NEW SIMPLIFIED ANALYTICAL METHOD FOR THE PREDICTION OF GLOBAL STABILITY OF STEEL AND COMPOSITE SWAY FRAMES

Jean-François Demonceau[1], Lam Ly[2], Ludivine Comeliau[3] & Jean-Pierre Jaspart[4]

ABSTRACT

Eurocode 4 is the European design code for composite construction; in its so-called EN 1994-1-1 version, the design of "non-sway buildings" is mainly covered. As a result, EC4 focuses on the check of structural elements like beams, columns, slabs and joints. However, in the last years, the construction of taller buildings and larger industrial halls without wind bracing systems tends to make global instability a relevant failure mode, which is not well covered by Eurocode 4. Recently, intensive experimental, numerical and theoretical investigations have been carried out at Liège University. The latter aimed at improving the knowledge in the field of sway composite building frames and at developing appropriate design rules. The rotational behavior of the beam-to-column composite joints is one of the key aspects of the problem to which a special attention has been paid. This paper reflects investigations carried out at Liege University on this topic. In particular, an innovative simplified analytical method to predict the ultimate loading factor and the associated collapse mode of both steel and composite frames subjected to static loadings is presented.

1 INTRODUCTION

Most composite structures are laterally restrained by efficient bracing systems, such as concrete cores. This practice does not favor the use of composite structures. Indeed, once concrete construction companies are

[1] Jean-François Demonceau, Assistant, Liège University, Argenco department, Chemin des Chevreuils, 1, 4000 Liège, Belgium.
[2] Lam Ly, Assistant, Liège University, Argenco department, Chemin des Chevreuils, 1, 4000 Liège, Belgium.
[3] Ludivine Comeliau, Research Engineer, Liège University, Argenco department, Chemin des Chevreuils, 1, 4000 Liège, Belgium.
[4] Jean-Pierre Jaspart, Professor, Liège University, Argenco department, Chemin des Chevreuils, 1, 4000 Liège, Belgium.

involved into major parts of a building, the reason for using composite structures for subsequent parts is often questionable.

Moment resisting frames offer a flexible solution to the user of the buildings, especially for the internal arrangement and the exploitation of the buildings. When sufficient stiffness and strength with regard to lateral forces are achieved, such frames offer a structural solution, which can resist lateral loads. In seismic regions, properly designed moment resisting frames are the best choice regarding the available ductility and the capacity to dissipate energy. This is stated in Eurocode 8 devoted to earthquake engineering in which high values of the behavior factor are recommended.

These frames are prone to second-order effects; the latter have to be predicted carefully because they may govern the design. First investigations in this field have been carried out; in particular, the applicability of the wind-moment method to unbraced composite frames was first examined in a Ph.D thesis submitted at Nottingham University (Hensman, 1998). As far as the European codes are concerned, Eurocode 4 (EN 1994-1-1, 2004), which deals with composite constructions under static loading, contains mainly design procedures for non-sway composite buildings and gives design rules for composite slabs, beams, columns and joints. That is why a research project on global instability of composite sway frames was funded in 2000 by the European Community for Steel and Coal (Bitar & al, 2006). The objective of this project was to provide background information on the behavior of such frames under static and seismic loads and to provide simplified design rules. Liège University, as part of this project, has contributed to the conducted experimental, numerical and analytical investigations (Demonceau, 2008). In particular, a simplified analytical method aiming at predicting the ultimate load factor of steel and composite sway frames have been developed and validated. The present paper will describe in details the developed method.

A first section briefly describes the preliminary investigations which were requested prior to the development of the simplified analytical method. Then, the developed method is described and its validation through parametrical numerical studies is detailed.

2 PRELIMINARY INVESTIGATIONS

Before the development of the simplified analytical method, some preliminary investigations were conducted with the objective (i) to validate some useful analytical and numerical tools and (ii) to identify the particularities in the behavior of composite sway frames. These preliminary investigations are briefly summarized herein.

2.1 Validation of useful analytical and numerical tools

The behavioral response of the beam-to-column joints is known to significantly influence the global behavior of sway structures. Accordingly, experimental and analytical investigations devoted to the study of the behavior of composite joints were conducted. Through the performed investigations, the use of the so-called “component method”, which is the method recommended in the Eurocodes for the characterization of steel and composite joints, was validated. In particular, the component method was improved in order to be able to predict the response of composite joints subjected to “sagging” moment, situation not actually covered in the codes (Demonceau, 2008) but which can appear in sway frames. Then, a homemade finite element software, called FINELG, used for the prediction of the composite sway frame responses, was validated through a benchmark study (realized amongst European Institutions) and through comparisons with experimental test results performed on composite frames in two European laboratories. At the end of these investigations, the ability of FINELG to accurately simulate the behavior of composite sway frames was demonstrated.

2.2 Identification of the particularities in the behavior of composite sway frames

Composite sway structures present a particularity according to steel ones: the concrete cracking. This phenomenon leads to an amplification of the lateral deflections and, consequently, to an amplification of the second-order effects, which reduces the ultimate resistance of the frames. In other words, for a same number of hinges formed at a given load level in a steel frame and in a composite frame respectively, larger sway displacements are reported in the composite one. Accordingly, numerical and analytical investigations, realized with the previously validated tools, were performed with the objective to characterize the behavior of composite sway frames under static loading (Demonceau, 2004 and Demonceau et al, 2005). In particular, five composite sway frames extracted from actual or tested buildings were numerically studied. From these numerical studies, it was demonstrated that the general behavioral response of such structures to static vertical and horizontal loads is quite similar to the one exhibited by steel sway frames. Starting from this observation, the applicability to composite sway frames of two simplified analytical methods initially dedicated to steel ones was investigated: the "*amplified sway moment method*" and the "*Merchant-Rankine approach*" (respectively based on elastic and plastic design philosophies).

For the "*amplified sway moment method*", it was demonstrated that a good accuracy is obtained when applied to sway composite structures and, so, this method can be recommended for this type of structures.

For the "*Merchant-Rankine approach*", which allows to predict the ultimate load factor of a structure, λ_u, as a function of the plastic load factor, λ_p, obtained through a first-order rigid-plastic analysis and the critical load factor, λ_{cr}, obtained through a critical analysis, it was shown that the conclusions concerning the accuracy of this method which were drawn for steel sway structures (Maquoi et al, 2001) still valid for composite sway structures, i.e the method is *safe* when λ_p is associated to a beam plastic mechanism, *adequate* when λ_p is associated to a combined plastic mechanism and *unsafe* when λ_p is associated to a panel plastic mechanism. Moreover, the nature of the plastic mechanism considered in the Merchant-Rankine approach does not always correspond to the one occurring at failure of the frame (computed through a non-linear analysis), i.e. when λ_u is reached; this phenomenon is due to the second-order effects which differently influence the yielding of the structure according to the nature of the considered plastic mechanism. For instance, if λ_p is associated to a beam plastic mechanism, the ultimate load factor λ_u may be associated to the development of a panel plastic mechanism, as the latter is strongly influenced by the geometrical second-order effects while the beam not (Demonceau, 2008).

According to these observations, it was decided to develop a new simplified analytical method able to predict with a good accuracy the ultimate load factor and its associated collapse mode; this method is presented in the following section.

3 DEVELOPED SIMPLIFIED ANALYTICAL METHOD

The proposed solution is to develop a procedure based on three formulas, one for each type of plastic mechanisms which could appear in a frame (i.e. beam, panel and combined plastic mechanisms):

- Formula1($\lambda_{p,beam}$, λ_{cr}) $\rightarrow$ $\lambda_{u,beam}$;
- Formula2($\lambda_{p,panel}$, λ_{cr}) $\rightarrow$ $\lambda_{u,panel}$;
- Formula3($\lambda_{p,combined}$, λ_{cr}) $\rightarrow$ $\lambda_{u,combined}$.

Through these formulas, three predicted ultimate load factors are computed; the smallest one is then considered as the ultimate load factor of the studied frame: $\lambda_u = \min(\lambda_{u,beam}, \lambda_{u,panel}, \lambda_{u,combined})$.

These new formulas could be derived from the Merchant-Rankine one; in fact, the actual Merchant-Rankine formula could be used as "Formula3" as it was demonstrated in (Maquoi et al, 2001) and in (Demonceau, 2008) that this formula gives satisfactory results for frames with a first-order rigid-plastic mechanism associated to a combined one. Nevertheless, it is chosen to develop these formulas from the Ayrton-Perry formulation (see Table 1), which is already used in the Eurocodes to deal with the member instability phenomena (plane buckling, lateral buckling and lateral torsional buckling); this proposal is in agreement with the recommendation of the last draft of Eurocode 3 (EN 1993-1-1, 2005) where it is stated that such formulation should be used to verify "*the resistance to lateral and lateral torsional buckling for structural components such as single members (built-up or not, uniform or not, with complex support conditions or not) or plane frames or subframes composed of such members which are subject to compression and/or mono-axial bending in the plane...*" (§ 6.3.4 (1) of EN 1993-1-1, 2005*)*. A great advantage is that the Ayrton-Perry formulation implicitly permits to respect the limit conditions which are: (i) when λ_{cr} is very high, no instability phenomena will appear and the failure occur through the appearance of a plastic mechanism ($\lambda_u \rightarrow \lambda_p$) and (ii) when λ_p is very high, no yielding appears in the frame and the failure occurs through an instability phenomenon ($\lambda_u \rightarrow \lambda_{cr}$).

Table 1. From the Ayrton-Perry formulation to the formulas to be included in the new simplified analytical design method

Ayrton-Perry formulation for a column buckling – Eurocode 3		**Formulas included in the new simplified design method for sway frames**
$N_{b,Rd} = \frac{\chi \alpha_{ult,op}}{\gamma_{M1}}$	➡	$\lambda_u = \chi \lambda_p$
$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}_{op}^2}}$	➡	$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}_{op}^2}}$
$\bar{\lambda}_{op} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr,op}}}$	➡	$\bar{\lambda}_{op} = \sqrt{\frac{\lambda_p}{\lambda_{cr}}}$
$\phi = 0,5\left[1 + \alpha(\bar{\lambda}_{op} - \bar{\lambda}_0) + \bar{\lambda}_{op}^2\right]$	➡	$\phi = 0,5\left[1 + \mu(\bar{\lambda}_{op} - \bar{\lambda}_0) + \bar{\lambda}_{op}^2\right]$

Within this formulation, χ is called the reduction factor and $\bar{\lambda}_{op}$ the non-dimensional relative slenderness. The parameter $\bar{\lambda}_0$ represents the length of the plateau in a $\bar{\lambda}_{op}$ - χ graph where χ is equal to 1 (see Figure 1), i.e. the length on which the ultimate resistance is assumed to be equal to the plastic resistance and, accordingly, where the influence of the second-order effects is neglected; as no strain hardening and cladding effects are considered within the presented study, the plateau length is taken equal to 0 as in the Merchant-Rankine approach.

So, to develop this new method, only the parameter μ had to be determined. The parameter μ is used to implicitly take into account of the second order effects within the developed procedure. In fact this parameter influences the shape of the curve presented in Figure 1; the highest μ is, the smallest the reduction factor χ is and, accordingly, the smallest the predicted λ_u is.

Three values of the parameter μ had to be calibrated, one for each plastic mechanism (i.e. μ_{beam} for the beam plastic mechanism, $\mu_{combined}$ for the combined plastic mechanism and μ_{panel} for the panel plastic mechanism), as each type of plastic mechanisms is influenced differently by the second order effects. These values have been calibrated through parametrical studies. At the end of this calibration, it is intended to obtain a higher value of μ for the panel plastic mechanism than the one for the combined plastic mechanism and the latter higher than the one for the beam plastic mechanism ($\rightarrow \mu_{panel} > \mu_{combined} > \mu_{beam}$) as the influence of the second order effects is more important for the panel plastic mechanism than for the combined one and is not significant for the beam plastic mechanism (Demonceau, 2008).

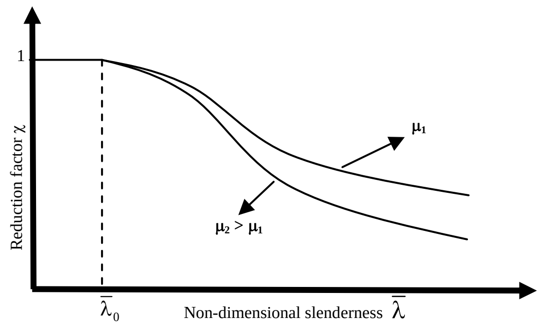

Figure 1. Example of “Ayrton-Perry” curves

As the same problems of accuracy are met with the Merchant-Rankine approach for steel and composite sway frames, the proposed method has been developed for both types of frames. The calibration of the coefficient μ and the validation of the developed method are presented in the following section.

4 CALIBRATION AND VALIDATION OF THE DEVELOPED METHOD

The calibration of the coefficient μ and the validation of the developed method are performed through parametrical studies conducted on steel and composite frames. The predictions obtained through the analytical method are compared to numerical predictions obtained through full non-linear analyses (realized with the previously validated software FINELG), considered as the “reference” results.

4.1 Parametrical study on steel sway frames

4.1.1 Studied steel frames

Within this study, four types of 2-D simple frames have been investigated (Figure 2); in total, 181 frames have been analyzed.

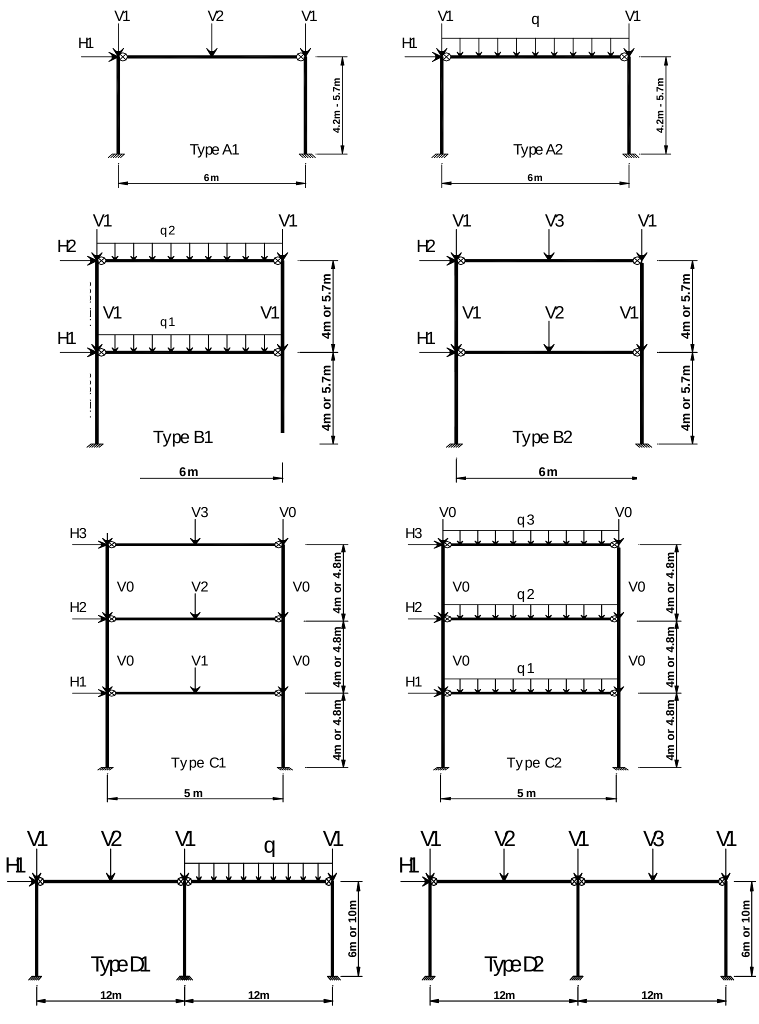

Figure 2. Studied steel frames – Types A, B, C & D

The beams and the columns are steel hot-rolled profiles of class 1 (to be able to develop plastic mechanisms) bent around their major axis; the steel material is modeled through an elastic-plastic behavior law for the non-linear analyses.

The beam-to-column joints are classified as partial-strength and semi-rigid ones with a sufficient ductility to develop plastic hinges and to allow plastic analyses; they are modeled with rotational springs with an elastic-plastic law. The column base joints are assumed to be rigid and fully resistant. The properties of the frames have been defined so as to cover the three types of plastic mechanisms, i.e. beam, combined and panel plastic mechanisms (obtained through first-order rigid-plastic analyses) with each type of structures and to obtain different types of collapse modes (plastic mechanisms or instability) through the full non-linear analyses. The parameters which are modified within these frames are:

- the height of the columns;
- the properties of the joints;
- the beam and column cross sections and;
- the applied loads.

The analyses which have been performed are:

- Critical elastic analyses (λ_{cr});
- First-order rigid-plastic analyses (computation of the three plastic load factors, i.e. $\lambda_{p,beam}$, $\lambda_{p,combined}$ and $\lambda_{p,panel}$);
- Full non-linear analyses (λ_u).

For the computation of λ_{cr} and λ_u, the software FINELG was used. As recommended in Eurocode 3 (EN 1993-1-1, 2005), an initial deformation has been introduced in the computation. The shape of the initial deformation introduced in the computations is proportional to the first global instability mode obtained through the critical elastic analysis (which is in agreement with the Eurocode recommendations); this permits to introduce at the same time a global initial deformation (to initiate P-Δ effects) and local initial deformations for the members (to initiate P-δ effects). For the computation of the plastic load factors, a software (based on an Excel sheet and Visual Basic modules) has been developed and validated through comparisons to numerical results. The M-N interaction in the columns for the computation of the plastic load factors is taken into account through formulas which permit to analytically predict with a very good accuracy the actual M-N interaction curve of a double-T cross section.

4.1.2 Parametrical study results

For each frame, the results obtained with the new method and with the Merchant-Rankine method are compared to the numerical results obtained through non-linear analyses considered as the "reference" ones. The investigated frames were defined so as to cover a wide range of λ_p/λ_{cr} values (from 0,09 to 0,61), λ_p being the minimum value of the three plastic load factors $\lambda_{p,beam}$, $\lambda_{p,combined}$ and $\lambda_{p,panel}$.

The three values of μ, i.e. μ_{beam}, $\mu_{combined}$ and μ_{panel}, have been calibrated so as to minimize the difference between the predicted values of λ_u through the new method and the ones numerically predicted. The three values which have been obtained are the following ones:

- μ_{beam} = 0,07;
- $\mu_{combined}$ = 0,29 and;
- μ_{panel} = 0,596.

The comparison between the predicted values of λ_u obtained through the analytical methods (the new one and the Merchant-Rankine approach) and the numerical simulations is given in Figure 3 and Figure 4 for all the frames.

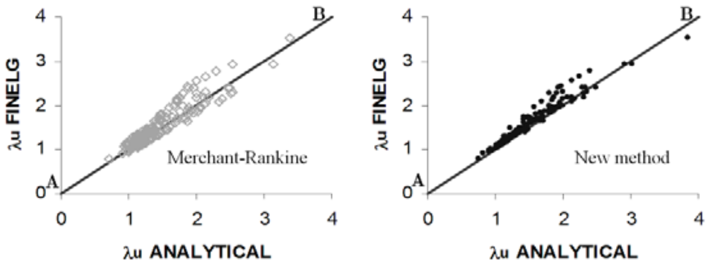

Figure 3. Comparison between the analytical and the numerical results for the prediction of λ_u (all the investigated steel frames)

In Figure 3, the abscissa represents the values of λ_u analytically predicted while the ordinate, the values of λ_u numerically computed. If the analytical methods were perfectly accurate, all the points of the figures would exactly be on the line "AB", i.e. the analytical prediction would be equal to the numerical computation results; so, the more accurate the analytical method is, the closer to the line "AB" the points are. Also, all the points which are in the upper zone of the graph according to the line "AB" are cases where the analytical method underestimates the ultimate load factors (i.e. "safe side" of the graph) while the points in the lower zone are cases where the analytical method overestimates the ultimate load factors (i.e. "unsafe side" of the graph). From Figure 3, it can be observed that the new method gives more accurate results than the Merchant-Rankine approach; indeed, the points obtained with the new method are closer to the line "AB" than the ones obtained with the Merchant-Rankine approach. Also, more points are present on the "unsafe side" of the graph with the Merchant-Rankine approach than with the new method; indeed, the Merchant-Rankine approach is unsafe for 66 cases (i.e. 36 % of the investigated frames) while the new method is unsafe for only 13 cases (i.e. 7 % of the investigated frames).

These observations are confirmed by the graph presented in Figure 4. The latter represents the number of frames which are included in ranges of differences, expressed in %, between the analytical predictions and the numerical results; for instance, it can be seen on this graph that the number of frames for which the difference between the λ_u analytically predicted and the λ_u numerically computed is included in the range [0 % ; 1 %] is equal to 23 with the new method and to 4 with the Merchant-Rankine approach. From Figure 4, it can be observed that the number of frames for which the differences on the value of λ_u is between 0 % and 10 % is equal to 148 with the new method (i.e. 81,8 % of the frames) and to 57 with the Merchant-Rankine approach (i.e. 31,5 % of the frames) which confirms the better accuracy of the proposed method.

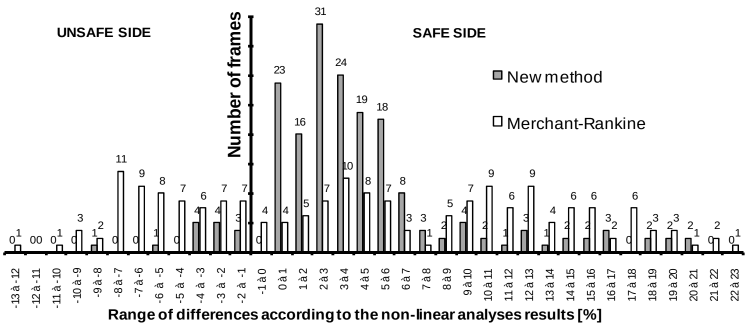

Figure 4. Evaluation of the accuracy of the analytical methods (all the investigated steel frames)

Also, as mentioned previously, the collapse mode associated to the ultimate load factor λ_u does not necessary correspond to the one associated to the plastic load factor λ_p; it reflects the situation of 112 of the investigated frames. It is interesting to underline that, with the new method, the type of plastic mechanism associated to the minimum value of λ_u corresponds to the one appearing through the fully non-linear numerical analysis for 93 % of the investigated frames.

In the presented results, the Merchant-Rankine approach is applied to all the frames with values of the λ_p/λ_{cr} ratio from 0,09 to 0,61; however, it is recommended to apply this approach to structures with this ratio between 0,1 and 0,25. If only the frames respecting this condition are considered (which is the case for 133 of the investigated structures), the previous observations are still valid; in particular:

- Only 4 unsafe situations (i.e. 3 % of the considered frames) are obtained with the new method for 45 (i.e. 34 % of the considered frames) with the Merchant-Rankine approach.
- The number of frames for which the differences on the value of λ_u is between 0 % and 10 % is now equal to 123 with the new method (i.e. 92,5 % of the considered frames) and to 47 with the Merchant-Rankine approach (i.e. 35,3 % of the considered frames) what confirms the better accuracy of the proposed method.
- The type of plastic mechanism associated to the minimum value of λ_u obtained with the proposed new method corresponds to the one appearing through the full non-linear numerical analysis for 93 % of the investigated frames.

4.2 Parametrical study on composite sway frames

4.2.1 Studied composite frames

Within this study, three types of 2-D simple frames have been investigated (Figure 5); in total, 199 frames have been studied. Different types of structural elements are met within the investigated frames as described here below:

- Two types of composite beam configurations bent around their major axis:
  - upper hot-rolled profile flange fully connected to a concrete slab or;
  - upper hot-rolled profile flange fully connected to a composite slab.
- Two types of columns bent around their major axis:
  - steel hot-rolled profile ones or;
  - partially encased composite ones.
- The beam-to-column composite joints are rigid or semi-rigid ones and full-strength or partial-strength ones; the column bases are assumed to be rigid and fully resistant. The beam-to-

column joints are assumed to have a sufficient ductility to develop plastic hinges and to allow a plastic analysis.

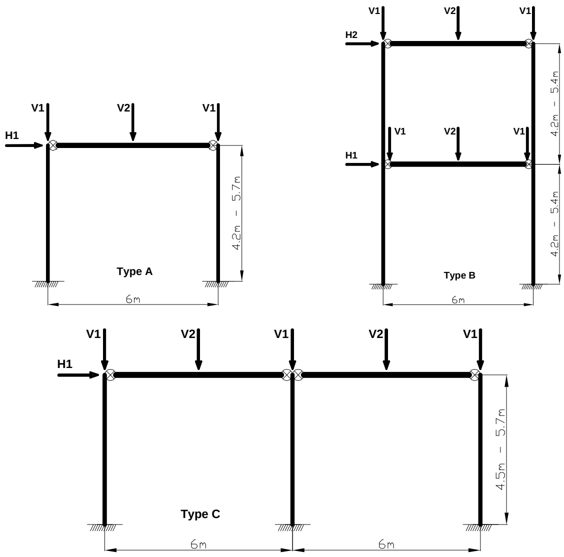

Figure 5. Studied composite frames - Type A, B and C

For the numerical simulations, the steel material and the joint behavior are modeled through an elastic-perfectly plastic bilinear law. For the concrete material, a parabolic behavior law with account of tension stiffening is used.

As for the parametrical study performed on the steel frames, the properties of the frames have been defined so as to cover the three types of plastic mechanisms, i.e. beam, combined and panel plastic mechanisms (obtained through first-order rigid-plastic analyses) for each type of structures and to obtain different types of collapse modes (plastic mechanisms or instability) through the full non-linear analyses. The parameters which are modified within these frames are:

- the type of structural elements (as mentioned previously);
- the height of the columns;
- the properties of the joints;
- the beam and column cross sections and;
- the applied loads.

For the computation of λ_{cr} and λ_u, the software FINELG has been used. As recommended in Eurocode 4 (En 1994-1-1, 2005), an initial deformation has been introduced in the computation. Also, as for the steel frames, the shape of the initial deformation introduced in the computations is proportional to the first global instability mode obtained through the critical elastic analysis. For the computation of the plastic load factors, a software based on an Excel sheet has been developed and validated through comparisons to numerical results. The M-N interaction in the columns for the computation of the plastic load factors has been taken into account.

4.2.2 Parametrical study results

The investigated frames were defined so as to cover a wide range of λ_p/λ_{cr} values (from 0,05 to 0,31). The three values of μ, i.e. μ_{beam}, $\mu_{combined}$ and μ_{panel}, calibrated so as to minimize the difference between the predicted values of λ_u through the new method and the ones numerically predicted are the following ones:

- μ_{beam} = 0,02;
- $\mu_{combined}$ = 0,42 and;
- μ_{panel} = 0,7.

It can be observed that these coefficients are higher than the ones calibrated for the steel structures (except for the values corresponding to the beam plastic mechanism which are very close), which means that, for a composite structure and a steel structure with the same value of λ_{cr} and the same values of plastic load factors $\lambda_{p,beam}$, $\lambda_{p,combined}$ and $\lambda_{p,panel}$, the ultimate load factor λ_u obtained through the new method would be smaller for the composite structure than for the steel one.

This observation is in line with the remark on the effect of concrete cracking reported previously; this phenomenon leads to an amplification of the lateral deflections and, consequently, to an amplification of the second-order effects, which reduces the ultimate resistance of the frames. In other words, for a same number of hinges formed at a given load level in a steel frame and in a composite frame respectively, larger sway displacements are reported in the composite one. So, this particularity is reflected within the developed method through the "μ" values which are higher for composite sway frames than for the steel ones. The fact that the μ factors associated to the beam plastic mechanism are very closed can be explained by the small influence of the second order effects on this type of collapse mode.

The comparison between the predicted values of λ_u obtained through the analytical methods (the new one and the Merchant-Rankine approach) and the numerical simulations is given in Figure 6 and Figure 7 for all the frames.

From Figure 6, it can be observed, as for the steel sway frames, that the new method gives more accurate results than the Merchant-Rankine approach; also, more points on the "unsafe side" of the graph are present with the Merchant-Rankine approach than with the new method (the Merchant-Rankine approach is unsafe for 81 cases, i.e. 40,7 % of the investigated frames, while the new method is unsafe for only 15 cases, i.e. 7,5 % of the investigated frames).

From Figure 7, it can be observed that the number of frames for which the difference between the analytically predicted values of λ_u and the numerical ones is between 0 % and 10 % is equal to 167 with the new method (i.e. 83,9 % of the frames) and to 51 with the Merchant-Rankine approach (i.e. 25,6 % of the frames) which confirms the better accuracy of the proposed method.

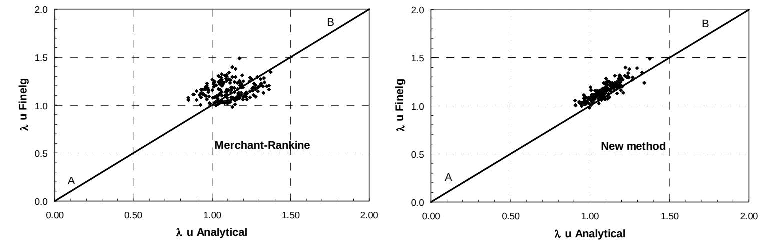

Figure 6. Comparison between the analytical and the numerical results for the prediction of λ_u (all the investigated composite frames)

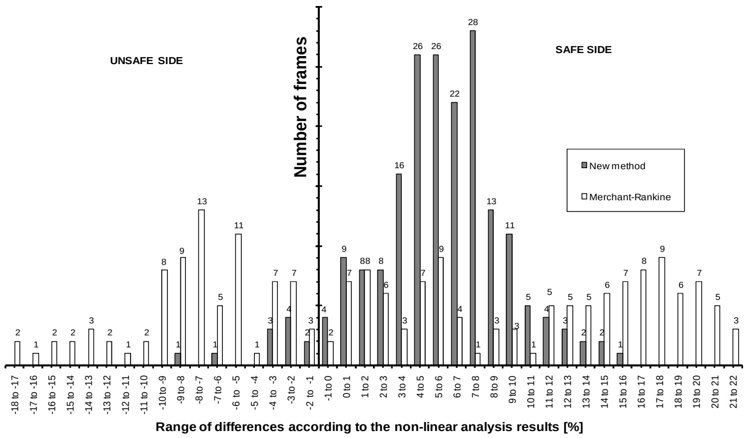

Figure 7. Evaluation of the accuracy of the analytical methods (all the investigated composite frames)

Also, amongst the investigated composite frames, there are cases (38 in total, i.e. 19,1 % of the investigated composite frames) where the collapse mode associated to λ_u do not correspond to the one associated to λ_p. It is interesting to underline that, with the new method, the type of plastic mechanism associated to the minimum value of λ_u corresponds to the one appearing through the fully non-linear numerical analysis for 99,5 % of the investigated frames.

As previously mentioned, it is recommended to apply the Merchant-Rankine method to structures with a λ_p/λ_{cr} between 0,1 and 0,25. If only the frames respecting this condition are considered (which is the case for 150 of the investigated composite structures), the previous observations are still valid:

- Only 13 unsafe situations (i.e. 8,7 % of the considered frames) are obtained with the new method for 57 (i.e. 38 % of the considered frames) with the Merchant-Rankine approach.
- The number of frames for which the difference on the value of λ_u is between 0 % and 10 % is now equal to 131 with the new method (i.e. 87,3 % of the considered frames) and to 40 with the Merchant-Rankine approach (i.e. 26,7 % of the considered frames), which confirms the better accuracy of the proposed method.
- The type of plastic mechanism associated to the minimum value of λ_u obtained with the proposed new method corresponds to the one appearing through the fully non-linear numerical analysis for 100 % of the investigated frames.

5 CONCLUSIONS

In the last years, the construction of taller composite buildings and larger composite industrial halls without wind bracing systems tends to make global instability a relevant failure mode, which is not well covered by Eurocode 4.

Within the present paper, an innovative simplified analytical method, in full agreement with the Eurocode recommendations, aiming at predicting the ultimate load factor and the associated collapse mode of steel and composite sway frames has been presented. The latter has been validated through parametrical studies; in particular, the very good accuracy of the developed method was demonstrated.

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