DEVELOPEMENT OF A GENERAL METHOD FOR THE VERIFICATION OF COMPOSITE BEAMS AGAINST LATERAL TORSIONAL BUCKLING IN THE ERECTION PHASE

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ABSTRACT

This paper deals with the verification of composite beams in the erection phase, i. e. when the composite action between the supporting steel beam and the composite slab is not yet effective. Indeed, it appears that almost no stability verification is usually performed for the erection phase, while lateral torsional buckling could occur because of the lack of adjacent restraints.

In the present paper, a general method for the verification of the stability of beams against lateral torsional buckling during the erection phase is exposed. Through comparisons with non-linear FEM results, the method is proved to be safe and accurate; it should then provide great help for design office engineers, according to its rapid application and user-friendliness.

As a particular point, the method gives an analytical expression for the calculation of the torsional restraint of a partially encased beam, which clarifies Eurocode 4 proposed recommendations.

1 INTRODUCTION

In order to improve the fire resistance of their composite beams, the ARCELOR Long Carbon Steel Research Centre has developed a new type of partially encased composite beams. The basic idea consists in concreting successively, on site or in workshop, the spaces between the flanges of the profile, on both sides of the web. Then, under fire conditions, the steel profile is partially protected by the concrete, and the loss of resistance of the lower flange can be transferred partially to the lower longitudinal rebars. Of course, some stirrups are also necessary to ensure the integrity of the concrete. Few days after concreting, the beam may be put in place on site. Whenever shear connectors have been welded to the upper flange of the beam, then a composite action may take place with the reinforced concrete slab.

During the construction phase, instability problems may occur even if the beam is at that moment subjected to lower actions than in service conditions. There are two main reasons for that:

- First, the concrete of the slab is not resistant yet, and the strong stabilizing effect it provides during the final composite stage is not yet effective.
- Secondly, the concrete in the encasement, if available, is only 5 to 7 days old; as a consequence, the increase of torsional stiffness it provides to the beam is lower than after 28 days, making the beam more sensitive to lateral torsional buckling.

In reality, some restraints contribute actually to the lateral torsional buckling resistance, but are disregarded because of the difficulty in accounting for their beneficial effects.

It is worth mentioning that quite often *no verification at all* is performed in practice. On one hand, the design office generally does not care for erection conditions in the building construction, because the responsibility belongs to the constructor. On the other hand, the latter makes most often use of its practical expertise rather than to detailed stability calculations, with the consequence that the actual safety margin may be questionable.

In this context, it appeared useful to provide simple means for a realistic evaluation of the lateral torsional buckling resistance of partially encased beams against lateral torsional buckling during construction.

In this paper, a method is proposed that intends at being a quite efficient and practical solution to this problem. Paragraphs 2 and 3 give background information on the method, while paragraph 4 is dedicated to its validation; paragraph 5 describes a new dedicated stand-alone software, derived accordingly. Finally, paragraph 6 briefly summarizes two parametric studies conducted with the software, respectively on partially encased beams and on beams restrained by metal sheeting during the erection phase.

2 SEVERAL POSSIBLE APPROACHES

2.1 Introduction – Mechanical model

During the construction phase, partially encased beams can be supposed to be simply supported beams, or eventually cantilever beams. In addition to their self-weight, the loads they are submitted to during the construction phase are the weight of dry concrete, the weight of steel sheets or pre-slabs, and that of men concreting the slab.

As explained in § 1, the concrete in the encasement is only 5 to 7 days old when the beam is erected in the structure. Depending on the efficiency of the connection between the beam profile web and the encased concrete, a slip can be observed, or not, at the interface between the two materials. But, usually, shear studs are placed along the web, thus providing an efficient link between the steel profile and the encasement, and no slip therefore occurs.

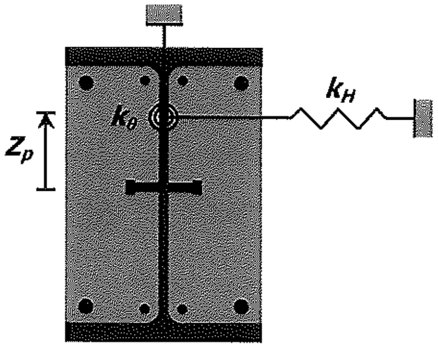

Fig. 1: Cross-sectional mechanical model

The cross-sectional model considered in the present study is represented on Fig. 1; k_H represents the lateral restraint provided by the steel sheet, and k_θ the corresponding torsional restraint. Z_p is the distance between the centroïd of the steel profile and the torsional centre of rotation of the whole cross-section, which can be any, depending on the values of k_H and k_θ.

Obviously, the proposed method should be able to account for all these aspects. Furthermore, it should meet the expectations of designers, i. e. efficiency and accuracy. Nevertheless, it should not be forgotten that the method applies here during the *construction* phase. In this context, simplicity should prevail against accuracy, because of all the erection phase related uncertainties.

Several possible approaches can be proposed to study the stability of the whole member; they are briefly described in the following paragraphs.

2.2 Full FEM approach

This first method consists in resorting to systematic non-linear FEM calculations to determine the ultimate bending resistance of the beam M_u. It presents the advantages of being rather accurate in the modelling of the actual physical problem. In addition, it allows decreasing the number of assumptions to be made in comparison to a full analytical method; this results in a relatively rigorous treatment of the composite behaviour.

Nevertheless, this method does not appear suitable for design purposes, as it is time-consuming and involves sophisticated software that are usually not available in design offices. Furthermore, it requires a relative high experience in the field on non-linear computation.

Whenever this method does not really meet the requirements exposed in § 1, it will be used as a numerical reference for the validation of the proposed method (see § 4).

2.3 Hybrid method

As an alternative to a full FEM approach, the so-called “hybrid method” consists in calculating the plastic bending resistance of the beam cross-section M_{pl} in an *analytical* way, while the elastic critical lateral torsional buckling resistance M_{cr} is computed *numerically*. This is the way the adjective “hybrid” should be here interpreted. A reduced member slenderness is then calculated, based on the values of M_{pl} and M_{cr}, and the ultimate lateral torsional buckling resistance of the beam is finally reached through the use of a so-called “buckling curve”, in the same way as for the buckling resistance of columns in compression.

Indeed, if the manual determination of M_{pl} does not involve complex calculations, an analytical estimation of M_{cr} appears to be much more complex (external restraints, different types of bending moment diagrams, ...).

It is proposed here to use the finite element technique to determine the value of M_{cr} in each particular case: this allows a rather quick but accurate calculation, provided that a little calculation module dedicated to the evaluation of M_{cr} is developed.

This method is the one that has finally been chosen (see § 3 and 4).

2.4 Analytical method

The last possibility consists in developing a whole analytical method, which would follow the same steps than in § 2.3 but with a full analytical evaluation of M_{cr}. For example, the recommendations of EN 1993-1-1 for the determination of M_{cr} in a steel profile could be adapted; nevertheless, this appears too difficult, accounting for the complexity of the behaviour studied here, and this method has not been selected.

3 PROPOSED METHOD

3.1 General overview of the method

Accounting for all previously detailed considerations, a hybrid method is here followed. It is organised according to the following chart:

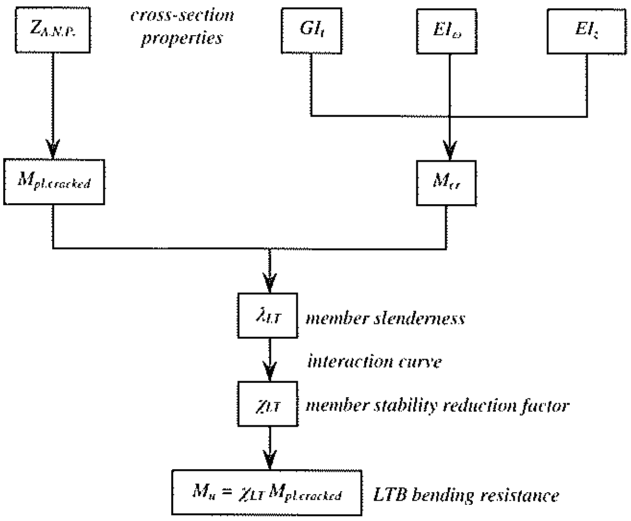

Fig. 2: Principle of the hybrid method

In this diagram, all cross-section properties are analytically evaluated; M_{cr} is separately estimated by means of a FEM calculation module. M_{pl} (or $M_{pl,cracked}$ in case of partially encased beam) and M_{cr} being known, the classical procedure of EN 1993-1-1 for lateral torsional is followed, with the successive calculations of ϕ_{LT} and χ_{LT}, and finally the ultimate lateral torsional buckling resistance M_u.

3.2 Calculation of GI_t

As can be seen on Fig. 2, the values of the cross-section stiffness EI_z, GI_t and EI_ω are required for the calculation of M_{cr}. And in the particular case of a partially encased beam, it seems obvious that the torsional stiffness GI_t is rather different from the case of a steel profile resisting alone. The problem is here to estimate in a realistic way the contribution of the concrete to the cross-sectional properties.

After validation through extensive FEM calculations, it is proposed to calculate the partially encased beam torsional stiffness as the sum of the following contributions:

$$GI_{t,tot} = G_{steel} I_{t,steel} + G_{concrete} I_{t,concrete} \tag{1}$$

with:

$$\begin{aligned} I_{t,steel} &= \frac{2}{3}\left(b - 0{,}63\, t_f\right) t_f^{\,3} + \frac{1}{3}\left(h - 2\, t_f\right) t_w^{\,3} \\ &+ 2\left(\frac{t_w}{t_f}\right)\left(0{,}145 + 0{,}1\frac{r}{t_f}\right)\left[\frac{\left(r + 0{,}5\, t_w\right)^2 + \left(r + t_f\right)^2 - r^2}{2\, r + t_f}\right]^4 \end{aligned} \tag{2}$$

and:

$$I_{t,concrete} = \begin{cases} \dfrac{1}{3}\left(1-0{,}63\dfrac{(b-t_w)}{(h-2t_f)}\right)(h-2t_f)(b-t_w)^3 \; if \; (h-2t_f)>(b-t_w) \\ \dfrac{1}{3}\left(1-0{,}63\dfrac{(h-2t_f)}{(b-t_w)}\right)(b-t_w)(h-2t_f)^3 \; if \; (h-2t_f)<(b-t_w) \end{cases} \quad (3)$$

Eq. (2) is based on theoretical considerations, and is the one proposed in the ARCELOR Sections Commercial Sales Programme. Eq. (3) implicitly considers that the two concrete encasements do not resist in an independent way to torsional shear stresses, but bring to the cross-section an additive torsional stiffness equal to that of a concrete rectangle whose dimensions are $(b - t_w) \times (h - 2\, t_f)$. This is physically consistent with the practical way such beams are built, because of the presence of shear studs on both sides of the web.

The value of the warping stiffness, EI_ω, is supposed to be equal to that of the sole I-shaped profile, for sake of simplicity.

3.3 Calculation of EI_z

In the same way as for GI_t, the concrete in the encasement is influencing the weak axis stiffness EI_z; in order to be consistent both with the *elastic* concept of critical load and with the non linear behaviour of concrete (zero resistance in tension), it is suggested to calculate EI_z as follows:

$$EI_{z,tot} = EI_{z,steel} + EI_{z,concrete} \quad (4)$$

where $EI_{z,concrete}$ is determined through an elastic cracked calculation, i. e. by accounting for the stress-strain relationship for concrete as illustrated in Fig. 3:

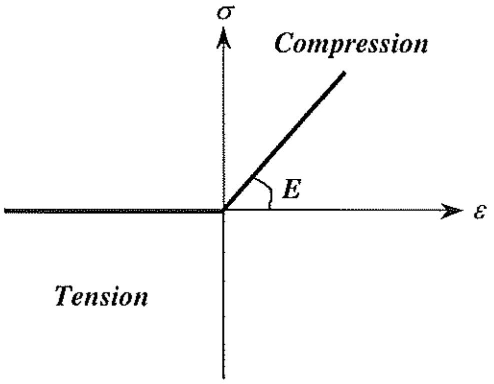

Fig. 3: Elastic behaviour of concrete for linear stability analysis

This procedure provides reasonably accurate results, as shown in [1].

4 VALIDATION OF PROPOSAL

4.1 SAFIR software as validation tool

In order to estimate the accuracy and safety of the proposed method, a validation study has been performed, through an extensive comparison with results provided by the software SAFIR ([3]). SAFIR is a non-linear FEM software, developed at the University of Liège (M&S Department), which is devoted to the study of structures submitted to fire.

Each analysis consists of two steps: the first one is the discretization of the cross-section into fibres, and the second one the non-linear analysis of the whole member. The results provided by SAFIR are then not only useful for the evaluation of M_u, but also to check the accuracy of the cross-sectional properties GI_t and EI_ω determined according to § 3.2.

4.2 Saint-Venant's torsional stiffness GI_t for partially encased beams

As a first step in the evaluation of M_{cr}, the Saint-Venant's torsional stiffness GI_t is required (cf. § 3.1). In order to check the accuracy of the set of formulae proposed in § 3.2, a validation work has been carried out.

Table 1: Validation of the analytical calculation of GI_t

Profiles (number)	*Mean error on GI_t (%)*	*Standard deviation σ (%)*
IPE (5)	16.1	0.9
IPEA (5)	12.8	0.8
HEAA (20)	14.0	2.2
HEA (20)	15.4	2.1
HEB (20)	18.7	2.1
HEM (20)	25.6	3.1

Table 1 summarizes the differences between the results got through Eq. (1) to (3) and SAFIR on a large number of I-shaped cross-sections; SAFIR results are taken as a reference.

At first sight, the differences appear relatively important (up to 25.6%). However, it may be shown that this difference has only a significant impact on the ultimate bending resistance in the cases where lateral torsional buckling effects are important, what is not at all the case in the present study (rolled profiles partially encased). As a consequence, a rough estimation of GI_t is assumed to be sufficient here. Furthermore, GI_t is not the sole cross-sectional stiffness involved in the value of M_{cr}.

As a conclusion, the differences reported in Table 1 are fully acceptable. The standard deviation values σ, all lower than 3,5%, confirm the reasonable accuracy of the formulae.

4.3 Critical bending moment M_{cr}

In this paragraph, the accuracy of the evaluation process of M_{cr} for partially encased beams is checked. M_{cr} not only includes the effects of GI_t, but also the influence of EI_z (cf. § 3.3) and EI_ω. Table 2 and Table 3 show results on I-profiles particularly sensitive to lateral torsional buckling.

Table 2: Validation of the calculation process for M_{cr} *on IPE 500 profile*

	$M_{cr\,SAFIR}$ *(kNm)*	$M_{cr\,method}$ *(kNm)*	*Error (%)*
L= 5 m	5718	5188	10.2
L= 8 m	3420	3232	5.8
L= 15 m	1748	1721	1.6
L= 20 m	1305	1290	1.2

As can be seen, the results get through SAFIR ([1]) are in close agreement with the proposed method, the maximum difference only reaching 10%. And as explained above, a high accuracy on the values of M_{cr} is not really decisive for the precision of the full method in the case of partially encased beams. Accordingly, the proposed calculation procedure appears to be fully satisfactory for design purposes.

Table 3: Validation of the calculation process for M_{cr} *on HEA 1000 profile*

	$M_{cr\ SAFIR}$ *(kNm)*	$M_{cr\ method}$ *(kNm)*	*Error (%)*
L= 15 m	12660	11875	6.6
L= 20 m	9358	8899	5.2

4.4 Bending resistance

Once the plastic resistance M_{pl}, on one hand, and the critical resistance M_{cr}, on the other hand, are determined, the ultimate bending resistance M_u of partially encased beams can be easily calculated through the successive calculation of a relative slenderness and a reduction factor to be applied on M_{pl} (see § 3.1). The last parameter to be chosen to fully validate the method is the appropriate buckling curve, i. e. the imperfection parameter α.

Several calculations, including the effects of yield strength, bending moment distribution, length and type of profile (see [1], [2]) have shown that the buckling curve "*a*", according to EN 1993-1-1 ($\alpha = 0{,}21$), leads to quite satisfactory results, the maximum difference between the non linear FEM SAFIR calculation and the proposed method being less than 5% and almost all results being on the safe side. The proposed method is then found safe and accurate.

5 DEVELOPMENT OF A DEDICATED SOFTWARE

According to the above-described method, a windows-type stand-alone software has been developed. The aim was to propose a practical tool that could be used for a rapid verification of the beam in the erection phase.

Indeed, whenever a verification is performed for the *erection* phase, then the profile is normally known, because the design of the beam is most of the time only done for the *service* phase of the building. Then, the need for a rapid verification tool in the erection phase is obvious, in order to ensure the sufficient resistance of the beam under these particular load cases and restraints.

This software, named LATORCON, has been developed by PSP Technologien GmbH, Aachen (Germany). It allows rapid and user-friendly calculations, both for serviceability and ultimate limit states for the construction phase. It may be freely downloaded on the ARCELOR web site (www.sections.arcelor.com).

6 PARAMETRIC STUDIES

A method and a related design tool being available, two parametric studies on beams in the erection phase have been performed, in order to evaluate the influences of the type of profile, beam length, span of the metal sheeting and yield strength. Paragraphs 6.1 and 6.2, which are respectively dedicated to partially encased beams and beams restrained by metal sheeting, underlines the main conclusions of these studies.

6.1 Partially encased beams

The most important conclusion for design purposes that can be drawn from the parametric study is that the behaviour of partially encased beams, even in the construction phase, is mostly influenced by *resistance* aspects, i. e. the *instability* phenomena have very little influence. Nevertheless, the little decrease of resistance, characterised by χ_{LT} values just below unity, needs to be taken into consideration.

It also showed that the serviceability criterion is most of the time governing the maximum possible length. This can be quite easily solved through beams pre-cambering.

6.2 Influence of metal sheeting

The second parametric study was dedicated to the stabilising influence of metal sheeting on beams during the erection phase. It can be shown that the steel sheet may have a non-negligible stiffening effect on the ultimate resistance of the system, as Fig. 4 shows. Nevertheless, this influence is almost negligible in the case of partially encased beams, because the improvement of stiffness induced by the steel sheet is small compared to the significant GI_t and EI_z stiffness of such beams (cf. Fig. 4).

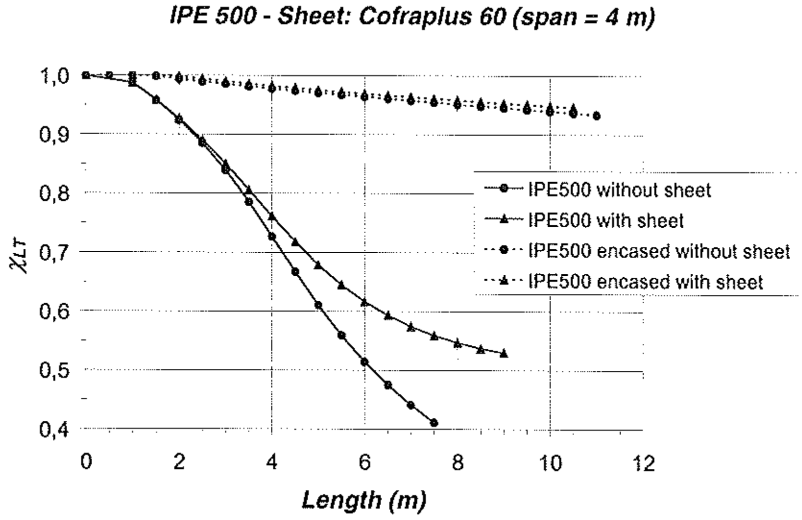

Fig. 4: Influence of metal sheeting on the bending resistance

7 CONCLUSION

The aim of this paper was to present a general method for the verification of composite beams in the erection phase, with a particular attention to the lateral torsional buckling phenomena. The proposed method, that needs to be suitable for design offices, appears to be quick and easy-to-use while accurate.

It is based on a “hybrid method”, which mixes both analytical and numerical approaches to get the final resistance of the beam. It has been developed and validated for a general application field, including partially encased beams and beams restrained by metal sheeting.

Finally, it is worth mentioning that the method has been implemented in an stand-alone windows-type software, free for download on internet.

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