Feature-Based Cost and CO_2 Equivalent Optimization of Semi-rigid Steel Frames

Jaakko Haapio[1], Timo Jokinen[2], Markku Heinisuo[2], and Mauri Laasonen[2]

[1] Metso Power Oy, Finland
jaakko.haapio@kotikone.fi
[2] Tampere University of Technology, Finland
{timo.jokinen,markku.heinisuo,mauri.laasonen}@tut.fi

Abstract. We wish to introduce a building information model (BIM) based tool for cost and emission analysis of steel frames. A BIM is used as the data source for the cost and emission calculations, which means that the designer can perform cost and emission calculations from cradle to site without extra work using the tool, provided that a BIM is available. The BIM may include all features of steel frames already at the pre-design phase so that estimations of costs and emissions are quite accurate. A simple example is used to demonstrate that the emissions from a steel frame correspond quite closely with the reduction in the cost of the frame when rigid beam-to-column joints are replaced by semi-rigid ones.

Keywords: semi-rigid joints, costs, emissions, BIM, optimization.

1 Introduction

Steel frames designed with semi-rigid joints have been shown to lead to 14-17% savings in the costs of steel structures (Simoes, 1996), (Anderson et al 1987), (Grierson and Xu 1992), Weynand et al 1998), (Haapio and Heinisuo 2010). However, steel designers must not consider only the costs of structures, but also the effect of completed structures on the environment. Buildings are responsible for a large share of global emissions which puts pressure also on steel designers. Emissions to air are commonly used to measure global warming potential (GWP) based on standard (EN 15978, 2011) and the unit of measure is the CO_2 equivalent.

Designers lack the tools to perform cost and emission calculations fluently. (Heinisuo et al, 2010) introduced a BIM-based tool for the fabrication cost calculations of steel structures. The idea of the tool is to transfer data from the BIM to a separate cost calculation program which allows the designer to compare the costs of different solutions, e.g. different joint layouts. The main point is that quite complete BIMs are available for steel structures already at the early stages of projects, at least in Finland. The developed tool enables the steel designer to compare the costs with little extra work. BIMs are more widely used with steel than other building materials, but the difference is narrowing down continuously. The tool was demonstrated in (Haapio et al 2011) to find cost optimal joints for a sway frame.

In this paper the system used in (Heinisuo et al 2010) has been enlarged to cover not only fabrication costs but also transportation and erection on site, as presented in (Haapio 2012). It was also found that the same process-based approach used in (Haapio 2012) suits well the calculation of CO_2 equivalents. The basic data is derived from environmental product declarations (EPDs) which are now widely available for steel structures (Dowling 2012). The first results of cost and emission calculations using the updated tool are presented in this paper. Both the costs and the emissions cover the "cradle to site" stage, including module A and re-cycling module D of (EN 15978, 2011). The use stages of the steel frames, modules B and C, do not involve costs and emissions and are not considered.

The example presented in (Haapio et al 2011) is presented again including updated cost data (Haapio 2012). The manual search for a cost optimal steel frame starting with rigid joints and ending with semi-rigid joints is presented. Emissions are calculated at each step and the interesting research question is: are the emissions in line with cost decreases? It should be noted that the search for an optimal frame was done without changing member sizes, only joint layouts were altered. If costs and emissions are calculated using weight-based methods, no difference in costs and emissions can be detected.

2 Example Frame and Iterations

A plane steel frame was chosen from of the European ACCESS STEEL (Access-steel 2010) database as a starting point for the simulations. The frame and the numbering of the joints are shown in Fig. 1 and the actions of the frame are shown in Fig. 2. The steel grade is S355.

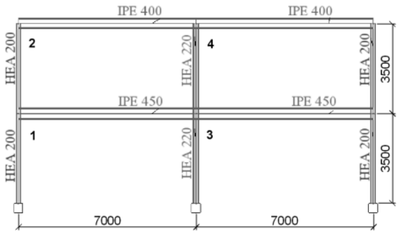

Fig. 1. Examined frame

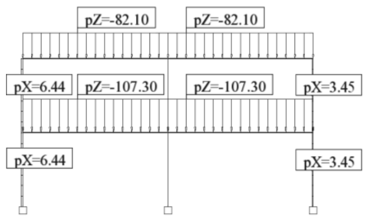

Fig. 2. Actions of the frame, kN, m

The first step involved analysing the frame using absolutely rigid beam-to-column joints (only end plate joints were considered). The frame including all joint components was modelled using a commercial product modelling software (Tekla Structures 15.0). The resistance checks were made according to the Eurocodes using commercial software; joints: Weynand et al, 2005 (CoP); members: Autodesk Robot. The base joints remained rigid in all steps, but they were not modelled. Joints 1-4 in the first step are shown in Fig. 3 and can be considered rigid (Eurocode 3, 2005).

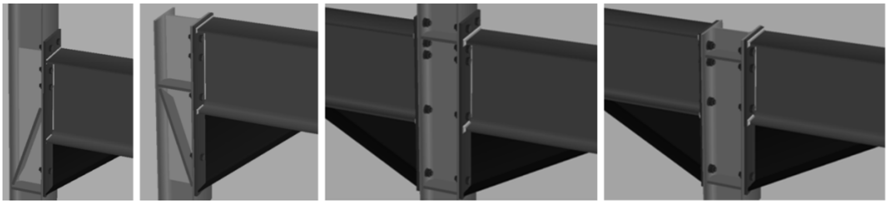

Fig. 3. Joints 1-4 in the first step

Then, rotational stiffnesses of joints 1–4 were reduced in steps. This was done manually by changing the end plate joint layouts so that the profile of the frame members did not have to be changed. At each step resistance checks were carried out to see if the solution was still feasible. When joint stiffness changes, flexural buckling lengths of columns also change. Critical load factors were defined at each step to calculate the buckling lengths of columns for column resistance checks. The best solution among the analysed alternatives was found after six steps and the rotational stiffnesses of joints 1–2 were reduced by as much as 85% from step 1 and those of joints 3–4 by as much as 75%. Joints 1-4 in the last step are shown in Fig. 4 and can be considered semi-rigid (Eurocode 3, 2005).

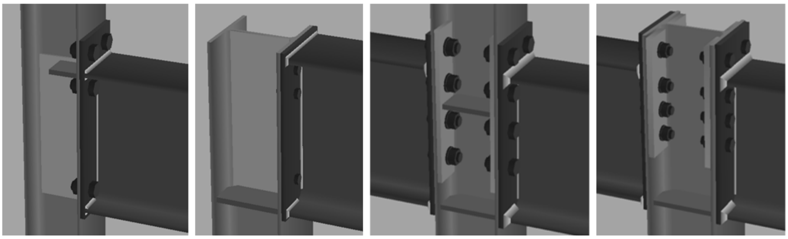

Fig. 4. Joints 1-4 in the last step

According to (Haapio et al 2011), the maximum utility ratios for the frame with rigid joints (first step) are: members 0.98, joints 1.00. The maximum utility ratios for the frame with semi-rigid joints (last step) are: members 0.94, joints 0.99, and the smallest utility ratio for the members with semi-rigid joints is 0.64 for the IPE400 member (roof beam, see Fig. 1). This means that it may be possible to use smaller members with semi-rigid joints, but this option was not considered in this study.

3 Cost and Emission Calculations

Costs and emissions are calculated using the method presented in (Haapio 2012). It involves dividing the manufacturing process into cost centres of a specified floor area and height, equipment suitable for executing the required process (i.e. drilling a hole) and a certain number of workers. These resources have a fixed per minute cost, whether the process is running or not. Some cost components are related only to process time, i.e. electricity consumption of the equipment. They are called variable costs. The time required by the process is the sum of non-productive time, i.e. fixing the profile to the equipment, and process time, i.e. drilling. Total process cost is the sum of the fixed cost multiplied by total time plus the variable cost multiplied by process time. Some processes may also involve non-time related cost components. These are added to time-dependent costs. The cost equation can be presented in the form:

$$C_k = (T_{Nk} + T_{Pk}) \times (c_{Lk} + c_{Eqk} + c_{Mk} + c_{REk} + c_{Sek})/u_k + T_{Pk} \times (c_{Ck} + c_{Enk}) + C_{Ck} \tag{1}$$

where:

C_k = total cost of cost centre k [€];

T_{Nk} = non-productive time of cost centre k [min];
T_{Pk} = productive time of cost centre k [min];
c_{Lk} = unit labour cost of cost centre k [€/min];

c_{Eqk} = equipment installment unit cost of cost centre k [€/min];

c_{Mk} = unit cost of equipment maintenance of cost centre k [€/min];

c_{REk} = unit cost of real estate of cost centre k [€/min];

c_{Sek} = unit cost of real estate maintenance of cost centre k [€/min];

c_{Ck} = unit cost of time-related consumables needed in processing of cost centre k [€/min];

c_{Enk} = unit cost of energy needed in processing of cost centre k [€/min];

C_{Ck} = total cost of non-time-related consumables used in cost centre k [€];

u_k = utilisation ratio of cost centre k [decimal, ≤ 1].

Truck transportation cost is determined based on the weight and volume of the assembly and transportation distance. Erection cost is calculated on the basis of the time required to lift the assembly to its final position and to fasten the bolts. Crane, man lift, fork lift and labour costs are also considered.

Emissions of the manufacturing process are calculated based on the time components used in cost calculation, multiplied by the emission units of cost centre real estate (heating and ventilation) and equipment (electricity consumption). Emissions from the production of materials, i.e. steel, bolts and consumables, are obtained from EPDs published by material manufacturers. Emissions from transportation and erection deriving from the use of fuel consuming motors are calculated using a Finnish web publication (Lipasto).

4 Results

Fig. 5 illustrates the cost distributions between members and joints of six frames from Step I (rigid joints, see Fig. 3) up to Step VI (semi-rigid joints, see Fig. 4).

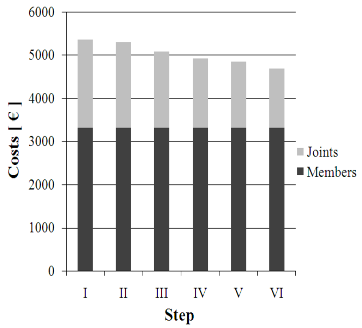

Fig. 5. Cost distributions of frames

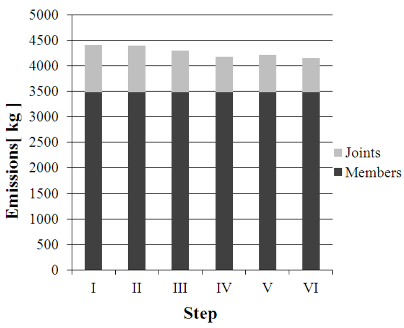

Fig. 6. Emission distributions of frames

Fig. 6 shows the emission distributions for the same frames.

5 Conclusions

The results show that the total cradle-to-site costs of the frame decrease about 12% if semi-rigid joints are used instead of rigid ones in the above case. The sizes of the frame members were kept the same resulting in about 33% savings in fabrication costs, which can be considered large. The emissions did not decrease as much as costs, but reduction was about 6% in total emissions and 28% in fabrication emissions. The fourth solution (Step IV in Fig. 6) produced almost the same emissions as the last one (Step VI in Fig. 6).

Yet, the proposed BIM-integrated cost and emission calculations seem to be a suitable way of improving the steel design process. Designers need tools like this to face future challenges.

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