Economy Studies of Steel Building Frames with Semi-Rigid Joints

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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).

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.

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.

To classify the joints as rigid EC 3 requires for the given unbraced frame $S_{j,ini} \geq 25 \frac{EI_b}{L_b} = 85628$
kNm/rad. According to the revised Annex J of Eurocode 3 the joint characteristics in Figure 3 are calculated as follows:

- design moment resistance \( M_{j,Rd} = 281.6 \text{ kNm} \)
- initial stiffness \( S_{j,ini} = 114,971 \text{ kNm/rad} \)

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 layout of the joints is then chosen for economy. Usually, this leads to more flexible, i.e. semi-rigid joints. The joint behaviour has to be taken into account in the frame analysis. This is possible by modelling the joint with rotational springs at beam ends. Their behaviour influence the global response of the frame, i.e. moment redistributions and displacements. As a consequence the size of the members may increase in comparison with a design with rigid joints. The decrease of the fabrication cost for the joint on one side has to be compared with the increase of the material and anti-corrosion costs due to larger profiles on the other side. The optimum solution can only be found when a detailed calculation of the costs is carried out. Examples of such investigations are given later in this paper. Beside the positive effect in view of economy the use of joint without stiffeners provides more advantages: It becomes more easy to connect secondary beams, service pipes may be installed between the column flanges, easier coating and less problems with corrosion. The steel construction
can appear more aesthetic and lighter and again, joint without stiffeners are usually more ductile. With respect to ultimate limit state design this is an important aspect as well.

**SAVINGS OF MATERIAL COSTS**

In the previous section, strategies were discussed when a frame is designed with so-called moment connections. This is usually required for unbraced frames. However for braced frames simple joints are normally more economic. However the moment diagram for the (simple supported) beams leads to beam sizes which are optimized for the mid-span moment, but ‘oversized’ at their ends. Further - due to the fact that the joint do not transfer any moment (this is the assumption for the frame analysis) - it becomes sometimes necessary to install additional temporary bracings during erection. However in many cases joints which are assumed to behave as nominally pinned (e.g. flush end-plates) can be treated as semi-rigid joint. The strategy therefore is:

“Simple joints may have some inherent stiffness and may transfer moments - take profit from that actual behaviour”

This can improve the distribution of moments and reinforce the frame, i.e. lighter members (also for the bracing systems) without any change in joint detailing. And - as a consequent step - a further strategy is as follow:

“Check if small reinforcements of simple joints may strongly reinforce the frame”

Sometimes it will be possible to reinforce simple joints without a large increase of fabrication cost (e.g. flush end-plates instead of a short end-plates). As those joints can transfer significant moments, the bending diagram is more balanced and the dimensions of the members can be lighter. Here again, increase of fabrication costs for the joints and decrease of weight of the structure are two competing aspects and a check of balance is necessary. However recent investigations show that the most economical solutions can be found if the contributions of the stiffness and resistance of the joints are considered, i.e. semi-rigid joints are used.

**ECONOMY STUDIES**

In the following section different economy studies undertaken in various countries are briefly described. All investigations are comparative studies where steel frames designed with ‘traditional’, i.e. either rigid or nominally pinned joints were compared with solutions using the semi-rigid joints. The resulting savings of the costs are reported.

**Investigations in France and USA**

In a study presented by Bjorhovde and Colson (1991), an unbraced, three storey, two bay frame and a braced, four storey, four bay frame with different types of joints were investigated. The cost evaluations were provided by steelwork companies in France and USA. For details of the systems studied reference is made to the paper of Bjorhovde, Colson (1991). The following Table 2 gives the outcome of their study:

**Investigations in Belgium**

In the report of Guisse (1995) three steel frames were investigated:
- a building frame (2 storeys, 1 bay, \( b = h = 7 \) m), braced and unbraced and
- a braced industrial frame (1 storey, 1 bay, \( b = 14 \) m, \( h = 12 \) m)

where \( b \) is the beam span and \( h \) is the storey height.

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.

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 costs 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.

**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.

**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.

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 strategies 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.

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.

FIGURES

Paper 063, Figure 1: Traditional modelling of the moment-rotation behavi

![Figure 1: Traditional modelling of the moment-rotation behaviour of joints](image_url)
Paper 063, Figure 2: Optimization of rigid joints

Figure 2: Optimization of rigid joints

Paper 063, Figure 3: Example for the optimization of rigid joints

Figure 3: Example for the optimization of rigid joints
Paper 063, Figure 4: Optimization with semi-rigid joints

Figure 4: Optimization with semi-rigid joints

Paper 063, Figure 5: Frames investigated by Weynand (1997)

Figure 5: Frames investigated by Weynand (1997)
Paper 063, Figure 6: Joints used for the different approaches

Figure 6: Joints used for the different approaches

Paper 063, Figure 7: Example of an braced frame used for the economical studies

Figure 7: Example of an braced frame used for the economical studies
Paper 063, Figure 8: Pinned and partial strength joints

**Figure 8:** Pinned and partial strength joints

Paper 063, Figure 9: Costs of steel structures depending on the relative joint stiffness

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

**TABLES**
Paper 063, Table 1 Variations in joint detailing and relative savings in fabrication costs

<table>
<thead>
<tr>
<th>Variations</th>
<th>$M_{j,Rd}$ [kN*m]</th>
<th>$S_{j,ini}$ [kN*m/rad]</th>
<th>Stiffness classification</th>
<th>Relative fabrication costs *</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>255.0</td>
<td>92 706</td>
<td>rigid</td>
<td>87 %</td>
<td>13%</td>
</tr>
<tr>
<td>HEA 300</td>
<td>IPE 360</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>250.6</td>
<td>89 022</td>
<td>rigid</td>
<td>73 %</td>
<td>27%</td>
</tr>
<tr>
<td>HEA 300</td>
<td>IPE 360</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>247.8</td>
<td>87 919</td>
<td>rigid</td>
<td>72 %</td>
<td>28%</td>
</tr>
<tr>
<td>HEA 300</td>
<td>IPE 360</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*) fabrication costs of the joints relative to those of the configuration shown in Figure 3

Paper 063, Table 2 Results of the studies by Bjorhovde & Colson (1991)

<table>
<thead>
<tr>
<th>System</th>
<th>Joints</th>
<th>Costs</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>France</td>
<td>USA</td>
</tr>
<tr>
<td>unbraced frame</td>
<td>rigid (*)</td>
<td>100 %</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>82 %</td>
<td>80 %</td>
</tr>
<tr>
<td>braced frame</td>
<td>nominally pinned (*)</td>
<td>100 %</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>96 %</td>
<td>105 %</td>
</tr>
<tr>
<td></td>
<td>rigid</td>
<td>120 %</td>
<td>115 %</td>
</tr>
</tbody>
</table>

(*) reference system
### Paper 063, Table 3 Results of the investigations by Guisse

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

(*) reference system  
(**) costs higher due to bigger increase of workshop costs compared to savings in material
Paper 063, Table 4 Results of the investigations by Grandjean

<table>
<thead>
<tr>
<th>System</th>
<th>Joints</th>
<th>Costs</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 2</td>
<td>1 2</td>
</tr>
<tr>
<td>braced frame</td>
<td>nominally pinned</td>
<td>100 %</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(reference)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>97,8 %</td>
<td>2,2 %</td>
</tr>
<tr>
<td></td>
<td>extended end-plate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>97,7 %</td>
<td>2,3 %</td>
</tr>
<tr>
<td></td>
<td>flush end-plate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>97,6 %</td>
<td>2,4 %</td>
</tr>
<tr>
<td></td>
<td>flange cleats</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Paper 063, Table 5 Cost savings for the frames studied by Weynand (1997)

<table>
<thead>
<tr>
<th>System</th>
<th>Joints</th>
<th>Costs</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>braced frame</td>
<td>pinned (reference)</td>
<td>100 %</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>96 %</td>
<td>4 %</td>
</tr>
<tr>
<td></td>
<td>(solution for company 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>92,5 %</td>
<td>7,5 %</td>
</tr>
<tr>
<td></td>
<td>(solution for company 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unbraced frame</td>
<td>rigid (reference)</td>
<td>100 %</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>76 %(*)</td>
<td>24 %</td>
</tr>
<tr>
<td></td>
<td>(solution for company 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>semi-rigid</td>
<td>97 %(*)</td>
<td>3 %</td>
</tr>
<tr>
<td></td>
<td>(solution for company 2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*) 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.
References


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)


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