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Conceptual design of joints in braced steel frames

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Summary

To help practitioners to find the most economical design of braced frames, this paper proposes a classification of joints in 'simple' (e.g. web cleated connections), 'moderate' (e.g. flush end plated connections) and 'complex' (e.g. stiffened extended end plate connections) with respect to the fabricational complexity (low, medium and high costs). Different types of joints are classified into the three aforementioned classes in a table format. This enables a practitioner to simply read the class of a given joint from the table, without calculation. For each class, recommendations are given what strength and what stiffness should be used during the conceptual design stage of the frame. Furthermore, the paper shows that, during the final design of the braced frame, the recommended stiffness values can be used safely without further checks. In other words, there is no need to determine the 'actual' stiffness of the joint during final design, which lightens the design task dramatically. What remains is a check of the strength and, in case of plastic frame analysis, the rotation capacity.

A comparison of frame alternatives is included, which demonstrates that application of moderate joints compared to simple joints may be economical due to savings in beam costs.

List of symbols

b_{eff} is the effective width of the column web in compression;
f_y is the yield strength;
k_x is a stiffness factor dependent from the type of joint relative to the lever arm;
$k_{x,act}$ is a stiffness factor dependent on the 'actual' stiffness of a specific joint;
$k_{x,app}$ is a stiffness factor dependent on the type of joint relative to the beam depth;
l_b is the beam span;
$t_{f,c}$ is the column flange thickness;
$t_{w,c}$ is the column web thickness;
z is the distance between centre of compression and tension;
k_y is a strength factor dependent on the type of joint relative to the lever arm;
E is the Young's modules;
F_c is the design capacity of the column web in compression;
I_b is the moment of inertia of the beam;
M_{Rd} is the design moment capacity of a joint;

S_j is the initial stiffness;

$S_{j.act}$ is the initial stiffness calculated according to Eurocode 3 or another design standard;
$S_{j.app}$ is the 'good guess' of the initial stiffness;
γ_{M0} is the partial safety factor for members.

1. Classification of joints with respect to fabricational complexity

Eurocode 3 [1] presents two classification schemes for the design of joints with respect to strength and stiffness. For elastic frame analysis, the stiffness classification in 'nominally pinned', 'semi rigid' and 'rigid' may be used. For plastic frame analysis, the strength classification in 'nominally pinned', 'partial strength' and 'full strength' may be used.

Anderson et al. [2] demonstrated that braced frames with nominally pinned joints require heavier beams than frames with semi rigid, partial strength joints. They may be economical due to low fabricational costs of the joints. Dependent on beam span and fabricator, frames with semi rigid, partial strength joints may also be economical. In that case the economy is achieved by lower beam costs (despite higher costs for the joints). Frames with rigid and/or full strength joints are uneconomical due to high fabricational costs of the stiffened joints.

Gibbons [3] showed that alternatives for braced frames can be distinguished in terms of 'simple', 'moderate' and 'complex' with respect to their fabricational complexity. In this paper, we will use these terms in a classification system for joints. Possible economical solutions are braced frames with simple joints or braced frames with moderate joints. Table 1 shows the link between the classification with respect to the fabricational complexity and the Eurocode 3 classification. The grey cells in this table indicate the economical alternatives.

Tab. 1. Classification with respect to fabricational complexity compared to Eurocode 3

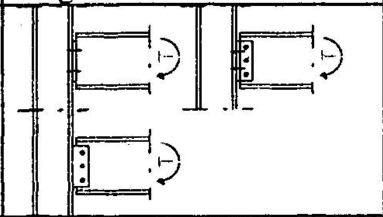
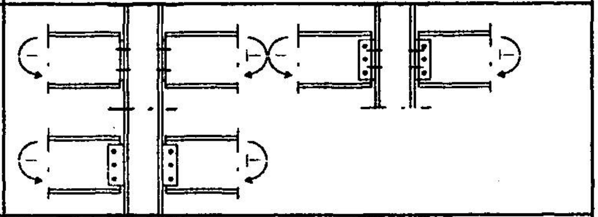
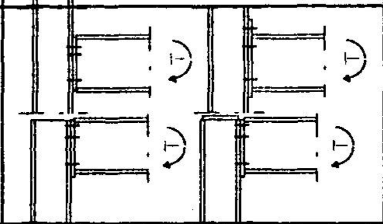
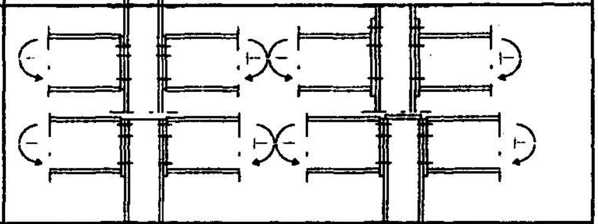
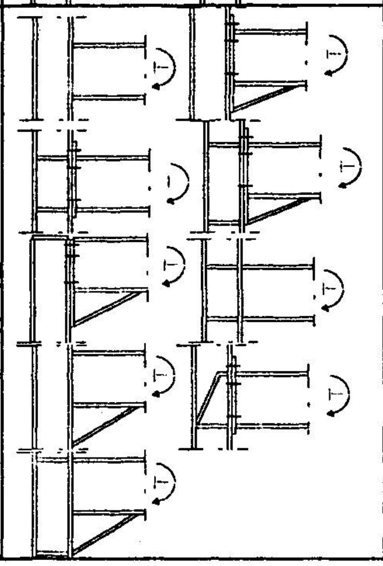
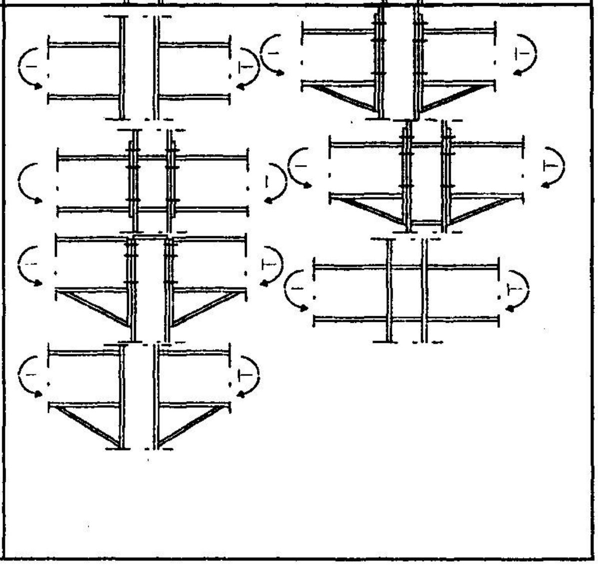
Classification with respect to fabricational complexity	Stiffness classification according to Eurocode 3	Strength classification according to Eurocode 3
Simple	Nominally pinned	Nominally pinned
Moderate	Semi rigid (but unstiffened)	Partial strength (but unstiffened)
Complex	Semi rigid (but stiffened) or Rigid	Partial strength (but stiffened) or Full strength

Table 2 shows how different types of joints are classified in simple, moderate and complex. Simple joints are those types of joints which are traditionally treated as nominally pinned, for example joints with flexible end plates, fin plates or web angle cleats. Moderate joints are for example joints with end plates. Complex joints are welded joints and stiffened joints with end plates. The welded joints have been shifted to the complex class, due to the costs of welding on site.

The background of the proposed classification is as follows. In various European countries, traditionally, two parties are responsible for the design of steel frames: the engineer designs the beams and columns and the steel fabricator designs the joints. In this design practice, the engineer specifies the mechanical requirements of joints. The steel fabricator designs the joints to fulfil these requirements. The fabricator also considers manufacturing aspects.

In this design practice, the use of simple joints is favoured, because the engineer can design beams and columns without knowledge of the lay out of the joints. The joints normally will be designed in a subsequent step by the steel fabricator based on the results of the frame analysis.

Tab. 2. Types of joints classified with respect to fabricational complexity

Class	Single sided	Cruciform
Simple		
Moderate		
Complex		

Ideally, for moderate and complex joints, it would be best if beams, columns and joints are designed by one single party (allowing the mechanical properties of the joints to be introduced in the frame analysis). As explained before, this is not current practice. Therefore, there is a need for simple design recommendations for engineers to assess the strength and stiffness requirements of moderate joints. These requirements should allow a steel fabricator to design economical joints.

In this paper, a proposal for the design recommendations is given. The scope of this paper is restricted to European H and I sections. It is assumed that the beam depth is greater than or equal to the column depth. Some further restrictions apply to end plated joints:

- a connection has two bolt rows in tension;
- the bolt diameter is approximately 1.5 times the thickness of the column flange;

- the location of the bolt is close to the root radius of the column flange, the beam flange and the web;
- the end plate thickness is similar to the column flange thickness.

In section 2, stiffness classification criteria are given to be used during elastic frame analysis. Section 3 focuses on strength classification criteria for plastic frame analysis. In the last section, a practical example demonstrates the benefits of the given recommendations.

2. Stiffness classification criteria

In this section, criteria are given as to what stiffness should be introduced in the frame analysis for each class of joints (simple, moderate or complex). These criteria are based on the work of Steenhuis, Gresnigt and Weynand in [4]. They presented a design method for elastic design allowing the frame to be designed by an engineer and the (semi rigid) joints to be designed by a steel fabricator. The design method is identical to the traditional design process for nominally pinned or rigid joints, but:

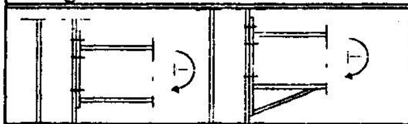
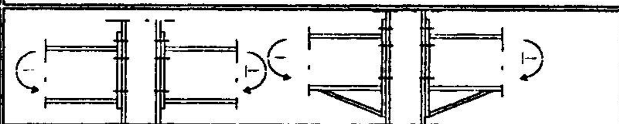
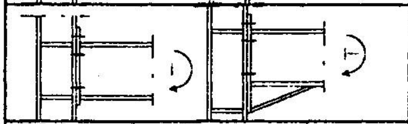
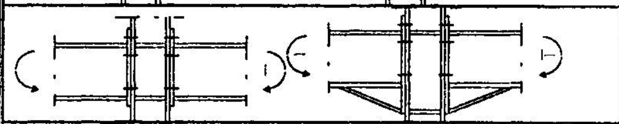
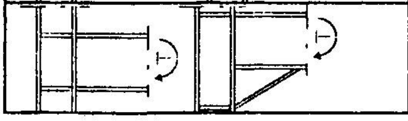
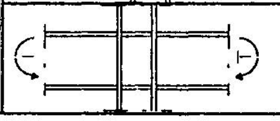
- instead of assuming that a joint is nominally pinned or rigid, the initial stiffness of the joint is assessed by means of a 'good guess'. For this 'good guess' only information is required about the connected beam and column and an impression about the type of joint;
- the agreement between the 'good guess' and the 'actual' stiffness (the design initial stiffness) of the joint needs to be verified. This is similar to the concept of checking that a joint is rigid.

The 'good guess' can be made with the help of the following formula:

$$S_{j.app} = \frac{E\, z^2\, t_{f.c}}{k_x} \qquad (1)$$

Factor k_x can be read from table 3 for a limited number of joints.

Tab.3. k_x - factor for beam to column joints (taken from [4])

Single sided	k_x	Cruciform	k_x
	13		7,5
	8,5		3
	5,5		0

In the case of braced frames, the agreement between the 'good guess' ($S_{j.app}$) and the 'actual' stiffness ($S_{j.act}$) of the joint can be verified with:

$$\text{In case } S_{j.app} < \frac{8\, E\, I_b}{l_b} \text{ then } \frac{8\, S_{j.app}\, E\, I_b}{10\, E\, I_b + S_{j.app}\, l_b} \le S_{j.act} \le \frac{10\, S_{j.app}\, E\, I_b}{8\, E\, I_b - S_{j.app}\, l_b} \qquad (2)$$

$$\text{else}\ \frac{8\ S_{j.app}\ E\ I_b}{10\ E\ I_b + S_{j.app}\ l_b} \leq S_{j.act} \leq \infty \tag{3}$$

If these requirements are fulfilled, the bearing capacity (column buckling load) of a frame with joint stiffness $S_{j.act}$ will differ less than 5% from the same frame with joint stiffness $S_{j.app}$. For backgrounds to these formulae, we refer to [4].

In section 2.1 we will investigate whether instead of k_x -factors for each type of joint, we then can give k_x -factors for each class of joint. We expect that this is possible due to the fact that the response of braced frames is relatively insensitive to variations in stiffness.

2.1 Sensitivity of a braced frame to variations in stiffness

When we know $S_{j.app}$, boundaries for the allowed variation of $S_{j.act}$ are given with equations (2) and (3). We will now investigate whether these criteria can be presented in a managable format, in order to draw some conclusions concerning the sensitivity of a braced frame to variations in stiffness. For the sake of simplicity we only focus on the situation that $S_{j.app} < \frac{8\ E\ I_b}{l_b}$.

The approximate stiffness $S_{j.app}$ can be determined with equation (1).We can remove z from this equation by defining:

$$k_{x.app} = k_x \frac{h_b^2}{z^2} \tag{4}$$

This yields to the following result:

$$S_{j.app} = \frac{E\ h_b^2\ t_{f.c}}{k_{x.app}} \tag{5}$$

The expression for allowable variation in stiffness (equation (2)) can be rewritten as:

$$\frac{8}{10 + \frac{h_b^2\ t_{f.c}}{k_{x.app}\ I_b}\ l_b} \leq \frac{k_{x.app}}{k_{x.act}} \leq \frac{10}{8 - \frac{h_b^2\ t_{f.c}}{k_{x.app}\ I_b}\ l_b} \tag{6}$$

The frame response is sensitive to variations in joint stiffness when the beam is stocky. Hence we take $l_b = 15\ h_b$.

$$\frac{8}{10 + \frac{15\ h_b^3\ t_{f.c}}{k_{x.app}\ I_b}} \leq \frac{k_{x.app}}{k_{x.act}} \leq \frac{10}{8 - \frac{15\ h_b^3\ t_{f.c}}{k_{x.app}\ I_b}} \tag{7}$$

From formula (7) it appears that for small values of $t_{f.c}$, the frame is sensitive to variations in $k_{x.app}$. We use $\frac{h_b^3\ t_{f.c}}{I_b} = 4$ as a lower bound for frames with stocky beams and slender columns.

This leads to:

$$0{,}8\ k_{x.app} - 6 \leq k_{x.act} \leq 1{,}25\ k_{x.app} + 7{,}5 \tag{8}$$

If $k_{x.app} < 7{,}5$, the joint is rigid. Figure 1 shows this expression in a graphical form. From this graph, we can conclude that the response of a braced frame is insensitive to variations in stiffness of the joints. For example, if $k_{x.app} = 13$, the 'actual' stiffness may be up to 13/23.75 = 0.55 times lower and up to 13/4,4 = 2,95 times higher. The value $k_{x.app} = 13$ corresponds for example to a joint with an extended end plate (single sided). This enormous variation is despite the worst case assumptions we did when deriving the relation between $k_{x.app}$ and $k_{x.act}$.

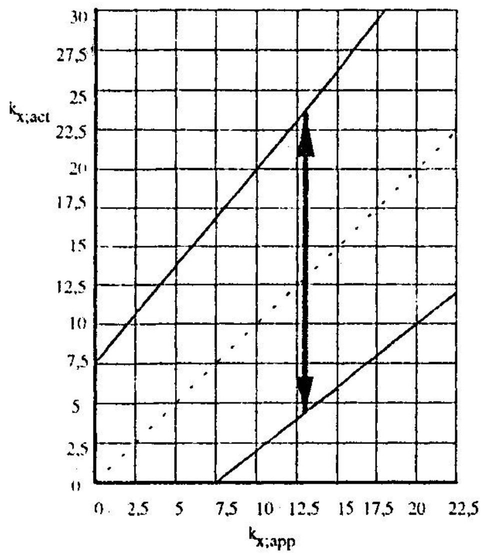


Fig. 1. $k_{x,act}$ as function from $k_{x,app}$

Since variations in stiffness have such a limited influence on the frame behaviour, stiffness criteria can be given as in table 4, where different types of joints are grouped in three classes. The chosen stiffness for each class of joints is rather low for two reasons:

- the moments found during elastic analysis will be lower. Therefore there is more chance to find an economical solution;
- when the 'actual' stiffness is higher than the 'good guess', deformations will be smaller and the frame bearing capacity (column buckling load) will be higher. This is on the safe side.

Tab. 4. Stiffness classification of joints in braced frames for predesign

Class	Single sided	Cruciform
	S_j	S_j
Simple	0	0
Moderate	$\frac{E\,h_b^2\,t_{f,c}}{22}$	$\frac{E\,h_b^2\,t_{f,c}}{13}$
Complex	$\frac{E\,h_b^2\,t_{f,c}}{11}$	$\frac{E\,h_b^2\,t_{f,c}}{6,5}$

If the approximate stiffness $S_{j,app}$ (adopted in the frame analysis) is low compared to the 'actual' stiffness $S_{j,act}$, the joints should have sufficient rotational capacity to allow for some plasticity. Eurocode 3 [1] gives some guidance. As a general rule, we recommend to design the welds for the full moment capacity of the joints. For an end plate or a column flange in bending, yielding of the plate or flange is the preferred failure mode.

2.2 Need for stiffness verifications

Now we will investigate whether there is a need to verify the agreement between the stiffness design recommendations given in table 4 and the 'actual' stiffness.

In this verification we used information from design tables [5, 6] according to Eurocode 3. Types of joints investigated are:

- single sided flush end plate joints, see figure 2;
- single sided extended end plate joints, see figure 3;
- cruciform extended end plate joints, see figure 4;
- cruciform welded joints, see figure 5.

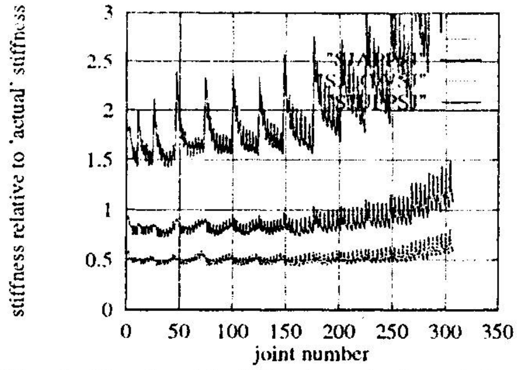


Fig. 2. Single sided flush end plate joints (moderate)

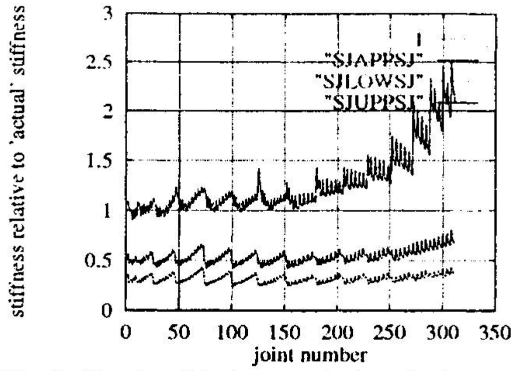


Fig 3. Single sided extended end plate joints (moderate)

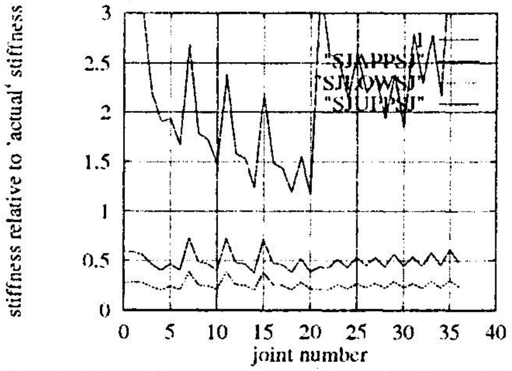


Fig 4. Cruciform extended end plate joints (moderate)

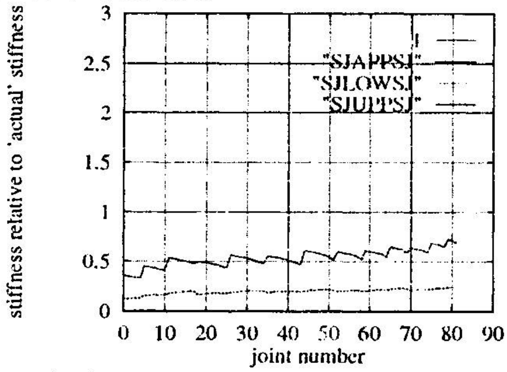


Fig 5. Cruciform welded joints (complex)

Figures 2 to 5 show each four lines:

- '1'. This line represents the case that $S_{j.app}$ equals $S_{j.act}$;
- 'SJAPPSJ'. This line represents $S_{j.app}$ divided by $S_{j.act}$;
- 'SJLOWSJ'. This line represents the lower bound for the 'actual' stiffness ($\frac{8\,S_{j.app}\,E\,I_b}{10\,E\,I_b + S_{j.app}\,l_b}$) divided by $S_{j.act}$. For the lower bound, see equation (2) and (3);
- 'SJUPPSJ'. This line represents the upper bound for the 'actual' stiffness ($\frac{10\,S_{j.app}\,E\,I_b}{8\,E\,I_b - S_{j.app}\,l_b}$, or ∞) divided by $S_{j.act}$. For the upper bound, see equation (2) or (3).

The approximate stiffness $S_{j.app}$ is calculated according to table 4 and the 'actual' stiffness $S_{j.act}$ is read from the design tables [5, 6]. The horizontal axis represents the different joints in consecutive order. Conservatively it is assumed that the beam span is 15 times the beam depth.

It appears in all cases that none of the lower bounds is crossing the line '1'. Only few joints touch the upper bound, which means that possibly an additional safety of 5% has been achieved in these cases. It can be concluded that the classification scheme can be used without formal check of the stiffness.

3. Strength classification criteria

In section 2 we introduced stiffness criteria for a classification system for joints in braced frames with respect to the fabricational complexity. This system consists of stiffness recommendations for different classes of joints to be adopted during frame analysis. It is suitable for elastic frame analysis.

When adopting plastic frame analysis or when verifying the strength of joints after elastic analysis has been carried out, it could be helpful for a designer to have a quick impression of the moment capacity of different joint types. In analogy to the prediction formula for stiffness [4], a formula can be derived to make a first approximation of the joint strength. This formula has the form:

$$M_{Rd} = k_y f_y \, z \, t_{f,c}^2 \,/\, \gamma_{M0} \quad (9)$$

Factor k_y is dependent on the type of failure expected in the joint. For an unstiffened single sided joint, this is for example column web in shear, for an unstiffened cruciform joint, this is for example column web in compression or tension. It is assumed that bolt failure or end plate in bending is not the governing failure mode in the joint.

Determination of k_y, see also [4], for a joint failing due to column web in compression:

$$M_{Rd} = F_c \, z \approx \frac{f_y \, b_{eff} \, t_{w,c} \, z}{\gamma_{M0}} \approx \frac{f_y \, 12 \, t_{f,c} \, 0{,}6 \, t_{f,c} \, z}{\gamma_{M0}} \approx \frac{7{,}2 \, f_y \, z \, t_{f,c}^2}{\gamma_{M0}} \quad (10)$$

The value of k_y has been determined by calculating $M_{Rd} \,/\, (f_y \, z \, t_{f,c}^2 \,/\, \gamma_{M0})$ for a number of joints from the design tables [5, 6]. This has been reported in figures 6 and 7. The joints selected in figure 6 fail due to shear of the column web. The joints selected in figure 7 fail due to column web in compression. We choose: $k_y = 5$ (single sided joint) and $k_y = 7$ (cruciform joint).

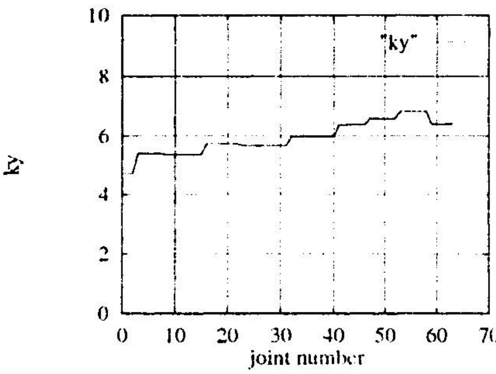


Fig 6. Unstiffened extended end plate joints failing in shear

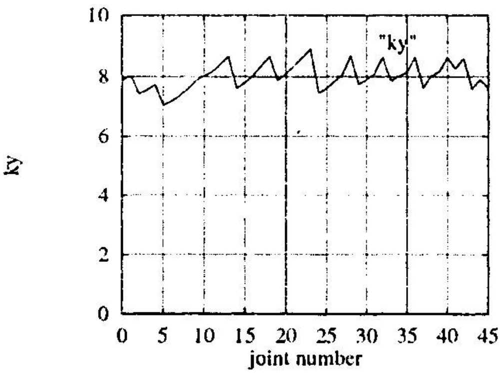


Fig 7. Unstiffened welded joints failing in compression or tension

For two reasons, the approximation formula for strength is not as accurate as the stiffness formula. Firstly, there is the direct impact of the strength of the joint on the frame behaviour. Secondly, the formula is based on a specific failure mode (e.g. column web in shear) of the joint. In reality, another failure mode may govern the joint behaviour. Therefore, the approximation formula can only be used in a first design step. Strength verifications according to the code always have to be carried out after a joint has been designed. We present design recommendations in table 5. With the help of this table, a designer can quickly check whether a certain solution runs into costs.

Tab. 5. Strength recommendations for joints in braced frames during predesign.

Class	Single Sided	Cruciform
	M_{Rd}	M_{Rd}
Simple	0	0
Moderate	$\leq 5 f_y\, z\, t_{f,c}^2 / \gamma_{M0}$	$\leq 7 f_y\, z\, t_{f,c}^2 / \gamma_{M0}$
Complex	$> 5 f_y\, z\, t_{f,c}^2 / \gamma_{M0}$	$> 7 f_y\, z\, t_{f,c}^2 / \gamma_{M0}$

4. Example

In this example, the difference in costs between two frames has been determined. It concerns a frame with simple joints and a frame with moderate joints. Figure 8 shows the lay out of the frames. In the frame with simple joints, web angle cleat connections have been adopted. In the frame with moderate joints, full depth end plates have been used, see figure 9. Full details of the design are given in [7].

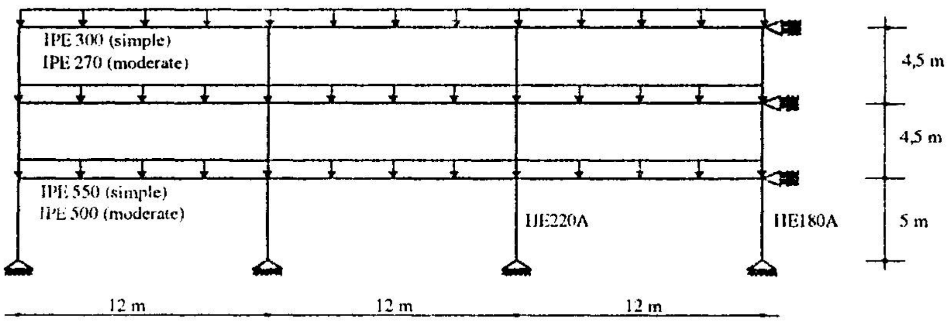


Fig 8. Geometry of frame

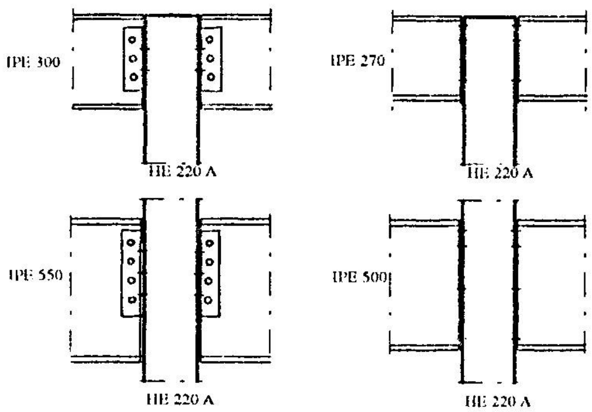


Fig 9. Simple and moderate joints

Table 6 gives the cost breakdown in Dutch guilders for 5 frames. It can be concluded from the table the total costs of the frames with moderate joints are lower than the costs of the simple frames. Despite higher fabricational costs, this is due to materials savings, lower assemblage costs and savings in anti corrosion measures.

Tab. 6. Costs comparison of frames, (in guilders)

Category	Simple	Moderate	Simple compared to moderate
Material	65.724	54.791	120%
Production	12.103	17.278	70%
Anti Corrosion	19.520	18.192	104%
Assemblage	16.800	12.800	131%
Engineering	6.124	7.164	85%
Unforeseen (10%)	12.027	11.022	
total	132.298	121.247	109%

Conclusions

Joints in braced frames can be classified in terms of simple, moderate and complex with respect to fabricational aspects. For these classes, we established design recommendations for both stiffness and strength. These recommendations can be used during frame design. For stiffness, values are given to be introduced in the frame analysis. These values are in good agreement with the 'actual' stiffness of joints from a certain class. For strength, simple criteria have been derived to find out in what class specific joints will fall.

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