 1980. *Überschlägliche Dimensionierung für das Entwerfen von Druckgliedern*. Düsseldorf: Werner, 1980.

Girkmann, K., Königshofer, E., 1952. *Die Hochspannungsfreileitungen*. Wien: Springer.

Gehler, W. and Amos, H., 1936. *Versuche an Säulen mit Walzprofilbewehrung. Versuche über Balkenanschlüsse bei Säulen mit Walzprofilbewehrung*. Deutscher Ausschuß für Eisenbeton. Heft 81. Berlin: Ernst & Sohn.

Klöppel, K., 1935. “Berechnungsvorschlag für Stahlstützen mit Betonkern auf Grund von Versuchsergebnissen”. *Zentralblatt der Bauverwaltung,* vol. 55, pp.536-540.

Klöppel, K., Goder, W., 1957. “Traglastversuche mit ausbetonierten Stahlrohren und Aufstellung einer Bemessungsformel”. *Stahlbau* ,vol. 26, pp.1-10; 44-50.

Kurrer, K.-E., 2002. *Geschichte der Baustatik*. Berlin: Ernst & Sohn.

Memmler, K., Bierett, G., and Grüning, G., 1934. Tragfähigkeit von Stahlstützen mit Betonkern bei mittigem Kraftangriff. *Stahlbau*, vol. 7, pp.49-53, 61-64.

Roik, K., Bergmann, R., Bode, H., Wagenknecht, G., 1975. “Tragfähigkeit von ausbetonierten Hohlprofilstützen aus Baustahl”. *Techn.-wissenschaftl. Mitteilungen*, Institut für konstruktiven Ingenieurbau, Ruhr-Universität Bochum, Heft 75-4.

Roik, K., Bergmann, R., Bode, H., Wagenknecht, G., 1976. “Tragfähigkeit von einbetonierten Stahlstützen”. *Techn.-wissenschaftl. Mitteilungen*, Institut für konstruktiven Ingenieurbau, Ruhr-Universität Bochum, Heft 76-4.

Swain, F. W., Holmes, A. F., 1915. “An Investigation of the Strength and Elastic Properties of Concrete-filled Pipe Columns”. *Proceedings*, vol. 15, Part II, ASTM, pp.230-244.

Talbot, A. N., Lord, A. R., 1912. “Tests of Columns: An Investigation of the Value of Concrete as Reinforcement for Structural Steel Columns”. University of Illinois, *Engineering Experiments Station Bulletin,* No. 56.

VDE 0210, 1953. “Vorschriften für den Bau von Starkstrom-Freileitungen”. Verband Deutscher Elektrotechniker. Wuppertal, Berlin: VDE-Verlag.

Viest, I. M., Colaco, J. P., Furlong, R. W. et al., 1997. *Composite Construction. Design for Buildings*. New York: McGraw-Hill and ASCE.