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Fundamental Concepts of Joints in Design of Steel Structures

Regarding joints, the first fundamental concept the engineer must be clear about when he or she starts to design is which connections will develop moment resistance and which can be executed as simple pin joints. To do this, it is necessary to clarify the lateral load resisting system.

1.1 Pin Connections and Moment Resisting Connections

1.1.1 Safety, Performance, and Costs

Steel structures should be safe, able to perform, and be cost-effective.

They must be safe because they act as canopies, mezzanines, buildings, skyscrapers, bridges, and much more that give shelter, protect, and be welcoming to men and women. A structural collapse is extremely dangerous and likely to cause severe harm to anyone in the surrounding area.

Structures must also effectively serve their commercial purpose while efficiently and comfortably (for the users) maintaining their design features over time. These are the basic notions of serviceability limit state design specifying that, just as a nonlimiting example, deformations will not damage secondary structures or that excessive vibrations will not make users uncomfortable.

Poor performance might also decrease the structure’s value and harm the property owner.

Simultaneously, the market logic requires that the structural system be economically sound and cost-effective when compared to alternatives using different materials and design. Being economically sound is a complex matter that must take into account many factors in the building design. However, the engineer must make the structure as cost-effective as possible without compromising safety and performance. The service and expertise that engineers are expected to deliver should include reducing costs while maintaining high standards of functionality and protection.

For the principles stated, the design of connections is a focal point and it must be well defined in the engineer’s mind from the commencement of the project.

Design and Analysis of Connections in Steel Structures: Fundamentals and Examples,
First Edition. Alfredo Boracchini.

1.1.2 Lateral Load Resisting System

The choice of connections is related to the choice of the lateral load resisting system.

Taking a closer look at this key point, we consider these initial hypotheses: that the structure geometry is defined, that steel will be used as structural material, and that the design loads are provided. This means that the engineer can set up the analysis model with the finite element software available. However, before building the model wireframe, the engineer must have a clear vision of the lateral resisting system(s). This choice influences costs and architectural restraints.

Lateral load resisting systems can be diverse and variously combined among themselves. Each horizontal direction can have its own system, one that may be different from the other direction.

The basic lateral resisting systems (Figure 1.1) are as follows:

- Braces (bracings)
- Moment connections (portals)
- Base rigid restraints (cantilever columns or inverted pendulum)
- Connection to an existing structure or another ad hoc structure built with different materials (say a concrete staircase, masonry or concrete walls, etc.).

The structural engineer attentive to fabrication logics usually tries to adopt bracings as this will deliver maximum cost performance. The main advantages of using braces are as follows:

- The structure is easily sized against horizontal forces (mainly wind and earthquakes) allowing less weight for beams and, most of all, columns (braces take care of lateral forces and the column can work only in compression).
- Connections can roughly be just in shear or axial action and so are light and economic.
- Lateral deflection control is excellent.
- Seismic response is good (given that the necessary detailing is provided).

At the same time bracing has some disadvantages:

- It laterally obstructs the transit, limiting windows or gates.
- The architect or the owner might not like it for esthetic reasons.

This last problem might be solved by "highlighting" the braces and assigning architectural importance to them. Some famous examples can be found, such as landmark skyscrapers (Figure 1.2) and more "ordinary" buildings (Figure 1.3), where the architect was able to create an interesting contrast with materials that nicely emphasize the braces.

The problem of transit obstruction is usually bypassed by choosing one specific bay for braces, if possible. This is done either in the middle or at the end of the building system. Horizontal braces are implemented to bring forces to the localized braces. (This book does not discuss the layout of horizontal braces. Rather it discusses one of their main functions, beyond limiting flexural torsional buckling of beams, that is, to connect unbraced bays to braced ones.)

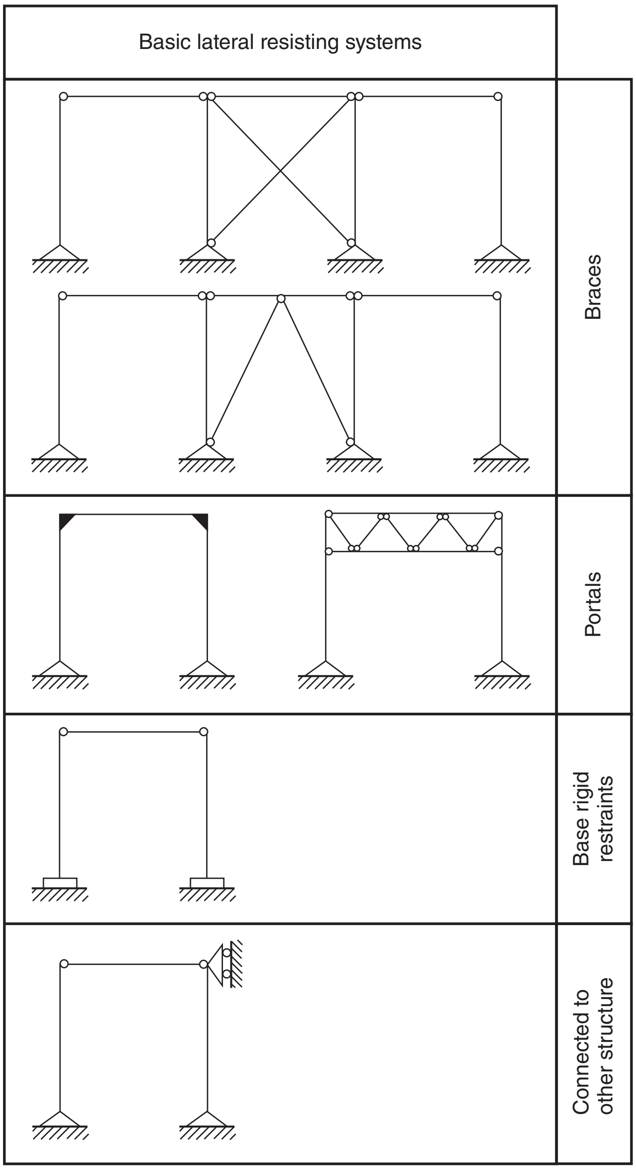

Figure 1.1 Lateral load resisting systems.

Another method to limit the obstruction in the space occupied by the braces is to adapt their geometry to the challenges of architectural restraints using different schemes and shapes (V, inverted-V, X, K, Y, and more).

Having given the many advantages of using braces and the importance of informing the owner and the other players about this solution in order to have it approved, in many situations it is not possible to use braces, especially in both directions. As a consequence, it is necessary to use portals or base rigid

Figure 1.2 Braces emphasized esthetically in the John Hancock Tower of Chicago. Source: From Wikipedia; photo courtesy of "Akadavid", 2008.

connections or a combination of them, if not different additional schemes such as shear steel walls or other concrete or composite systems that are outside the scope of this book.

The main advantage of using portals and rigid bases is what made braces undesirable; that is, there are no obstacles in fully exploiting all the space of the bays. In addition, moment resisting systems (by the way, it is not trivial to underline that a system made by trusses and columns is a specific case of a portal) have the following advantages:

- Possible savings (at the expense of the dimension and cost of the columns) in beam depth since the moment connection allows a better exploitation of the beam strength along the full length.
- A more "convincing" look of the columns that, being heavier, seem safer.
- Pin (hinge) connections at the base, then savings in foundation work (larger even compared to braces, which could give an uplift and require more expensive tension details and some "ballasting" of the plinths).
- Reasonable seismic resistance (if the necessary detailing is followed).

Figure 1.3 Valorization of internal braces (InterPuls, Reggio Emilia, Italy).

Disadvantages of portals might be the following:

- Moment connections are required and they are usually complex and more expensive.
- Additional encumbrance may be provided by the beam-to-column connection (net height at the eaves is impacted and this could make it mandatory to raise the whole structure); also, the obstruction given by trusses is similarly and evidently large.
- On average, the weight per unit of area will worsen.
- Lateral deflections should be checked carefully.
- Buckling length of columns worsens.

A lateral resisting system having the columns rigidly connected to the base may have the following benefits:

- No obstructed bays, as already mentioned.
- Larger columns inspiring more confidence in the safety of the building.

The following are some of the disadvantages:

- Expensive foundation work required: large plinths, piles likely mandatory
- Lateral deflections to check (but usually better than portals)
- More material (steel) necessary to build the structure
- Longer buckling length of columns
- Poor seismic performance (for example, the American Society of Civil Engineers (ASCE) basically bans this system for buildings if the area is highly seismic (see Ref. [1] for more precise information)).

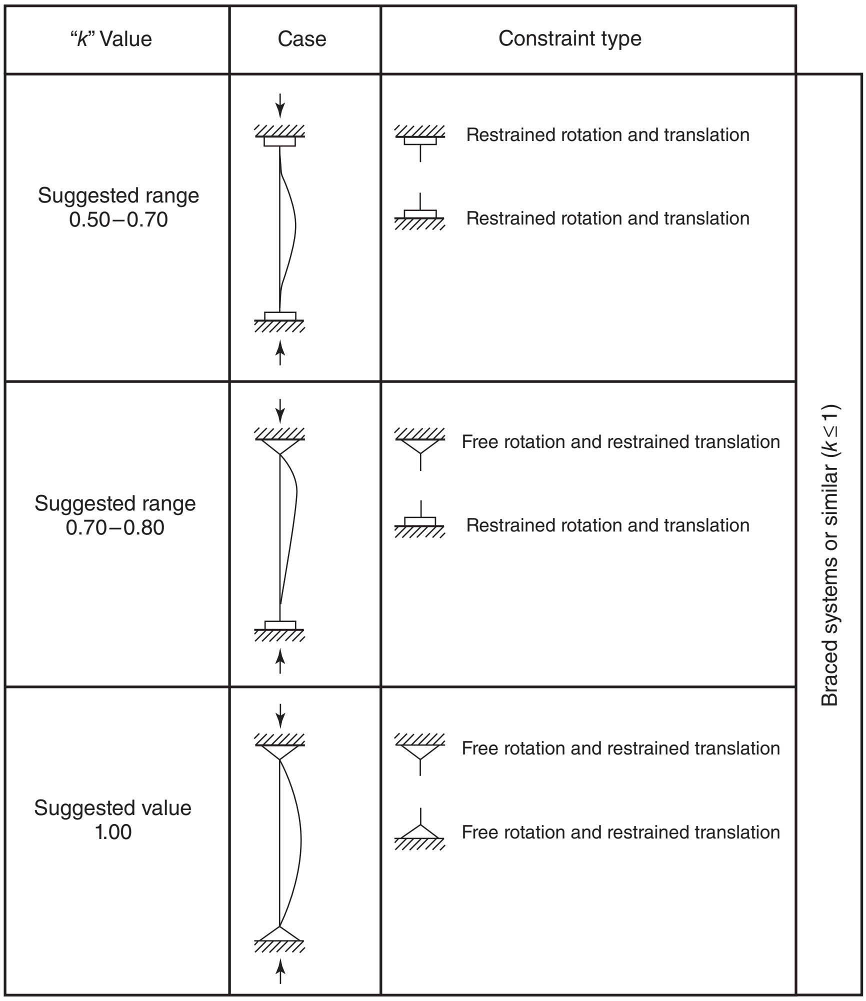

Figure 1.4 Buckling length coefficients (effective length factors) for braced systems.

Sometimes, to solve the problems of lateral deflections and column buckling length (see Figures 1.4 and 1.5 for reference values), both systems are contemporarily adopted.

As Figure 1.5 shows, the buckling length of columns is two times the physical length in each system when taken by itself, but it goes back to almost unity (braced systems have 1) when used in a combined system.

Every situation is different and braces are not always the best option. For example, if the structure has large bays (beyond 20 m, or 60 ft) and that direction already uses trusses in its architectural layout, it is already a moment resisting system that can be exploited as a lateral resisting system. Braces can be used only in the orthogonal direction, effectively restraining the weak side of the columns.

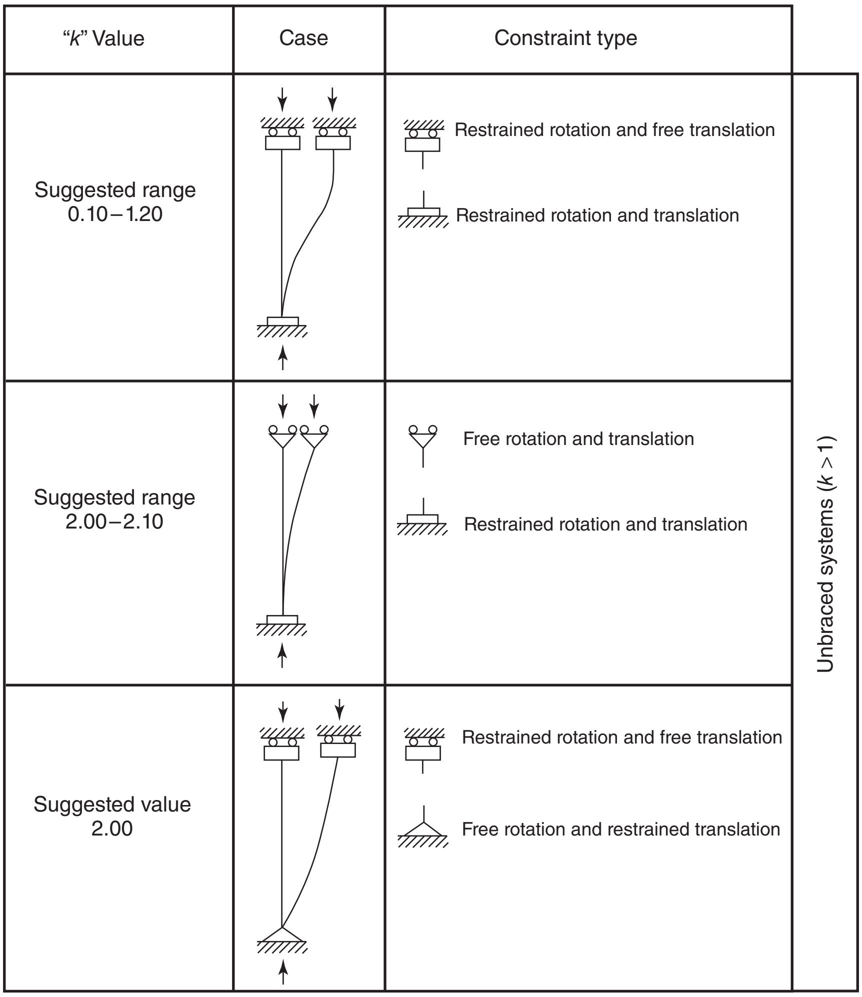

Figure 1.5 Buckling length coefficients (effective length factors) for unbraced systems.

An engineer with a clear understanding of a lateral load resisting system will correctly prioritize and evaluate, in any situation, the benefits of each option, choosing the best method with regards to economy, safety, and performance.

1.1.3 Pins and Fully Restrained Joints in the Analysis Model

As described, the designer must choose the lateral load resisting system, in agreement with the architect and the owner, before setting up the analysis model.

It is important to underline that the matter should not be considered to the owner in terms that are too technical, that is, the problem should not be introduced as a choice of lateral load resisting system. Rather, the designer should talk about this from an architectural perspective, where braces can be placed and about the economic and performance benefits that braces can bring. Where bracing is not accepted, for esthetic or other reasons, the engineer must think about the alternatives previously illustrated.

Only at this point will the engineer know where in the design model to put *fully restrained joints* and where it is possible to unrestrain beams and to consider their connections as *pins* (*hinges*).

Not taking into account possible decisions of having beams in continuity (therefore fully restrained) to help deflections and the final weight, all the connections that are not necessary for global stability (that is, to the lateral resisting system when it is a portal or an inverted pendulum) should be considered as pins. This is conservative and helps the project budget.

If an engineer who is not familiar with structural steel develops a model without careful consideration of the lateral load resisting system and the connections among members, it could severely impact the project. If the entire model has rigid connections, the structure could be underdesigned and unstable if the joints are not correctly dimensioned and realized as fully restrained. Also, in the event that the joints are correctly fabricated as rigid, the competitive price of a similar fully restrained system with complex and labor-intensive connections is suspicious.

To summarize, the correct order to follow during the design stage is as follows:

- Choose the lateral resisting system(s).
- Model as fully restrained the joints that are strictly necessary for this purpose (overall stability).
- Model as pins (hinges) all the other connections.
- Design the structure.
- Decide if stiffening some joints (from pin to fully restrained) can be beneficial to the total weight or deflections.
- Design the connections.

If following Eurocode (EC), the additional steps are:

- Calculate joint rigidity.
- Check if the assumptions in the model are consistent with the results of joint rigidity (pin or fully restrained joints).
- If necessary, update the calculation model; if needed, use joint springs in the model to simulate exact rigidity (semirigid joints).
- When necessary, rerun the analysis.

According to the classical elastic method, it is not required to check connection rigidity because the experience of the engineer is enough to assess this. However, some standards (EC primarily) have started to ask for an analytical check of this component.

1.2 Plastic Hinge

In contrast to reinforced concrete where simple supports and fully restrained connections are more easily understandable because the physical connection is similar to the ideal, this concept is less intuitive with regards to steel.

If a concrete construction has a beam leaning on a girder (a true simple support), in constructions made of steel the connections that are considered as hinges (pins) might not be immediately recognizable as such to designers unfamiliar with the material.

Hinge/pin connections are neither real pins nor simple supports. They are initially able to resist bending moments, more or less relevant in absolute value. The engineer must indeed learn that the experience (in the sense of the history of structural engineering) and the ductility of the material makes this kind of connection representable as a pin, and years of structural steel buildings have shown that this approach is both sound and reliable. This also means that it is not conservative to assign calculation moments to these kinds of connections, especially if those bending moments are essential to the overall stability of the structure. In fact, the steel is ductile and the material will become plastic when the yield limit is reached and there are no brittle or buckling behaviors. This means that the connection will develop into a hinge, thus redistributing forces. This explains why some joints that do not look like pin connections are represented as such in the design practice.

As mentioned in the previous section, intermediate behavior (semirigid) is discussed, for example in EC and AISC (partially restrained (PR) joints), but it is crucial that the designer comprehends the plastic hinge concept that has been used for many years in steel construction. With this in mind, we take a closer look at two typical examples of welded connections in trusses and base plates.

1.2.1 Base Plates

Base plates can be represented as either hinges or fully restrained joints.

It is not necessary to physically realize a “real pin” to represent a base plate as a pin connection. This method was used several years ago, as seen in the example of the Milan railway station in Figure 1.6. Nowadays, it is not considered necessary to put, for example, only one row of anchor bolts in order to have a pin because even configurations like the ones illustrated in Figure 1.7 have enough ductility to be considered as hinges: any yield due to an initial bending moment will make the connection evolve to a plastic state, similar to a hinge. This means that it is conservative and conventional to consider the joint as a pin (and the bending moment that can be resisted at least initially is an additional benefit). Many books, including [2], agree on this concept, explicitly articulating on the subject. French standards partially disagree since they take into account Yvon Lescouarc’h’s publications [3, 4], which set limits for the representations of base connections as pins. Another important concept that seems to give credit to [2] is that the plate-to-column systems (with stiffeners in case) and the base plate-to-concrete systems are always stiffer than the concrete-to-soil systems. Therefore, the behavior of the joint will depend on how the foundation is designed and realized: if an initial moment creates any settlement in the foundation, the whole connection system will behave like a hinge since the locally low stiffness will activate a more rigid lateral load resisting system.

In other words, it is the engineer’s choice whether the base joint is considered as a pin or a fully restrained connection. To arrive at a decision, he or she will

Figure 1.6 Column bases at the Milan Central Railway Station. Source: Picture courtesy of Massimiliano Manzini.

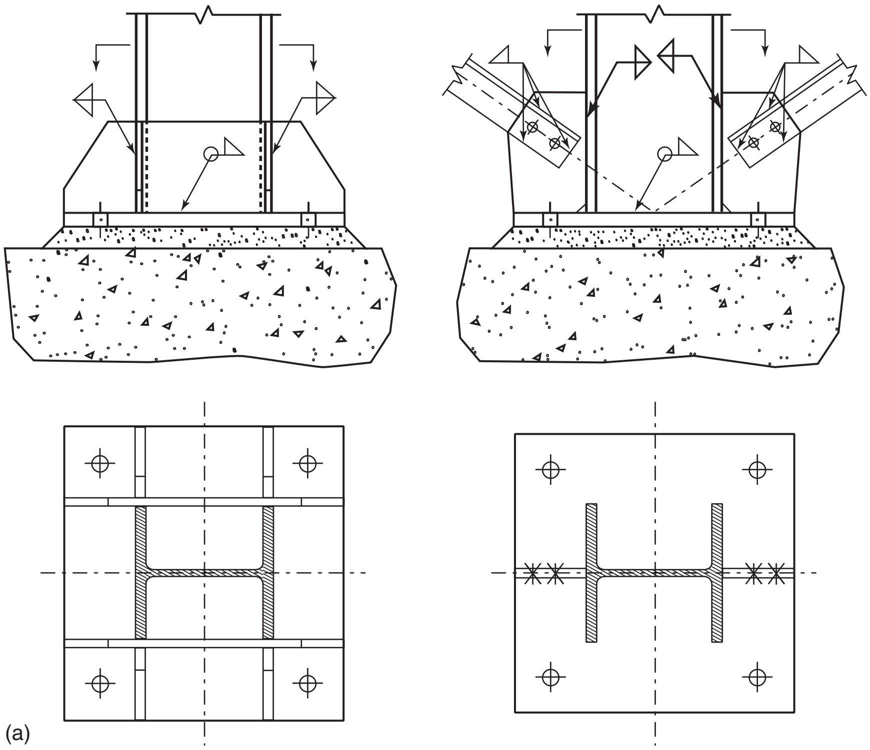

Figure 1.7 Base plate configurations that can be considered (last one excluded) as either a pin or a fully restrained connection. Source: Taken from [2].

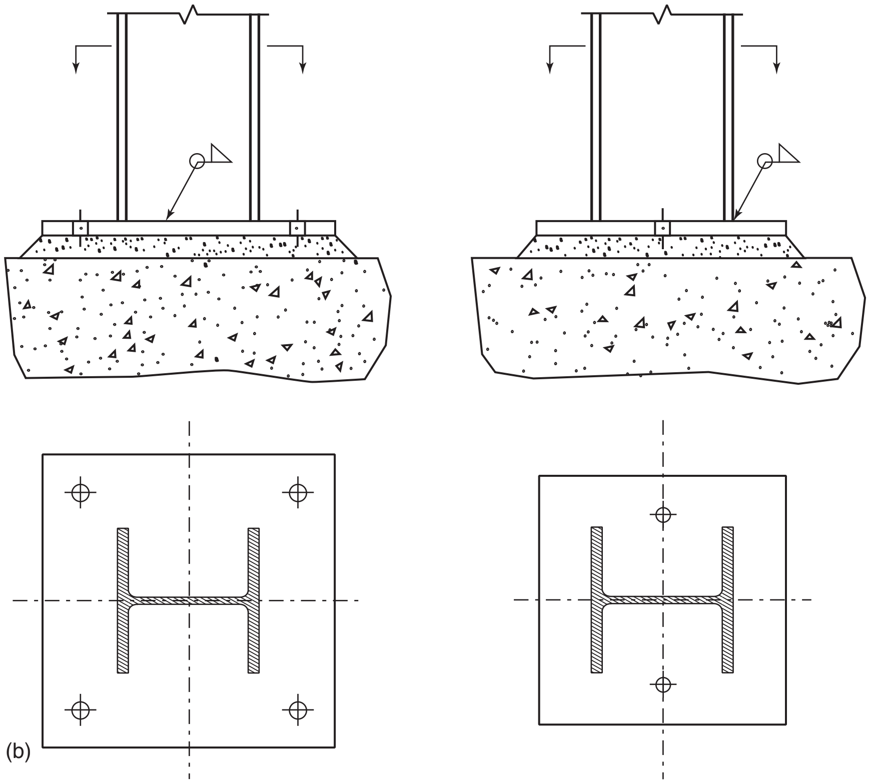

Figure 1.7 (*Continued*)

consider the lateral resisting system, the importance of lowering lateral displacements or adding hyperstatic restraints to better resist design forces (therefore saving some material but adding labor), and the characteristics of the foundation system and the soil (foundation costs are heavily impacted if rigid restraints have to be adopted).

The designer must carefully evaluate special situations: the project may be about designing a mezzanine inside an existing building/warehouse, leaning on the existing slab that should not be modified (due to either costs or possible delays in production); if a bending moment threatens to shear punch the concrete slab, it is certainly advisable to realize the connection with only a row of anchor bolts or without stiffening details in order to avoid any considerable moment, even if only initial.

1.2.2 Trusses

Truss connections are normally considered as pinned, even when welded (and the effective length factor taken as 1). The reason is that a plastic hinge will form: Even if the connection is initially rigid and able to resist non-negligible moments, it becomes a hinge after the material yields.

The history of steel construction confirms this method (and structural scheme) as conservative if the effective length factor is not taken less than 1 (which is the correct coefficient when the plastic hinges are in place).

References

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2 Ballio, G. and Mazzolani, F. (1983). *Theory and Design of Steel Structures*. London: Taylor & Francis.
3 Lescouarc'h, Y. (1982). *Le pied de poteaux articulés en acier*: CTICM. www.cticm.org (accessed 22 January 2018).
4 Lescouarc'h, Y. (1998). *Le pied de poteaux encastrés en acier*: CTICM. www.cticm.org (accessed 22 January 2018).