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Stiffness Design of Column Bases

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ABSTRACT

M y research actions have been devoted during the last decade to the study of the beam-to-column steel and composite joints, but less to column bases which ensure the link between the structure and the foundation. The behaviour of column bases in rotation is however influencing in a significant way the whole structural response of the building frames, and an accurate appraisal of this influence is likely to allow a precise evaluation of the structural safety as well as substantial benefits in terms of fabrication and erection costs. The present paper is aimed at giving an overview of the recent progress made in this field in the frame of the COST European Action. First the influence of the column base characteristics in rotation on the structural frame response is discussed and specific design criteria for stiffness classification into semi-rigid and rigid joints are derived. The particular case of an industrial portal frame is then considered. Finally, the background of the models for the analytical prediction of the stiffness, strength and ductility properties of the column bases which are presently in development at the European level is briefly summarised.

KEYWORDS
Civil Engineering, Steel Structures, Connection Design, Column Bases, Semi-Rigid Response. Strength Design, Stiffness Design, Classification.

1 INTRODUCTION

The impact of an appropriate joint design on the total costs of a building frame, including fabrication and erection costs, has no more to be demonstrated. As a consequence numerous intensive research actions have been devoted to this topic during the last decade in order:

- to derive design models for the analytical prediction of the stiffness, strength and ductility properties of beam-to-column joints and beam splices;
- to extent the scope of structural analysis procedures to so-called semi-rigid joints;
- to develop specific pre-design and design procedures enabling to take full profit of the actual joint response.

Besides the research activity, normative documents have been prepared in the form of:

- a revised Annex J on "Joints in Steel Building Frames" [2] to Eurocode 3 [1];
- an Annex J on "Joints in Composite Building Frames" [4] to Eurocode 4 [3].

In order to facilitate the use of the new concepts for joints in the industrial practice, design guidelines have also been prepared [5]; they cover the different aspects of the problem (local joint response, influence on frame, ...) and provide the designer with appropriate design tools for joints (design tables, design sheets and software). These design guidelines have been widely discussed at the European level, and in particular within the Committee 10 of the European Convention for Constructional Steelwork (ECCS); they should be printed soon as European recommendations.

Column bases have received much less attention. These ones connect the structure to the foundation mostly through the use of base plates, but configurations with embedded columns, possibly combined with base plates, are sometimes preferred. In this field, locally oriented research activities may only be reflected:

- prediction models for resistance and stiffness [15] based on a limited number of experimental tests;
- fixed predefined values of the stiffness of the column bases [10];
- soil interaction in the case of column bases with bolts located inside the column cross-section; a low influence of soil deformations is seen in typical practical cases [12].
- set of experiments [13] completing the design recommendations for cyclic behaviour under seismic action [6];
- Penserini - Colson's model based on component damages and aimed at predicting the cyclic response [14];
- study of the cyclic behaviour of base plates [9] and its influence on frame cyclic and dynamic response;
- work in Prague on column bases with base plates and embedded columns [25], [26] under static loading: experimental tests [16] -[20], [27] and prediction models [7],[23], [24];
- experimental tests [8], [21] in Liège and development of a simple analytical model and a complex mechanical model for the prediction of the static behaviour of column bases with two or four anchor bolts [8].

In Eurocode 3 revised Annex J [2], the component method is proposed as a tool for the prediction of the rotational behaviour of beam-to-column joints and beam splices. This is a three-step approach in which:

- the list of the active components within the joint is first established (bolt in tension, end-plate in bending, ...);
- the properties of the active components subjected to compressive, tensile or shear forces are derived (elastic deformation, resistance, ductility);
- the properties of the active components are « assembled » so as to derive the main characteristics of the joint as a whole (initial stiffness in rotation, moment resistance, rotation capacity).

Some recent experimental and theoretical works have be devoted to the application of the component method to the stiffness and strength prediction of the column bases ([7],[8],[18],[21],[23]).

In the present paper, the influence of the rotational behaviour of column bases on the structural response of building frames is first discussed, and in the second part, information on the ongoing research activity dealing with the application of the component method to column bases is given.

2 COLUMN BASES IN NON-SWAY FRAMES

2.1 Influence on the structural response of the frames

A modification of the actual moment-rotation characteristic of column bases is likely to affect the whole response of non-sway frames, and in particular the lateral displacements of the beams and the buckling resistance of the column. This second aspect - the buckling resistance of the columns - is the one for which the influence is rather important, as seen in Fig. 1 which shows how the buckling length coefficient of a column pinned at the upper extremity is affected by the variation of the column base rotational stiffness. The buckling length coefficient K is reported on the vertical axis and is expressed as the ratio between the elastic critical load ($F_{cr,pin}$) of the column pinned at both extremities and that of the same column but restrained by the column base at the lower extremity ($F_{cr,res}$); it is shown to vary from *1,0* (pinned - pinned support conditions) to *0,7* (pinned - fixed support conditions).

$$K = \sqrt{\frac{F_{cr,pin}}{F_{cr,res}}} \tag{1}$$

$$F_{cr,pin} = \frac{\pi^2 E\, I_c}{L_c^2} \tag{2.a}$$

Semi-rigid column bases: $S_{j,ini} < 12\,E\,I_c\,/\,L_c$ (10.b)

Such an approach allows to classify the column bases according to the column properties only. A more precise boundary dependent on the k_u coefficient could obviously be derived but its application would be more complicated, and this seems not to be in line with the expected simplicity.

A similar stiffness boundary could be defined, on the same basis, for pinned joints. The value obtained is however so low that few actual column bases are likely to exhibit such a lower initial stiffness. On the other hand, in the present case, the boundary is an upper value, and even if the actual joint stiffness is higher, nothing may prevent the designer to consider still the joint as pinned, as it is presently done in design. As a consequence, no pinned classification boundary is derived and proposed here.

3 COLUMN BASES IN SWAY FRAMES

3.1 Influence on the structural response of the frames

The sway frames are more sensitive than non-sway ones to the variation of the rotational properties of column bases, mainly because of their high sensitivity to lateral deflections as well as to changes of the overall stability conditions when the lateral flexibility increases.

To illustrate this statement, a single-bay single-storey sway frame is considered in Fig. 3. The diagram indicates the evolution with increasing values of $\overline{S}$ of the ratio $\beta_s = y_S / y_P$ between the lateral deflection y_S of the frame with actual column base stiffness and the deflection y_P of the frame with assumed ideally pinned column bases. The non-dimensional stiffness $\overline{S}$ defined by Equation (3) is again reported in a logarithmic scale. First order elastic theory is used to compute the y values.

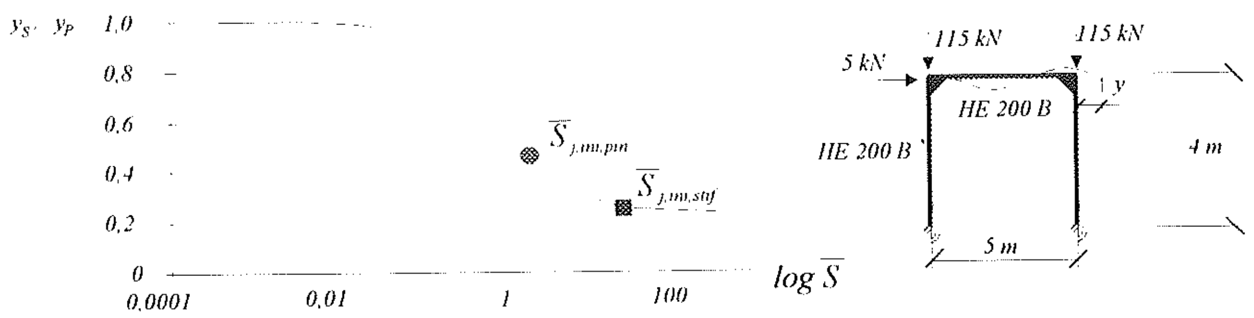

Fig. 3 Sensitivity of the sway deflection to a variation of the column base stiffness in a portal frame

3.2 Stiffness classification

A stiffness classification boundary similar to that expressed in the case of non-sway frames may again be derived here on the basis of a "5% resistance criterion". For sway frames also it may be demonstrated that the more restrictive situation corresponds to the limit case where the beam flexural stiffness is rather high in comparison with that of the columns. The derivation of the classification boundary is therefore carried out by referring to the isolated column represented in Fig. 4.b.

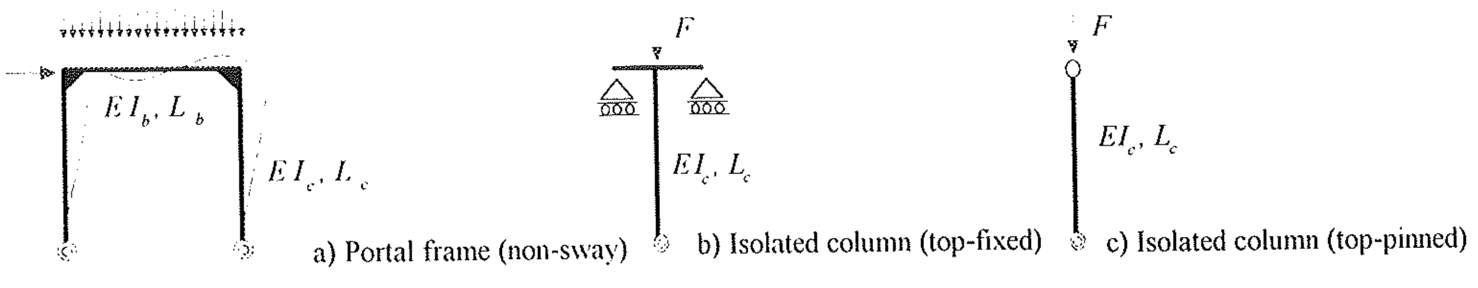

Fig. 4 Sway portal frame and isolated columns for classification study

The application of the "5% resistance criterion" writes in this case:

$$\frac{\dfrac{\pi^2 EI_c}{(KL_c)^2}}{\dfrac{\pi^2 EI_c}{(L_c)^2}} \geq 0{,}95 \tag{11}$$

As a result:

$$K \leq 1{,}026 \tag{12}$$

For sway frames, the K - k relationship given by Equation (6) has to be replaced by the following:

$$K = \sqrt{\frac{1-0{,}2\,(k_l+k_u)-0{,}24\,k_l\,k_u}{1-0{,}8\,(k_l+k_u)+0{,}6\,k_l\,k_u}} \tag{13}$$

while Equations (7.a) and (7.b) remain unchanged. The combination of these equations leads to the following expression of the stiffness classification boundary:

$$S_{j,ini} \geq 11\,E\,I_c \;/\; L_c \tag{14}$$

However the "5% resistance criterion" fully disregards the aspects of lateral frame deflections which have been pointed out as rather important in Section 3.1. It may be shown [22], that the lateral deflection y_s of the portal frame illustrated in Fig. 4.a writes:

$$y_S = \frac{F\,L_c^{\,3}}{2\,E\,I_c}\,\frac{1}{12}\,\frac{4\,(3+\bar{S})+6\,(4+\bar{S})\,\varsigma}{\bar{S}+6\,(1+\bar{S})\,\varsigma}. \tag{15}$$

where:

$$\bar{S} = \frac{S_{j,ini}}{E\,I_c \;/\; L_c} \tag{16}$$

$$\varsigma = \frac{E\,I_b \;/\; L_b}{E\,I_c \;/\; L_c} \tag{17}$$

For $\bar{S} \Rightarrow \infty$, the deflection for the frame with rigid column bases may be derived from (15):

$$y_R = \frac{F\,L_c^{\,3}}{2E\,I_c}\,\frac{1}{12}\,\frac{4+6\,\varsigma}{1+6\,\varsigma}, \tag{18}$$

In comparison with the case where rigid column bases are used (Formula 18), the actual frame - where the column bases possesses some degree of flexibility - will experience a larger deflection (Formula 15); this increase of the lateral displacement may be expressed in terms of percentage w as follows:

$$\frac{y_S}{y_R} = 1+\omega \tag{19}$$

As far as classification is concerned, an "ω% resistance criterion" may be suggested with the objective to limit the increase of the lateral displacement of the actual frame to ω% of the deflection evaluated in the case of rigid column bases. In Formula (19), this means that the sign "=" should be replaced by "≤" By combining expressions (15), (18) and (19), the value of the minimum rotational that the column bases should exhibit to be considered as rigid from a displacement point of view is derived:

$$\bar{S} \geq \frac{12 + 24\varsigma - 6\varsigma(1+\omega)\dfrac{4+6\varsigma}{1+6\varsigma}}{(4+6\varsigma)\omega} \tag{20}$$

This condition is illustrated in Fig. 5. The required stiffness is seen to be rather insensitive to the values of ς for significant values of w. Conservatively the values obtained for $\varsigma = 0,1$ may be selected, i.e.:

- for $\omega = 20\%$, the following stiffness boundary is obtained: $\bar{S} \geq 15$
- for $\omega = 10\%$ $\bar{S} \geq 30$
- for $\omega = 5\%$ $\bar{S} \geq 60$.

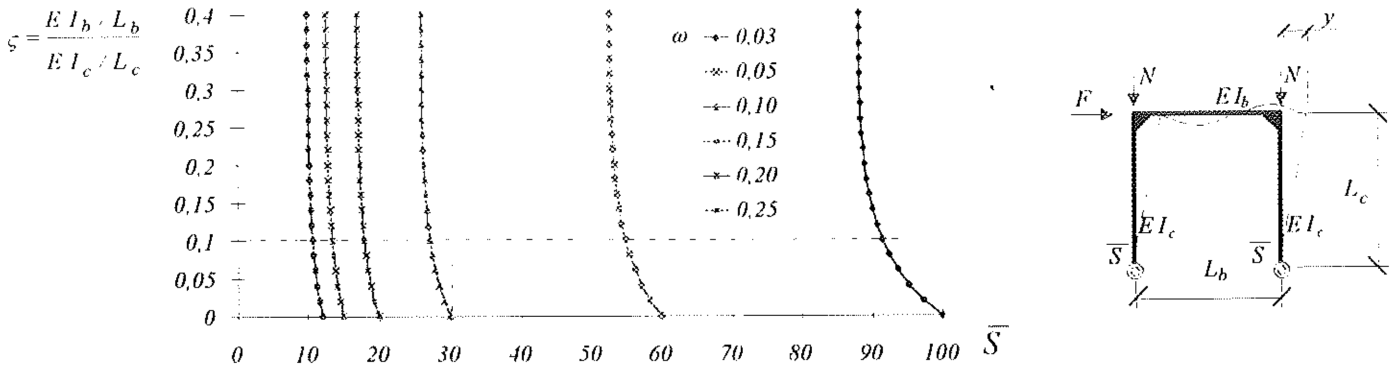

Fig. 5 Displacement classification criteria for column bases

As a consequence, the displacement classification criterion is seen to be much more restrictive than the resistance one given by Equation (14). The selection of the value for the boundary is obviously strongly related to the level of accuracy which is thought to be necessary for the evaluation of the lateral frame deflection. A value of 10% appears to be quite realistic and the following stiffness classification boundary for presumably rigid column bases may be therefore proposed:

Rigid column bases: $S_{j,ini} \geq 30\, E\, I_c \;\; L_c$ (21.a)

Semi-rigid column bases: $S_{j,ini} < 30\, E\, I_c \,/\, L_c$ (21.b)

F r similar reasons than those given in Section 2.2, no classification boundary for presumably pinned column bases is suggested.

4 EXAMPLE OF BENEFICIAL EFFECT OF COLUMN BASES ON STRUCTURAL RESPONSE

The industrial portal frame represented in Fig. 6 is chosen to demonstrate the potential benefit which may result from a refined design approach based on the actual rotational characteristics of the column bases. Two geometrical types of base plates, respectively with two bolts inside the column and four bolts outside the column are considered.

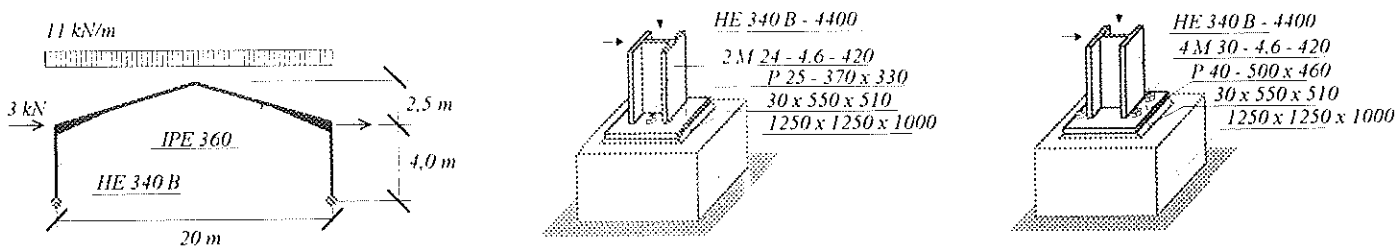

Fig. 6 Example of a portal frame

The frame is first designed for ultimate limit states with pinned column bases and rigid beam-to-column joints. But the maximum sway of the frame is the predominant design parameter ($L_c / 150$) and pinned column bases do not allow to fulfil this criterion, as seen in Figure 7. However the conclusion is quite different when the actual properties of the column bases are taken into consideration (stiffness computed according [19]). In a second step, the frame is designed by assuming rigid column bases and then by introducing their actual stiffness characteristic in the analysis (stiffness again computed from [19]). The difference between the corresponding sway deflections amounts 9% (y = *0,0189* and *0,0197* in Fig. 7). The classification stiffness boundary suggested in Section 3.2 (Formulae 21) equals 17331 kNm/rad while the computed stiffness amounts 17363 kNm/rad. The actual column base may then be considered as presumably rigid; this is confirmed by the fact that the above-mentioned difference in deflections is limited to 9%, i.e. is lower than 10%.

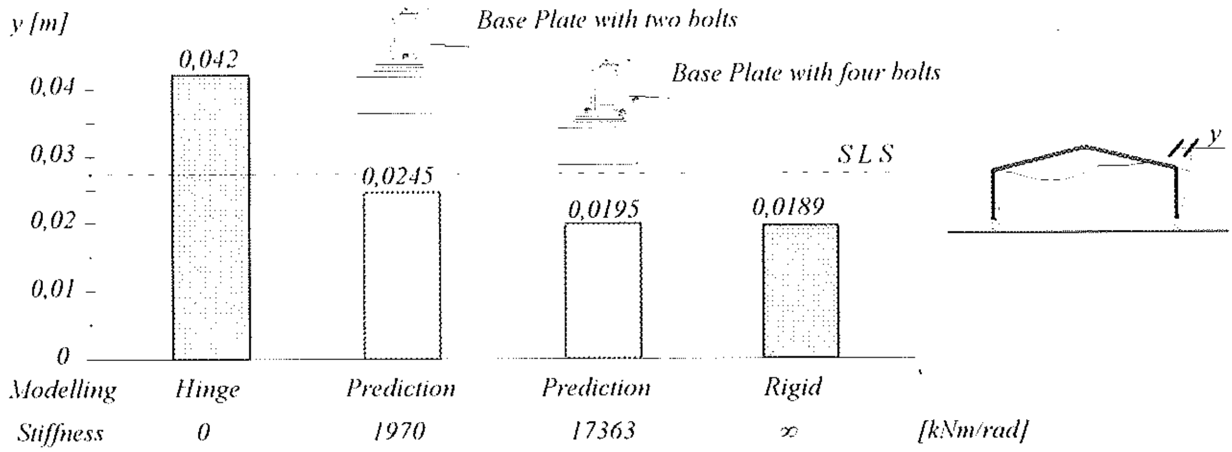

Fig. 7 Sway deflections for different types of column bases

5 PREDICTION OF THE ROTATIONAL PROPERTIES

Two levels of "connection" may be identified in column bases: the connection between the steel column profile and the concrete foundation, on the one hand, and the connection between the concrete foundation and the soil, on the other hand. The latter requires different means of investigation and is influenced by different probabilistic criteria [19]. This problem is not treated here.

For the first level of connection, indications on how to compute the resistance are provided in Annex L of Eurocode 3 [1]. For the evaluation of the stiffness and the deformation capacity, no guidelines are given. This differs from the revised Annex J of Eurocode 3 where detailed information is given for the prediction of the stiffness, strength and ductility properties of beam-to-column joints and beam splices.

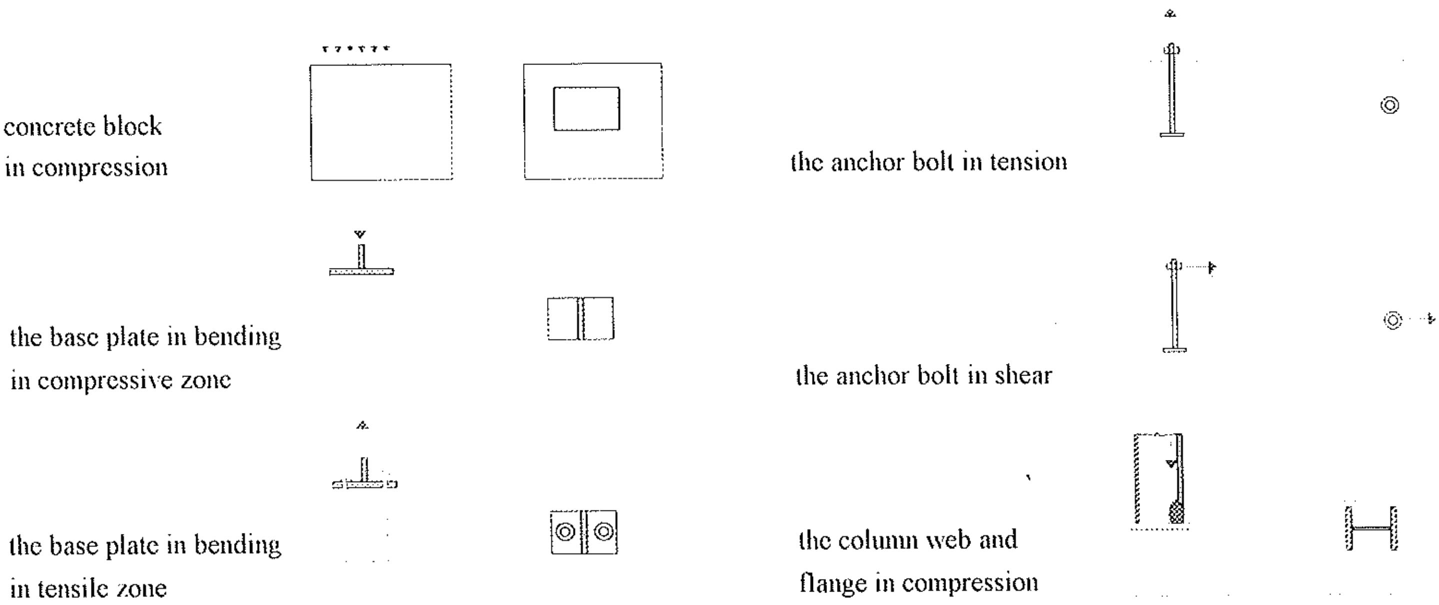

Fig. 8 The main components of the column base with base plates

In the frame of the activities of the COST C1 European Project and of the Committee 10 of ECCS, some works have however be initiated at the Technical University of Prague and at the University of Liège to investigate the possibility to extend the principle of the component method used in EC3 Annex J to column bases. Static experimental tests on components and full column bases have been carried out and introduced in databases ([25], [26]). They have been used to validate the first analytical models proposed ([8], [16]-[18], [20], [21], [27]).

Fig. 8 presents the list of components to be considered for column bases with base plates. The characterisation of the components in terms of stiffness, resistance and ductility is an important step. It is followed by the so-called assembly of the components which allows to distribute the internal forces between the components and then to derive the rotational properties of the whole column base.

6 CONCLUSIONS

- The introduction of the column base stiffness into the global frame analysis can bring important savings in structural costs. In particular for the industrial portal frames pinned at their foundations, it allows much more easier to fulfil the requirements for serviceability limit state by taking full profit of the rotational restraint that column bases usually designed as pinned are often able to exhibit.
- Eurocode 3 [1] proposes to classify the joints into rigid, semi-rigid and pinned ones; specific classification boundaries for column bases are suggested in the present paper. They are illustrated in Fig. 9.
- In a near future design rules for the characterisation of column bases should be available through the activities of an ECCS / COST C1 ad-hoc working group. They should be in line with the principles of the component method used in Eurocode 3 revised Annex J for beam-to-column joints and beam splices.

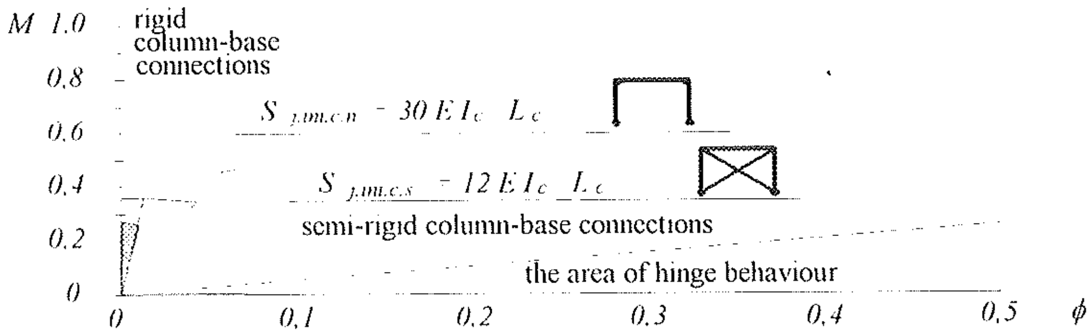

Fig. 9 Proposed classification system according to the initial stiffness

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The ad-hoc working group presently involved if the preparation of an European Manual for Column Base Design and which is referred to in Section 5 is composed of: Mr. Brown, SCI London; Mr. Gresnigt, TU Delft; Dr. Jaspart, University of Liége; Prof. Stark, TU Delft; Mr. Steenhuis, TNO Delft; Dr. Wald, CTU Praha; Dr. Weynand, RTWH Aachen.

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