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Autor: Johnson, R.P. / Anderson, David

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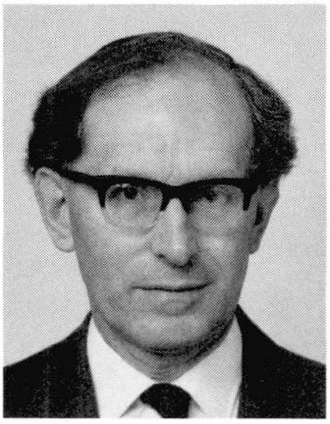
EC 4: Composite Beams, Connections, and Frames at Ultimate Limit States

EC 4: Etats-limites des poutres, assemblages et cadres mixtes

EC 4: Grenzzustände der Tragfähigkeit von Verbundträgern, Verbindungen und Rahmen

R.P. JOHNSON
Prof. of Civil Eng.
University of Warwick
Coventry, UK

David ANDERSON
Senior Lecturer
University of Warwick
Coventry, UK



SUMMARY

An outline is given of the design methods of Eurocode 4: Part 1.1 for simple and continuous beams, and for composite frames and connections for buildings. Subjects include the classification and resistances of cross-sections of beams, global analysis of beams and braced frames, and lateral-torsional buckling of beams. It is explained why no application rules are given for unbraced or sway frames or for the use of semi-rigid connections.

RESUME

On présente les méthodes de dimensionnement de l'Eurocode 4: partie 1.1 pour les poutres sur appuis simples et continus, et pour les cadres et les assemblages mixtes dans les bâtiments. Les sujets suivants sont abordés: la classification et la résistance des sections de poutre, l'analyse globale des poutres et des cadres contreventés et le déversement latéral des poutres. On explique pourquoi les règles se rapportant aux cadres non contreventés et aux assemblages semi-rigides ont été omises.

ZUSAMMENFASSUNG

Der Beitrag skizziert die Bemessungsmethoden im EC 4, Teil 1.1 für einfache und durchlaufende Träger, Verbundrahmen und Verbindungen in Hochbauten. Behandelt werden die Klassifizierung und Ermittlung der Widerstandsgrössen von Profilen, die Gesamtnachweise an Trägern und ausgefachten Rahmen sowie das Biegedrillknicken. Es wird begründet, warum keine Anwendungsregeln für unausgefachte oder verschiebliche Rahmen und für nachgiebige Verbindungen gegeben werden.

1. GENERAL

The subject of this paper is the content of Chapter 4, "Ultimate limit states" (except for columns) and Annex B, "Lateral-torsional buckling" of Eurocode 4: Part 1.1. It does not include shear connection or the use of composite or precast concrete floor slabs, as these are covered in other papers.

The Sections of Chapter 4 are arranged in order of increasing complexity. This enables simply-supported beams to be designed using Sections 4.1 to 4.4 only. For beams that are continuous over simple supports and do not take part in frame action, Sections 4.5 to 4.7 are also relevant. Section 4.8 is self-contained for no-sway columns subjected to known end loads and bending moments. The remaining Sections, 4.9 and 4.10, are on frames and connections respectively.

In Eurocode 3, three factors γ_M are defined for structural steel: γ_{M_0} when buckling is not relevant; γ_{M_1}, when it is; and γ_{M_2}, for the resistance of a net section at bolt holes.

For net steel sections, Eurocode 4 follows Eurocode 3; and for γ_{M_0} and γ_{M_1} it preserves the distinction made in Eurocode 3, even though the boxed values for both factors are the same, 1.1. This is to enable any country that so wishes to assign different values to γ_{M_0} and γ_{M_1}.

The *symbols* for γ_{M_0} and γ_{M_1} used in Eurocode 4 are different: γ_a and γ_{Rd}, respectively. This is done because the factors are used in a different way, as explained in other papers on Eurocode 4, and in clauses 2.2.3.2 and 4.1.1(5) of Part 1.1.

2. CROSS-SECTIONS OF COMPOSITE BEAMS

Specific reference is made only to beams where the concrete slab lies above a steel rolled or fabricated section that is symmetrical about the plane of bending, though other situations are not excluded. No information is given on torsional properties, because few composite beams in buildings have significant torsional stiffness.

Provision is made for the encasement of steel webs in concrete, and for the increase in resistance to local, shear, and lateral buckling that encasement provides; but no provision is made for full encasement, nor for the influence of encasement on resistance to bending or longitudinal shear.

Where plastic analysis of cross-sections is used, as is usual, welded steel mesh is normally excluded from the effective section, unless it has been shown to have sufficient ductility *when built into a concrete slab*, to ensure that it will not fracture.

The effective widths of concrete flanges given in Eurocode 4 are greater than those in Eurocode 2 (typically, span/4 rather than span/5). This is because underestimates are unsafe for the design of shear connection, and although overestimates are in theory unsafe for the prediction of resistance to bending, the error is small. Furthermore, both inelastic behaviour of reinforcement and flexural cracking of concrete tend to increase the effective width of a concrete flange.

Cracking of concrete has a complex influence on the flexural stiffness of a composite section. This has been simplified by using only two stiffnesses in Eurocode 4, denoted $E_a I_1$ and $E_a I_2$. These are for the "uncracked" and the "cracked reinforced" sections, respectively.

The classification system for composite beams, based on the slendernesses of steel elements in compression, is as similar as possible to the system defined in Eurocode 3: Part 1.1. The definitions of classes 1 to 4 and the slenderness ratios at class boundaries are the same, following work by Kemp [1]. He showed that the adverse influence of crushing of concrete on rotation capacity of sections is offset by some less obvious advantages of composite members over steel members, and that the rules in Eurocode 4 are supported by the test data on continuous composite members.

Composite beams are usually in Class 1 at midspan. The Class at an internal support is strongly influenced by the area of longitudinal reinforcement in the slab. A small increase can move the steel web from Class 1 to Class 3 [2]. Design of Class 3 beams has to allow for the method of construction (propped or not) and cannot use partial shear connection, which is necessary for most beams where profiled steel sheeting is used.

The anomaly caused by the abrupt change in design procedures at the Class 2/3 boundary, (particularly the change from plastic to elastic section analysis) is avoided in Eurocode 4 by allowing the replacement of a web in Class 3 by an effective web in Class 2. This has a region near its centre that is assumed not to contribute to resistance to bending. The effective web is an extension of the idea of an effective width that has long been used in the elastic analysis of steel sections in Class 4. The stress distributions at the design ultimate hogging moment for a Class 3 section with and without "hole" in its web are compared in Figure 1, assuming that propped construction is used, f_y = 355 N/mm², f_{sk} = 460 N/mm², γ_a = 1.10, γ_s = 1.15. Without the hole, $M_{p\ell.Rd}$ would be 307 kNm.

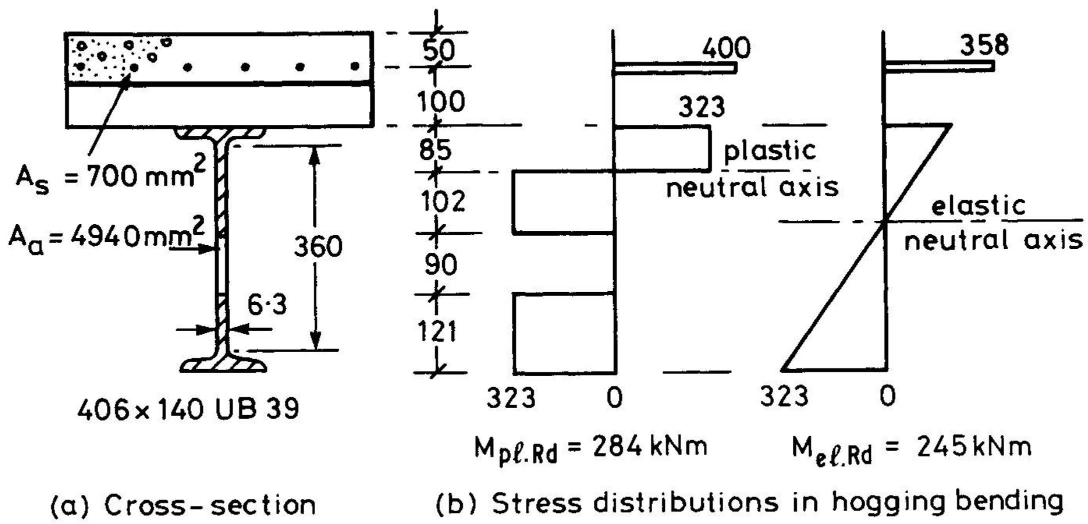


Fig. 1 Replacement of a Class 3 web by an effective web in Class 2

3. RESISTANCES OF CROSS-SECTIONS OF COMPOSITE BEAMS

3.1 Bending moment

For sagging bending of sections in Class 1 or 2, the rectangular stress block used for concrete (a compressive stress of 0.85 f_c) extends to the neutral axis. This is not in accordance with Eurocode 2, but is necessary to avoid complex calculations where (as commonly occurs) the neutral axis passes through a steel flange. Calibration has shown [3, 4] that the bending resistance thus calculated is satisfactory for beams with a concrete flange; but it can be unconservative for column sections, so a factor 0.9 is introduced in clause 4.8.3.13.

Account has been taken of the influence of crushing of concrete on the rotation capacity of a composite section by limiting the applicability of rigid-plastic global analysis where continuous beams have non-uniform spans, or carry concentrated loads.

Resistance to sagging bending is often determined by the degree of shear connection provided. In theory, this can also influence the classification of the section, but it rarely does so in practice.

3.2 Bending moment

The treatment of vertical shear is closely related to that in Eurocode 3, except that the resistance to buckling of slender webs is improved by the ability of shear connectors to anchor a tension field in the concrete slab, and also by encasement in concrete, if provided.

The curve of interaction between resistance to bending and to vertical shear is parabolic-rectangular, as in Eurocode 3, but intermediate points on the diagram are defined differently, for reasons explained elsewhere [2].

4. INTERNAL FORCES AND MOMENTS IN CONTINUOUS BEAMS

A distinction is made between "continuous beams", where the bending moments are not influenced by the properties of their connections and supports, and "beams in frames". Global analysis of the latter is discussed in Section 6, below.

Plastic global analysis is the simplest method for continuous beams in buildings, because no account need be taken of the method of construction or of creep or shrinkage of concrete. Where elastic analysis has to be used, redistribution of moments is allowed, depending on the classes of the cross-sections, the method of elastic analysis (i.e., "uncracked" or "cracked"), and whether midspan moments are being increased or decreased. The results of checks on these rules are available [5, 6].

Care has been taken to avoid giving any application rules in Eurocode 4 that are related to the position of a point of contraflexure in a beam. This is because these positions are different for each combination and arrangement of actions, and cannot easily be found where partial shear connection is used.

5. LATERAL-TORSIONAL BUCKLING IN BEAMS FOR BUILDINGS

A set of Principles of wide applicability is followed by Application Rules for the only relevant problem that commonly occurs in composite structures: lateral buckling of the bottom flange of a continuous beam, in a region of hogging moment. Under the "alternate-span" arrangement of variable load, such a region may extend over most of the length of an internal span.

Many designers doubt the need for such flanges to be braced. They dislike the complexity of methods based on the well-known elastic critical theory for non-distortional buckling, which has been shown to be over-conservative for beams where the steel top flange is restrained against rotation.

The three methods given in Eurocode 4 are based on the theory of distortional buckling and on tests [7, 8]. The simplest method (clause 4.6.2) defines the maximum depths of steel I and H sections for which no check on buckling is required. Its use has had to be qualified by many conditions, relating to the dimensions and loading of the structure. Graphs that simplify the checking of several of these conditions have been prepared [2].

The more general methods involve the calculation of a slenderness ratio $\bar{\lambda}_{LT}$ and the use of a reduction factor χ_{LT} taken from Eurocode 3. For many situations, a simplified expression for $\bar{\lambda}_{LT}$ can be used, based only on the properties of the steel section and the bending-moment distribution for the span concerned. The third method, the least conservative but the longest, involves calculation of the elastic critical moment at the internal support, and then $\bar{\lambda}_{LT}$.

6. INTERNAL FORCES AND MOMENTS IN FRAMES FOR BUILDINGS

A composite frame is defined as a structure in which some or all of the beams and columns are composite members. It is assumed that most or all of the remaining members are of structural steel. Eurocode 3 is therefore applicable during the construction phases. It can also be used as a basis for the composite stage. Eurocode 4 therefore mainly gives modifications and additions to Eurocode 3, necessary for the particular features of composite construction. Where the structural behaviour is essentially that of a concrete frame with only a few composite members, global analysis is to be in accordance with Eurocode 2.

As for steel structures, composite frames may be classified as sway or non-sway, braced or unbraced. For a frame to be considered as braced, it must be acceptable to assume that all horizontal loads are resisted by the bracing system. This requires the latter to provide a stiff response compared to other load paths. It has been usual to require the stiffness of the braced frame to be at least five times that of the unbraced structure [9]. This is expressed in Eurocode 4 as a reduction in horizontal displacements due to the inclusion of bracing. For a composite frame, the response will also be influenced by cracking of concrete and by creep. Neglect of cracking is permitted though, because this increases the unbraced stiffness and therefore increases the minimum stiffness required of the bracing.

A sway frame is one in which account needs to be taken of the additional internal moments and forces arising from horizontal displacements of the nodes (the 'P - Δ' effect). Sway frames are excluded from Section 4.9 because of their comparative rarity and because Section 4.8 on columns treats only non-sway members.

A frame that is classified as braced is treated as a non-sway frame. It is also possible for an unbraced frame to respond as a non-sway structure, but rules are not yet established to predict easily the appropriate portions of each span where the concrete should be taken as cracked. Unbraced non-sway frames are not excluded from the scope of Section 4.9, but no Application Rules are given for their analysis.

A further classification relates the method of global analysis to the anticipated behaviour of the connections, as shown in Table 4.8 of Eurocode 4. Some of the methods permitted by Eurocode 3 are not included in the Application Rules of Eurocode 4 because of their rarity in design practice.

Rules are given for rigid-plastic global analysis, but not for elastic-plastic analysis. Eurocode 3 distinguishes between two forms of the latter. "Elastic-perfectly plastic" analysis adopts the plastic hinge concept, and the rules for rigid-plastic analysis may therefore be used as a basis for the user to formulate rules for this approach. The second form, "elasto-plastic analysis", takes account of the spread of plastic zones and is therefore a specialised method for which it is inappropriate to give rules in a design standard.

The Application Rules include the use of partial-strength connections in frames analysed by rigid-plastic theory. A connection of this type has a design resistance moment less than that of the connected beam, so that a plastic hinge will tend to form in the connection. Tests on end-plate connections [10] with continuous slab reinforcement provided by mesh and by bars of diameter up to 12 mm have shown that fracture of reinforcement is the likely failure mode. It is important therefore to be sure that sufficient rotation capacity exists to develop the plastic collapse mechanism assumed in design.

For elastic global analysis, flexural stiffnesses for beams in braced frames may be taken as the uncracked values throughout each span, or a region each side of an internal support may be taken as cracked. Internal moments may be redistributed, usually by reducing support values. Limits to redistribution have been established by studies on continuous braced structures. Rules are not yet established for flexural stiffness and redistribution of moment in unbraced composite frames.

No Application Rules are given for elastic analysis of frames with semi-rigid connections. This is because methods to predict moment-rotation characteristics are not well-enough established for inclusion in Eurocode 4.

7. COMPOSITE CONNECTIONS IN BRACED FRAMES FOR BUILDINGS

Modifications and additions are needed to Eurocode 3, for connections in which reinforcement is intended to contribute to the resistance. A wide variety of composite connections can be envisaged and therefore only Principles are given in much of this Section.

For beam-to-column connections, Eurocode 3 has given rules for classification, in order that the appropriate method of global analysis can be determined. Eurocode 4 extends these to composite construction, for situations in which the slab reinforcement contributes to the tensile resistance of the connection. For this reason, Section 4.10 is restricted to braced frames.

To non-dimensionalise the classification, the properties of the connection are compared with those of the connected beam adjacent to the connection. The non-dimensional limits which define the classification have been adopted from Eurocode 3.
No detailed rules are given for the calculation of moment resistance, rotational stiffness and rotation capacity. Methods to predict these are not well-enough established to justify inclusion in Eurocode 4. At present, experimental evidence may therefore be required. Attention is drawn though to use of the rules in Eurocode 3, supplemented by consideration of the slab reinforcement. Limited studies [10] show reasonable agreement between resistance moments calculated on this basis and test results.

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