PAPER NUMBER: 63

Economy Studies of Steel Building Frames with Semi-Rigid Joints

K. Weynand[1], J.-P. Jaspart[2] and M. Steenhuis[3]

[1] Institute of Steel Construction, RWTH Aachen,
Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany
[2] MSM Department, University of Liège,
Quai Banning 6, 4000 Liège, Belgium
[3] Dept. of Structural Engineering, TNO Building and Construction Research
P.O. Box 49, 2600 AA Delft, The Netherlands

ABSTRACT

The traditional design of steel structures assumes for global frame analysis either rigid joints, typically in case of unbraced frames, or pinned joints, typically for braced frames. The design of the joints is usually performed independently of the frame analysis and the design of the members. Consequently it must satisfy the initial assumptions made in the frame analysis. For unbraced frames this may lead to uneconomical solutions for the joint detailing, e.g. when stiffening of the columns or haunches for the beams are needed to satisfy the stiffness requirements assumed in the frame analysis. In case of braced frames unfavourable moment distribution may cause uneconomical solutions for the choice of member sections, i.e. the weight of the structure.

Modern standards for steel design like Eurocode 3 allow to take into account the actual joint behaviour, i.e. semi-rigid and/or partial strength joints. Because of this they enable new concepts and strategies for economical design of steel structures where both the choice of members and detailing of the joints are done with respect to economy. Depending on the structural system, i.e. braced or unbraced frames, the designer can find optimum solutions by minimizing the weight of the structure or by simplifying joint detailing.

This paper discusses such aspects to find optimum solutions as well as the impact of the joint classification on economy. It presents existing and new comparative studies on the economy of steel building frames which are designed according to the traditional and the new concept respectively. The various studies on two- and three-dimensional frames are carried out in cooperation with steel construction industry in different countries and show possible cost savings for different design conditions.

KEYWORDS

Joints, Economy, Costs, Classification, Rigid, Semi-rigid, Partial-strength, Unbraced Frames, Braced Frames.

PAPER NUMBER: 63

Economy Studies of Steel Building Frames with Semi-Rigid Joints

K. Weynand[1], J.-P. Jaspart[2] and M. Steenhuis[3]

[1] Institute of Steel Construction, RWTH Aachen,
Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany
[2] MSM Department, University of Liège,
Quai Banning 6, 4000 Liège, Belgium
[3] Dept. of Structural Engineering, TNO Building and Construction Research
P.O. Box 49, 2600 AA Delft, The Netherlands

ABSTRACT

The traditional design of steel structures assumes for global frame analysis either rigid or pinned joints. Consequently the design of the joints must satisfy these initial assumptions in terms of joint behaviour. This may lead to uneconomical solutions for the joint detailing or for the choice of member sections.

Modern standards for steel design like Eurocode 3 allow to take into account the actual joint behaviour, i.e. semi-rigid and/or partial-strength. Because of this they enable new concepts and strategies for economical design of steel structures. This paper discusses opportunities for optimum solutions as well as the impact of the joint classification on economy. It presents existing and new comparative studies on the economy of steel building frames which are designed according to the traditional and the new concept respectively.

KEYWORDS

Joints, Economy, Costs, Classification, Rigid, Semi-rigid, Partial-strength, Unbraced Frames, Braced Frames.

INTRODUCTION

In the traditional approach for the design of steel building frames the modelling of the joints is such that the moment-rotation behaviour is either pinned or rigid, see Figure 1. This approach includes assumptions for the stiffness of the joints. However most standards for the design of steel structures contain models which allow for a resistance check only. A check of the stiffness is not possible because of the absence of appropriate models. If only two extreme cases for the modelling of the joints are available, the possibilities for the detailing of the joints are limited. In case of rigid joints, the joints must be stiffened in many cases in order to ensure that the actual joint behaviour fulfils the assumptions used in the frame analysis. Because of unavailable stiffness models, sometimes stiffeners are added 'to be sure' to be rigid. In Germany for example such 'extra' stiffeners are sometimes called 'Angststeifen' ('Angst' = fear, 'Steifen' = stiffeners).

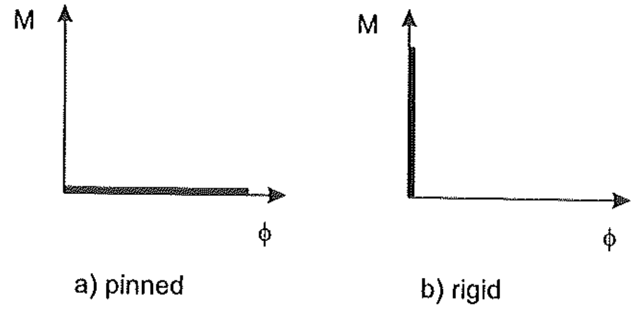


Figure 1: Traditional modelling of the moment-rotation behaviour of joints

To overcome this problem, in Eurocode 3 two important models are introduced:

- a stiffness model and
- a classification system.

The latter is necessary in order to check, for example, whether a joint behaves as rigid. It is important to know that a real joint never behaves as infinite stiff. However with a classification system it is possible to check whether a joint with a certain stiffness may be modelled as rigid, i.e. the frame response will not significantly change due to the actual stiffness of the joint compared to the ideal assumption that a joint is infinite stiff. In Eurocode 3 it is stated that 'the deformations of rigid joints should be such that they do not reduce the resistance of the structure by more than 5 %.'

For the practitioners, it seems more complicated to introduce new concepts, because this could lead to extra work for the designer. However this concept gives new possibilities for a 'clever' design of structures: it gives more freedom in joint detailing. The layout of such joints can be chosen according to economy. In general, any joint stiffness may be taken into account. However with the classification system in certain cases it is possible to avoid using a rotational spring when the joints are modelled for the frame analysis. It is not more difficult to include the joint behaviour in the calculation of the structure, if frame analysis programs are available which allow to take the joint stiffness into consideration. For the calculation of the joint properties appropriate design tools (design sheets, design tables, software) can be provided to the designer.

The aim of this paper is to discuss different aspects and strategies how to achieve possible economical benefits. It summarizes existing and new comparative studies on the economy of steel building frames which are designed according to the traditional and the new concept respectively.

SAVINGS OF FABRICATION AND ERECTION COSTS

Optimal Detailing of Rigid Joints

A first very efficient strategy can be summarized as follows:

> *"Optimize the joint detailing such that the joint stiffness comes close to the "rigid" classification boundary but remains higher".*

This is illustrated in Figure 2.

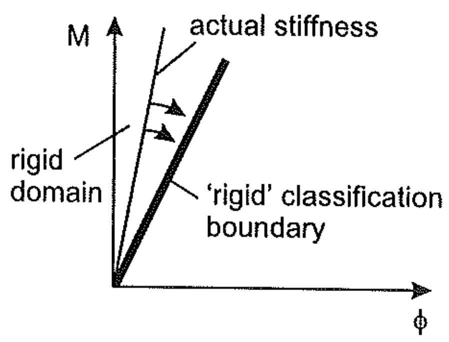


Figure 2: Optimization of rigid joints

The actual stiffness of a joint as well the classification boundary for rigid joints can be calculated according to Eurocode 3. The classification boundary is the minimum stiffness required to model a joint as rigid. If the actual joint stiffness is significantly higher, e.g. due to stiffeners, it should be checked whether it is not possible to omit some of the stiffeners while still fulfilling the criterion for rigid joints. This will not change the overall design at all, but it will directly reduce the fabrication costs of the joints (e.g. less welding). This procedure is used by Jaspart (1995) in the example described below:

The joints of a typical portal frame (see Figure 3) were designed using traditional design practice.

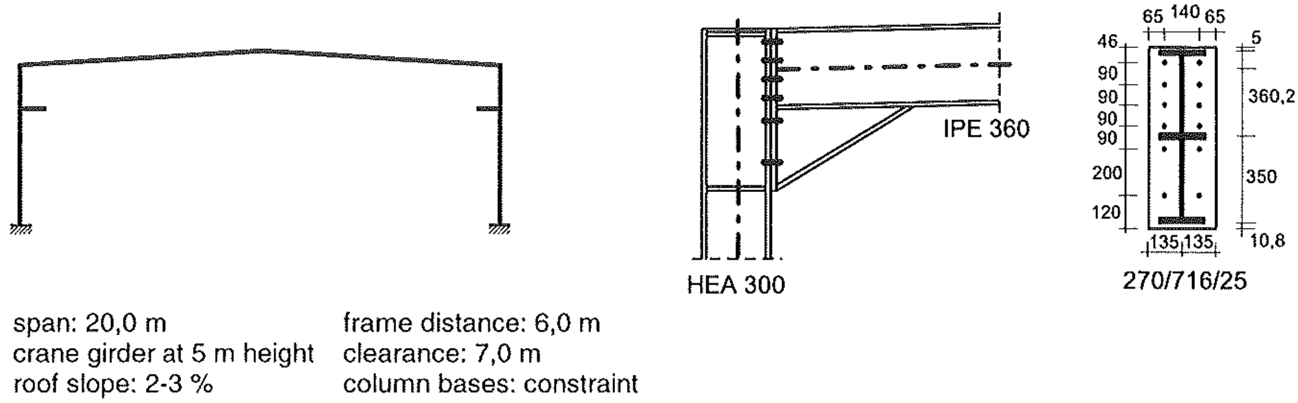


Figure 3: Example for the optimization of rigid joints

To classify the joints as rigid EC 3 requires for the given unbraced frame $S_{j,ini} \geq 25\ EI_b/L_b = 85\ 628$ kNm/rad. According to the revised Annex J of Eurocode 3 the joint characteristics in Figure 3 are calculated as follows:

- design moment resistance $M_{j,Rd} = 281,6$ kNm
- initial stiffness $S_{j,ini} = 114\ 971$ kNm/rad

Hence the joint is classified as rigid. In order to optimize the joint, the detailing of the joint is modified step by step as follows:

a) omit the stiffeners at compression side,
b) in addition, omit the stiffeners at tension side,
c) in addition, the lowest bolt row in tension is omitted.

For all variations it is requested that the joint may still be classified as rigid, i.e. the initial stiffness of the joint should be higher than the rigid classification boundary. Table 1 gives the resistance and stiffness for all variations. The design moment resistance is less than the applied moment and it can be seen that the joint behaves as a rigid one. The different joint detailings will have no influence on the design of the member as the joints remain rigid. Therefore, differences in the fabrication costs of the joint give direct indication of economical benefits. The fabrication costs (material and labour) are given for all investigated solutions in Table 1 as a percentage of the fabrication costs of the original joint layout. Beside the reduction of fabrication costs, the modified joints are more ductile. An other possibility to optimize the stiffness is the use of thinner plates. This can also lead to a more ductile behaviour. Other advantages are: smaller weld, the preparation of hole drilling is easier or hole punching becomes possible.

Economical Benefits from Semi-rigid Joints

A second strategy to profit from the extended possibilities in design can be expressed as follows:

"Use semi-rigid joints in order to have any freedom to optimize the global frame and joint design".

The ideal assumption that the joints are rigid often lead to situations where it is not possible to work without stiffeners. In consequence the joints are very expensive due to high fabrication costs (e.g. welding). In this case more economical solutions can be found by 'crossing the rigid classification boundary' to semi-rigid joints (see Figure 4).

The following types of connections were chosen for the different frames:

- For the braced frame: web cleated connection or flush end-plates 'used' as nominally pinned joints.
- For the unbraced frames and - for further comparative studies - also for braced frame: joints with extended end-plates. To be classified as rigid the joints were stiffened in the unbraced building frame.
- For the alternative design: flange cleated connections or connections with extended end-plates without stiffening selected as semi-rigid joints for both the braced and the unbraced frame.

For the calculation of costs the material, fabrication and erection costs were taken into account. The costs for the design, transportation and bracing systems were neglected. For these costs it was assumed, that they are 50% of the total costs of the steel frame, but that they will be constant for the different variation in design. The results of the studies of Guisse are summarized in Table 3. The cost were provided by a steel fabricator in Luxembourg.

TABLE 3
RESULTS OF THE INVESTIGATIONS BY GUISSE

System	Joints	Costs	Savings
braced building frame	nominally pinned (*)	100 %	-
	semi-rigid flange cleats	96,4 %	**3,6 %**
	semi-rigid extended end-plate	112,5 %(**)	**-12,5 %**
	rigid stiff. ext. end-plate	148,5 %(**)	**-48,5 %**
unbraced building frame	rigid (*)	100 %	-
	semi-rigid extended end-plate	79,4 %	**20,6 %**
braced industrial frame	nominally pinned (*)	100 %	-
	semi-rigid flange cleats	99,3 %	**0,7 %**
	semi-rigid extended end-plate	102,4 %(**)	**-2,4 %**
	rigid stiff. ext. end-plate	118,4 %(**)	**-18,4 %**

(*) reference system
(**) costs higher due to bigger increase of workshop costs compared to savings in material

The study of Grandjean (1994) was carried out in collaboration with the same steel fabricator in Luxembourg. For this work, an existing building was investigated. The building consists of seven braced frames with two bays and seven storeys (b = 7,80 m, h = 3,35 m). The beams are connected by nominally pinned joints. For the connections either web cleats or end-plates were used. For the economy studies, the influence of using different material grade was also checked. The joints were considered as '2D-joints' (in-plane), but also 3D-aspects (e.g.connections of secondary beams) were investigated. As an alternative to the simple design, semi-rigid joints were used and the cots were compared with the reference systems. The results are shown in Table 4:

Both Guisse and Grandjean conclude in their studies that semi-continuous framing using joint with flange cleated connections represent the most economical solution.

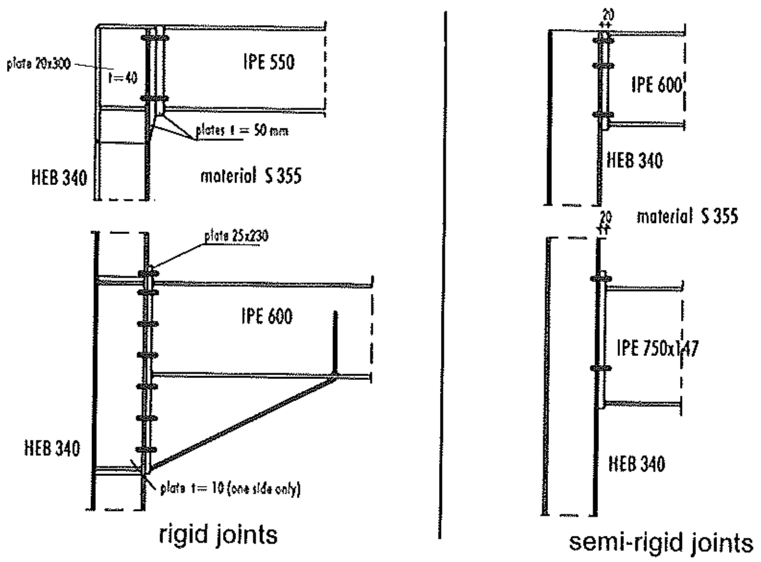


Figure 6: Joints used for the different approaches

TABLE 5

COST SAVINGS FOR THE FRAMES STUDIED BY WEYNAND (1997)

System	Joints	Costs	Savings
braced frame	pinned (reference)	100 %	-
	semi-rigid (solution for company 1)	96 %	**4 %**
	semi-rigid (solution for company 2)	92,5 %	**7,5 %**
unbraced frame	rigid (reference)	100 %	-
	semi-rigid (solution for company 1)	76 %(*)	**24 %**
	semi-rigid (solution for company 2)	97 %(*)	**3 %**

(*) The remarkable difference in savings is due to quite different practice in view of joint detailing and calculation of costs provided by the two steel fabricators.

Dutch Research to economy aspects of partial-strength joints

In the Netherlands, different authors (Jansen and Maatje (1988), Steenhuis (1988)) developed models to determine the fabrication costs of a steel structure. The models are based on a precise inventory of the fabrication process (cutting, welding, drilling, transportation of elements, galvanizing, assembly etc.). For each activity in the fabrication process, costs are calculated based on the geometry of the structural elements (beam, column, plate, angle cleat etc.). For instance:

Costs of drilling holes = function (*number of holes, hole diameter, plate thickness*).

The function parameters are company dependent. With help of the models, a commercial software program has been developed in the Netherlands. This program has been used in some recent studies. In the different studies presented before, the impact on the costs was investigated when the joint stiffness is considered in the design of steel structures. However similar advantages can be achieved when partial-strength joints are taken into consideration. For instance, the study of a braced frame pointed out that partial strength frames may be **9%** more economical than a braced frame with pinned joints due to savings in beam depth, see Figure 7 and Figure 8.

TABLE 4

RESULTS OF THE INVESTIGATIONS BY GRANDJEAN

System	Joints	Costs		Saving	
		1	2	1	2
braced frame	nominally pinned (reference)	100 %		-	
	semi-rigid extended end-plate	97,8 %	96,5 %	2,2 %	3,5 %
	semi-rigid flush end-plate	97,7 %	96,4 %	2,3 %	3,6 %
	semi-rigid flange cleats	97,6 %	96,2 %	2,4 %	3,8 %

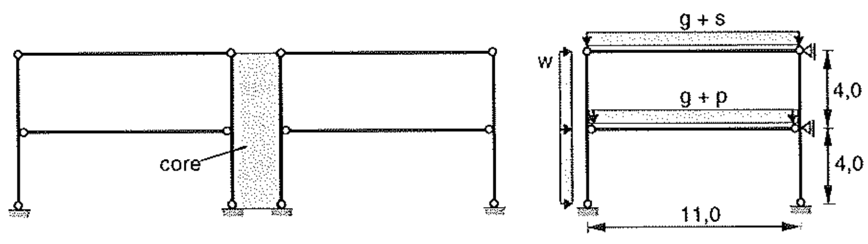
column 1: Consideration of costs for material and fabrication, fixed price for coating, transportation, erection and design

column 2: Consideration of costs for material, fabrication, erection and design

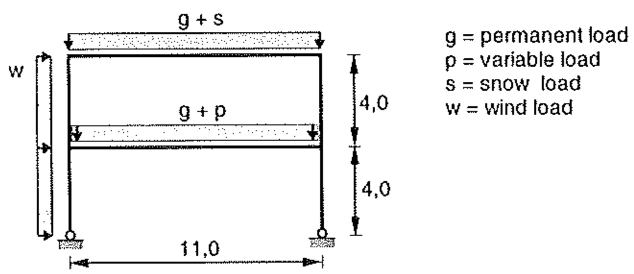
Investigations in Germany

Weynand (1997) reported on investigations carried out in cooperation with two German steel fabricators. Two systems were investigated, see Figure 5: A braced frame with pinned joints (system 1) and an unbraced with rigid joints (system 2). The design of the steel structures is based on the rules of EC3. In a first step the members were chosen and the joints were designed then by the steel fabricators. For the unbraced frame the joints were chosen such that their stiffness was close to the classification boundary, but still classified as rigid. In the second step semi-rigid joints were chosen. For the unbraced frame the steel fabricators selected the joint detailing in order to reduce as much as possible the fabrications costs. In consequence, the sizes of the members were modified when necessary. The layout of some joints chosen by the fabricators according to the traditional and the new concept are shown in Figure 6.

For both design approaches a detailed estimation of the cost of the pure steel structure including material, fabrication and erection costs were provided by the steel fabricators. The results are summarized in Table 5 were the savings due to the design with semi-rigid joints are reported.



System 1: braced frame (car park) and reduced system



System 2: unbraced frame (office building)

Figure 5: Frames investigated by Weynand (1997)

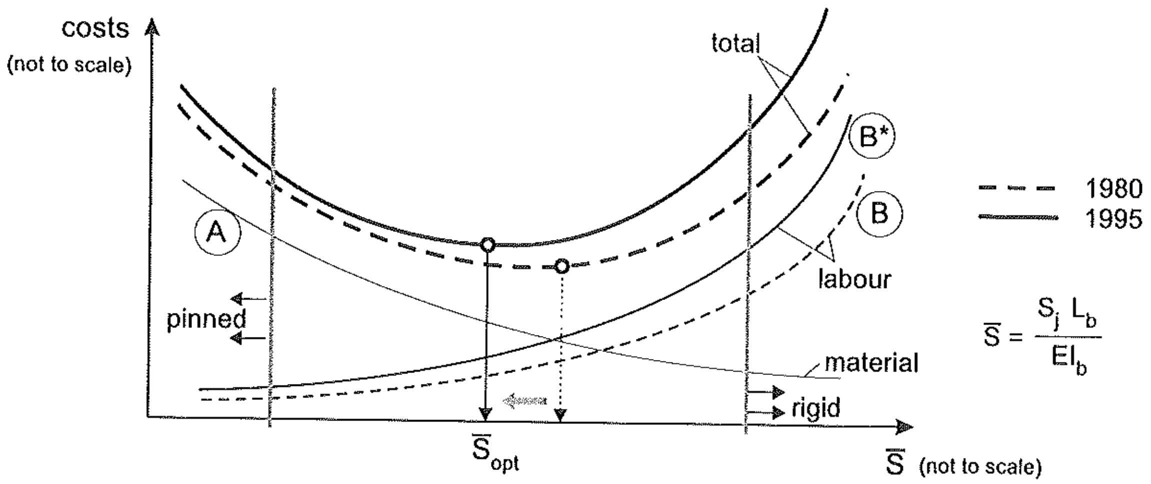


Figure 9: Costs of steel structures depending on the relative joint stiffness

Of course the results of the investigation presented in this paper can not be compared directly; particulary because different types of frames are used. However the following conclusion can be drawn as shown in Figure 9: The costs for material and fabrication (labour) are dependent on the relative stiffness of the joints. While the material costs decrease (curve A), the labour costs increase (curve B) with an increasing joint stiffness. For the total costs which are the sum of these both curves, a minimum can be found and from this an 'optimum joint stiffness'. In many cases the value (which leads to an optimized design of the structure with respect to minimum total costs) is neither pinned nor rigid. Following the tendency of the last decades, it is obvious that the labour costs are increasing in comparison to the material costs (see dashed curve B*). From Figure 9 it becomes clear that as a consequence there is a progressive evolution of the 'optimum joints stiffness' towards more flexible joints. Hence to find economical solutions for steel structures the use of semi-rigid joints will become more and more interesting.

REFERENCES

Bjorhovde, R., Colson, A. (1991). Economy of Semi-Rigid Frame Design, *Connections in Steel Structures II*, Proceedings of the 2nd International Workshop, Pittsburgh, USA

CEN (1992). ENV 1993 - Eurocode 3, Part 1.1: Design of steel structures, General rules and rules for buildings, Brussels, Belgium

CEN (1994). Revised Annex J of Eurocode 3 'Joints in Building Frames', *Amendment A2 to Eurocode 3*, Brussels, Belgium

Jansen, W.Ph., Maatje, F. (1988): Calculation of the costs of steel structures with help of the computer (in Dutch), *Report*, Technische Universiteit Delft, The Netherlands

Grandjean, O. (1994). Comparaison économique de structures mixtes 'acier-béton' dimensionnées avec ou sans prise en compte du caractère semi-rigide des noeuds, *Diploma Work*, Institut MSM, Univ. of Liège, Belgium

Guisse, S. (1995). Economical interest of semi-rigid joints in steel structures, *SPRINT Contract RA 352*, Institut MSM, Univ. of Liège, Belgium

Jaspart, J. P. (1995). Application example with clever joint design, *Report*, MSM Department Univ. of Liège, Belgium (unpublished material used for seminars devoted to practitioners in Belgium)

Steenhuis, M. (1988). Optimisation of costs for orthogonal frames (In Dutch), *Report,* Technische Universiteit Eindhoven, the Netherlands

Steenhuis, M. (1992). Frame Design and Economy, *Proceedings of the first COST C1 state of the art workshop*, Strasbourg, France

Steenhuis, M., Weynand, K., Gresnigt, A.M. (1998). Strategies for Economic Design of Unbraced Steel Frames, *Proceedings of the Second World Conference on Steel Construction*, paper 69, San Sebastián, Spain

Weynand, K. (1997). Sicherheits- und Wirtschaftlichkeitsuntersuchungen zur Anwendung nachgiebiger Anschlüsse im Stahlbau, *Ph.D. thesis*, RWTH Aachen, Shaker Verlag, Aachen, Germany

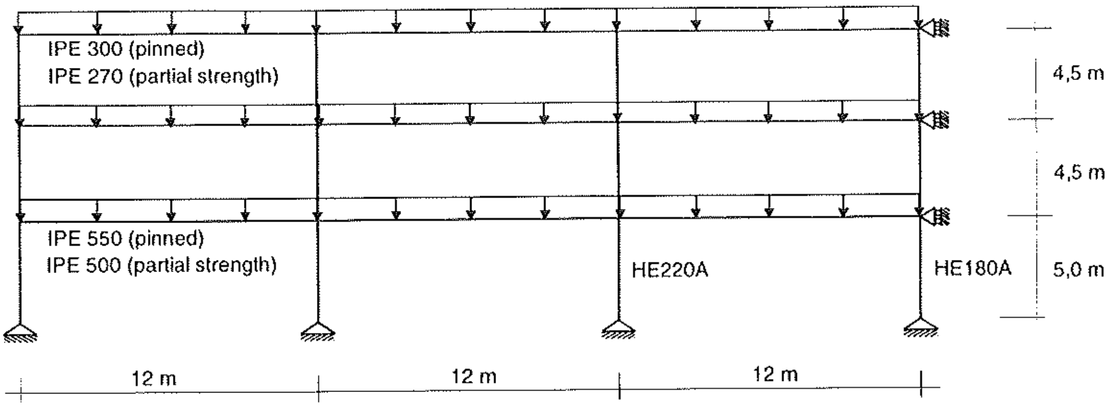


Figure 7: Example of an braced frame used for the economical studies

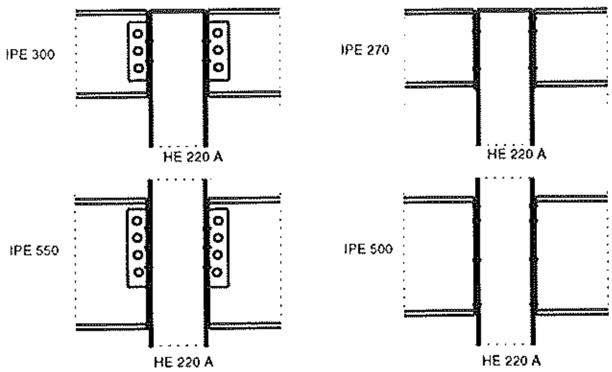


Figure 8: Pinned and partial strength joints

A more widely accessible report with detailed information about the work carried out in the Netherlands is given by Steenhuis (1992).

SUMMARY AND CONCLUSIONS

With respect to joint design basically two different strategies can be identified when minimum costs of steel structures are of interest:

- Simplification of the joint detailing, i.e. reduction of fabrication costs. Typically this is relevant for unbraced frames when the joints transfer significant moments (traditionally rigid joints).
- Reduction of profile dimensions, i.e. reduction of material costs. Typically this is relevant for braced frames with simple joints.

In general both stategies would lead to the use of semi-rigid joints. In case of rigid joints an economic solution may already be found if the stiffness of the joint is close to the classification boundary.

Economy studies in various countries have shown possible benefits from the use of the concept of semi-rigid joints. More significant savings can be achieved when moment connections are optimized in view of economy. It is remarkable that all studies came to similar values when the saving due to the use of the new concept is compared to traditional design solutions. However it should be understood that the savings depend on the preferences of the steel fabricators to design the joints and how the cost are calculated. From the different studies it can be concluded that the possible savings due to semi-rigid design can be 20 - 25 % in case of unbraced frames and 5 - 9 % in case of braced frames. With the assumption that the costs of the pure steel frames are about 10% of the total costs for office buildings and about 20 % for industrial building, the reduction of the total building costs could be estimated to 4-5% for unbraced frames. For braced systems savings of 1-2% are possible.