Enlargement of the component method into 3D

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ABSTRACT: The paper deals with the enlargement of the well-known component method presented in the most novel standard EN 1993-1-8 into three dimensional cases. The component method is used for the determination of the stiffness of the joints and for the resistance checks of the joints of steel skeleton. The component method is rather generic and it can be used to design for many kinds of structural steel joints both in ambient and in fire conditions. The component method can be logically enlarged into the design of the structural steel joints in three dimensions as shown in the paper. The examples of the base bolt joints and the effects of the joint stiffness for the design results are given. The automatic generation of the local analysis model of the base bolt joint starting from the product model of the steel skeleton is illustrated in the paper. By implementing the new methods into the software widely used by the engineers enable the use of new research results with a small time lag.

1 INTRODUCTION

Real joints behave in some extent in three dimensions, but unfortunately very limited information is available to design purposes of structural steel joints in 3D. An excellent recent paper (Simões da Silva 2008) summaries the literature up to today and introduces test results to be used in the component method.

The component method was initially developed in (Tschemmernegg et al. 1987) for ambient temperature conditions and after much development it is now included in the most novel standard EN 1993-1-8 (EN 1993-1-8 2005). The component method has been extended to elevated temperatures in (Leston-Jones 1997) and others. The paper (Simões da Silva 2008) includes some considerations for the use of the component method for dynamic cases.

The component method is used to define the stiffness of the joints and to perform the resistance checks of the joints in steel structures. The component method is rather generic and it can be used to design for many kinds of structural steel joints both in ambient and in fire conditions. The component method can be logically enlarged into the design of the structural steel joints in three dimensions as shown in this paper.

The members of the steel skeleton can be modeled with beam elements for the structural analysis done by the finite element method. Only beam elements are considered in this paper. The beam element is represented typically by the line between the joints. The beam elements are locating at the shear centers of the cross-sections of the uniform members. These beam elements are rather easy to generate from the geometrical model of the steel skeleton and many protocols have been developed and used in practical applications world wide (Heinisuo 2001).

Only one beam element from joint to joint can be used along members, if so called exact finite elements are used between the joints. The exact finite element means, that the behavior of the member between the nodes is described exactly based on the solutions of the equations describing the behavior. These kinds of solutions are available especially for material linear cases (Heinisuo 1989). The exact finite elements are not much available in commercial programs, but approximate solutions are used also for linear cases, and more than one element is used between joints. However, the beam element model is rather easy to generate automatically from the geometrical model for the members between the joints.

At the ends of the beam element are nodes including different amount of degrees of freedoms depending on the case under consideration. Typically three displacements and three rotations are used as degrees of freedoms for the three dimensional analysis. This case has been considered in the paper (Simões da Silva 2008). However, steel members may e.g. warp and distort when loaded. Exact and approximate beam elements have been developed for the warping torsion and an approximate beam element has been developed for the distortional cases (Heinisuo et al. 1995).

So, the different kinds of beam elements can be generated for the steel members between the joints. But how model the skeleton for the analysis near the joints? Different kinds of local joint models and the coupling of the local joint models to the beam models have been proposed, e.g. in (Heinisuo & Rautakorpi 1998).

The component model includes elements which can be used to develop the local joint analysis models for many kinds of structural steel joints. The enlargement of the component method into three dimensional behavior of the base bolt joint is given in this paper. The base bolt joint appears in almost every steel skeleton, so it is a good starting point to develop the method. This paper includes only the theoretical studies, no tests are so far available to confirm the results. The numerical examples deal with the traditional six degrees of freedoms per node, and one warping case is given.

The automatic generation of the local analysis model of the base bolt joint starting from the product model of the steel skeleton is illustrated in the paper. By implementing the new methods into the software widely used by the practicing engineers enable the use of new research results with a small time lag.

2 BASE BOLT JOINT IN 3D

When designing the base bolt joint applying the standard EN 1993-1-8, then the geometrical entities of the joint are split into spring elements. The stiffness of the spring elements is derived following the rules of EN 1993-1-8. If the connected member, typically the column, is locating vertically then the vertical springs are located at the compression side near the mid-lines of the parts of the cross-section of the connected member (see the examples later) and at the tension side at the mid-points of the bolts. Moreover, there are horizontal springs to resist the shear forces and the torsion. All the springs are connected to the beam element representing the member above the joint with rigid links. So, the local joint model for the base bolt joint is ready and can be transferred to the total analysis model of the steel skeleton. After the analysis the resistances of the spring elements are checked using the rules of EN 1993-1-8. This means the resistance checks of all the entities of the joints, such as grouting, base plates and base bolts as given in the standard.

It can be seen above, that the local analysis model of the base bolt joint can be derived based on the geometrical entities of the joint. The same conclusion holds for other structural steel joints of the skeleton, as well, as long as the component method can be used for those. Only difficulty arises, when defining the proper yield lines of the base plates for different geometries. The yield line lengths are needed when defining the stiffness of the tension side springs and when checking the resistances of those. Rather good, but not complete, algorithm was developed in (Lehtimäki 2009) for this purpose and in the cases considered it worked well.

One problem arises, when using the method described above. From the geometrical entities we get to the same analysis model both the potential compression and the potential tension spring elements. If we know the axial force and the bending moment of the joint, then we can put to the model only the active compression and tension spring elements applying the rules given in the standard EN 1993-1-8. This is the case when the skeleton is statically determinate, meaning that we can derive the actions of the joint using only the equilibrium equations. This is not the case in the general case, and typically the steel skeletons are not statically determinate.

This means that we end up to the non-linear case when considering the entire skeleton. The potential compression springs should be compression-only typed elements and the potential tension springs should be tension-only typed elements in the analysis. This means, also, that the computa-

tional time may be large using typical commercial programs if the total analysis model is large, because all the loading combinations should be calculated separately and the linear combination of the results of the basic load cases cannot be used. Some numerical results for that are given in (Laine 2008). This situation is changing all the time due to development of programs and computers.
The rotational stiffness of the base bolt joint can be calculated approximately as a mean of the negative bending moment and of the positive bending moment without the effect of the axial force. The best feature of this approximation is that then we get the linear analysis model for the entire skeleton. Other ways to linearize the problem are given in (Laine 2008).

3 EXAMPLES

Figure 1 illustrates the basic rules to derive the locations for the compression springs for different cross-sections of the member to be jointed at the base bolt joint. Similar rules can be derived for the joints with stiffeners. The flanges are derived into three parts although two parts would be the minimum to get results in 3D. Three parts are used to connect the stiffeners with more ease to the model and perhaps we get better results in 3D problems using three parts instead of two.

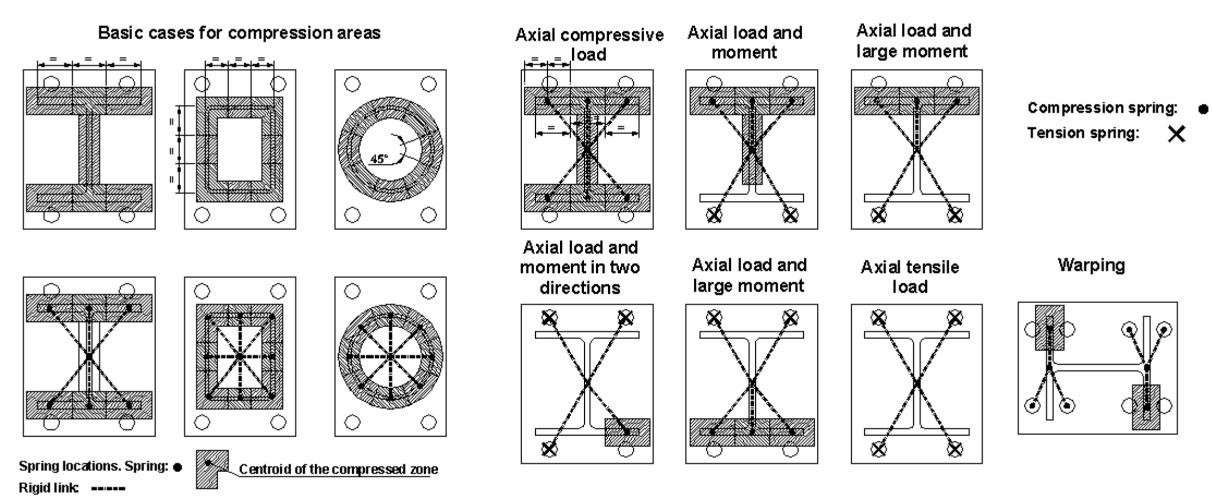

Figure 1. Examples of local analysis models for the base bolt joints.

The required stiffness of the rigid links can be derived analytically (Laine 2008), or absolutely rigid links can be used if available in the analysis program, or the stiffness can be defined based on the experience. Some control should be available to avoid too short and rigid elements to ensure the solution of the final system equations.
Figure 1 illustrates some local analysis models for different actions for I-profile member joint. Shear forces and torsion moments are transferred in this study by the friction under the base plate. This means that at the intersection of the rigid links is a horizontal support in two directions and the torsion of this node is prevented.
Figure 1 illustrates one (the last in the figure) local analysis model to take into account the local warping of the joint. It is supposed, that the warping is orthogonal to the other actions of the joint, as it is supposed in the analysis of the members. Then the warping model can be independent as shown in Figure 1. Only problem when analyzing the warping of steel structures, is that this degree of freedom is so far missing from the most commercial programs. And, so far this has not been implemented into the integrated system described later.
In Figure 2 is illustrated all the potential local components for one base bolt joint, an example joint layout and a frame.

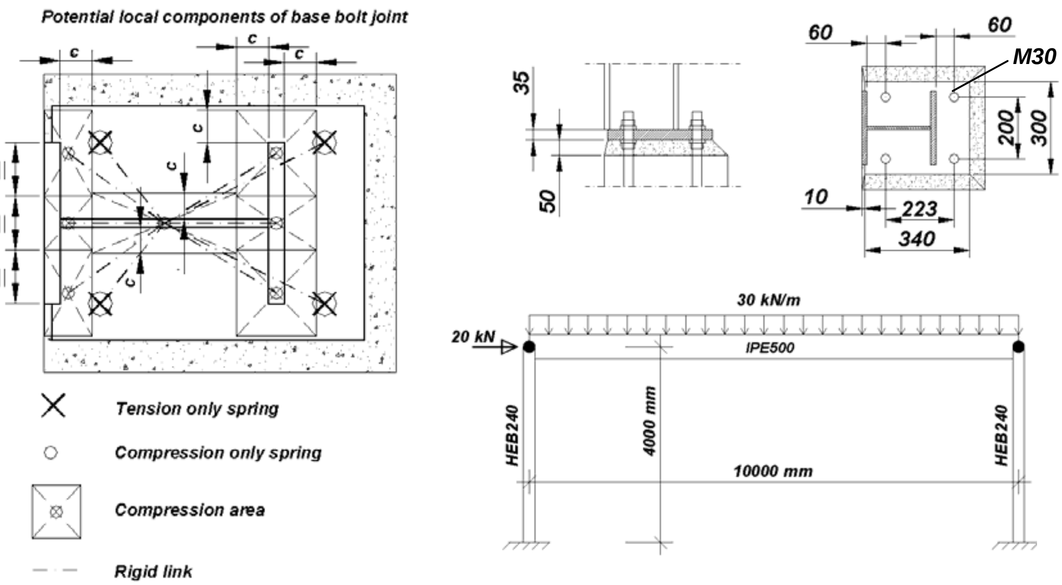

Figure 2. Potential local components, example joint and portal frame.

The joint shown in Figure 2 is at both column bases of the portal frame shown in Figure 2. The mirror of the joint presented in Figure 2 is at the right column base. The frame is a plane frame and at the top corners are hinges. The results for this case are given in Table 1. The non-linear and the linear cases are as explained above.

Table 1. Results for the plane frame example

Case	Stiffness/left kNm/rad	Stiffness/right kNm/rad	Moment/left kNm	Moment/right kNm	Horizontal disp. column top mm
Rigid	∞	∞	40.09	39.91	9.1
Non-linear	21321	58548	35.18	49.18	14.6
Linear	13016/26978	40929/26978	40.06	39.94	15.0

Case	α_{cr} of Eurocodes	L_{cr} / Height (4 m)	L_{cr} m	Max utility Left joint	Max utility Right joint
Rigid	24.31	2.00	8.00	-	-
Non-linear	17.68	2.35	9.38	0.27	0.53
Linear	16.51	2.42	9.71	0.32	0.42

It can be seen, that the stiffness of the base bolt joints have considerable effects to the buckling lengths of the columns and for the horizontal displacements in this case. It can be seen, that the linear theory means safe result (0.32 > 0.27) for the left joint utility and for the buckling length (2.42 > 2.35) compared to the non-linear theory. The situation is vice versa for the right joint utility (0.42 < 0.53), so it cannot be said that the linearization means the safe solution for all the results.
The same joint layout has been used in the next example. In this case we look for the good solution if the span, the actions (uniform and axial) and the base bolt joint layout are given for the column as shown in Figure 3. We look for the material grades and the cross-section of the column and the base bolt dimensions (bolt diameter and base plate thickness) and only discrete values for those are accepted. We apply here a layered particle swarm algorithm (Heinisuo et al. 2007) for the optimization (PSO).

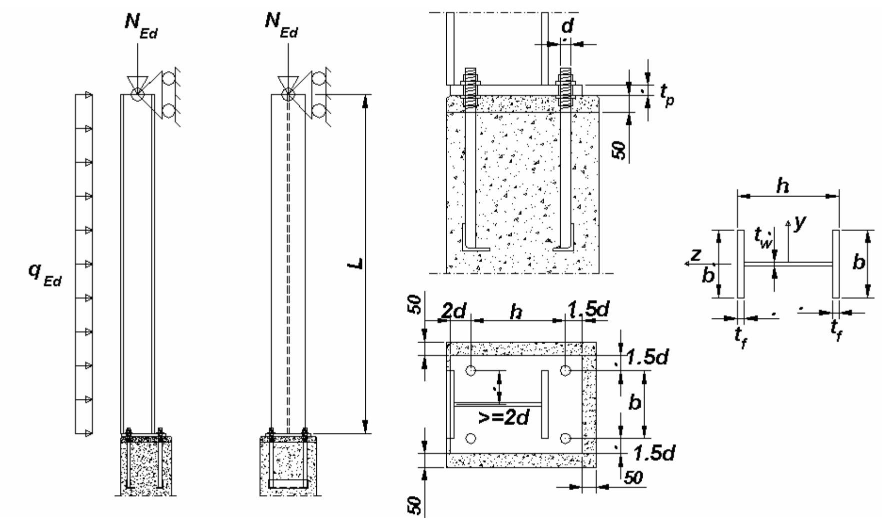

Figure 3. Example for the optimization

Now, seek for the good solutions (optimize) using the following data:

Fixed parameters: N_{ed}, q_{Ed}, L, grout concrete C40/50 (foundation below the grout is supposed to be strong enough), material factors, steel: $\gamma_{M0} = \gamma_{M1} = 1.0$, $\gamma_{M2} = 1.25$, concrete: $\gamma_M = 1.35$. Only positive axial load (meaning compression for the column) and the positive uniform load as shown in Figure 3 are possible. Elastic modulus of steel $E = E_p = E_b = 210000$ MPa.
Variables when seeking the good solutions: h, b, t_f, t_w, d, t_p, steel materials for the column (same material for the flanges and the web, hybrid not allowed) and the base plate, all base bolts are supposed to be type Peikko, HPM.
Constraints when seeking the good solutions: Resistance checks of the column and the joint following EN 1993-1-8 (Method B of EN 1993-1-1 for the column). Only restriction is that the cross-section class 4 is not allowed for the column.
Fitness function when seeking the good solutions: Search for the lowest fabrication costs of the column including the base bolt joint.

The design space for the variables is limited as follows:

t_f, t_w = 5, 6, 8, 10, 12, 15, 16, 20, 22, 25, 30, 35, 40 mm,
t_p = 15, 20, 25, 30, 35, 40 mm,
h, b = 50 – 1000 mm with 5 mm steps,
d = 16, 20, 24, 30, 39 mm,
Steel grades S235, S275, S355, S420, S460.

In this case it is used the linearized base bolt joint rotational stiffness for two bending moments, moments around the strong axis and around the week axis. The buckling lengths are defined from the analytical solution for these cases in both directions during the calculations. All the equations needed for the resistance checks of the column including the base bolt joint are given analytically for this case. The same holds also for the cost functions given in (Heinisuo et al.1999).
The fabrication costs include material costs and the following components for the activities to fabricate the steel members: sawing, flame cutting, drilling, profile welding (automatic sub-merged arc-welding supposed), plate welding (manual MAG welding supposed), blasting and painting (Polyurethane paint, final thickness 180 µm, three paints). Each activity cost is a combination of the following cost components: labor costs, equipment costs, use of the equipment, real estate costs, use of the real estate, cost of the materials for the activity, energy costs and inspection costs.
All the components are calculated based on the durations of the activities. The duration of one activity $T_{activity}$ is calculated using Equation (1)

$$T_{activity} = T_{pre\_action} + T_{action} + T_{post\_action} \quad (1)$$

The input data dealing with the entities appearing the in the steel skeleton to perform the very detailed cost calculations described shortly above, can be derived from the product model of the steel skeleton using a developed macro, but in this simple case the macro was not used.

Some solutions for the column case are given in Table 2. Notation PSO means the best of 10 solutions using the particle swarm optimization. Unit price for S235 grade steel plate was 1.17 Euro/kg. Steel grade cost effect was taken into account following (Johansson 2005). Other cost data were those used in Finland today and costs of equipments are based on the machine fabricators' data and the real estate and the energy costs used are hypothetical, but relevant to Seinäjoki area, Finland.

In all final cases the base bolt joints are classified as rigid for the rotation following EN 1993-1-8 in the both directions: weak and strong axis bending. During the calculations, the joint stiffness was calculated analytically and the effects of the joint stiffness to the buckling lengths in both directions were calculated based on the solutions of the well-known differential equation for the case. The second order effects were taken into account approximately using the Timoshenko factor for the actions and for the deflections. The factor was 1.24 for the final cost optimum solution and 1.36 for the final minimum weight solution. The used deflection limit was $L/600$.

Table 2. Results of the optimization L = 8 m, N_{Ed} = 2000 kN, q_{Ed} = 10 kN/m.

Case	d (mm)	t_p (mm)	h (mm)	b (mm)	t_f (mm)	t_w (mm)	f_y (MPa)	W (kg)	Cost (Euro)	Utility Column	Utility Joint
Min W (PSO)	24	40	270	280	15	8	420	700	1495	1.00	0.50
Min W (Exact)	20	30	275	280	15	8	420	689	1455	1.00	0.71
Min Cost (PSO)	16	40	325	330	15	8	235	826	1316	1.00	0.95
Min Cost (Exact)	16	35	325	330	15	8	235	820	1309	1.00	0.95

It can be seen, that in this case the minimum weight solution is quite different to the minimum cost solution. Moreover, it can be seen, that the layered particle swarm optimization solution is very near by the absolute best solution in these cases. The rotational stiffness of the base bolt joint was derived based on the component method for the weak axis bending.

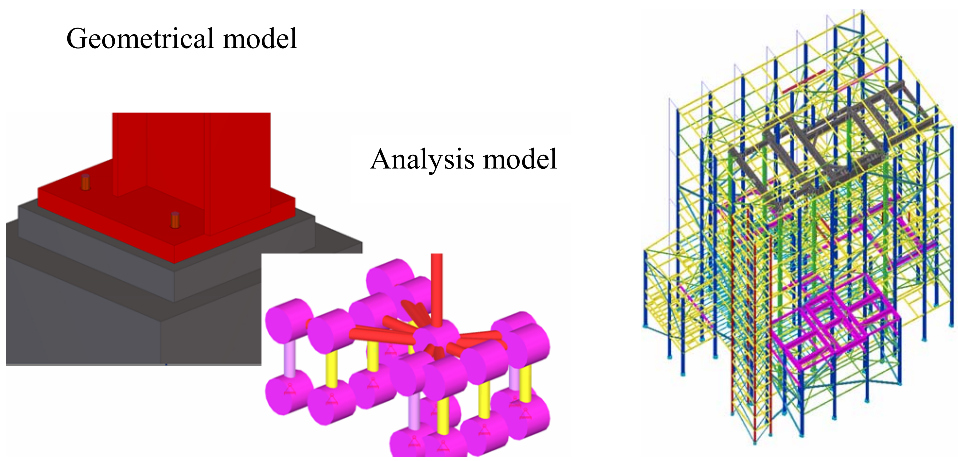

Figure 4. Industrial building skeleton and its base bolt models

Next example illustrates a real life example. The design was completed in Ramboll Finland Oy. The local analysis model including all the potential spring elements are shown in Figure 4 as they are generated in the product modeling software, Tekla Structures in this case. The analysis model of the steel skeleton of an industrial building has been generated into the analysis program Robot. After the analysis the forces of the active spring elements are get back to the product model and the resistance check is done there using a macro programmed into the product modeling software. Another macro was used to generate the local analysis models for the base bolt joints. One is shown in Figure 4.

4 CONCLUSIONS

The component model of the standard EN 1993-1-8 is suitable for the design of many structural steel joints in 3D due to its generic presentation. In this paper the base bolt joint is as an example. The analysis model can be generated from the geometrical model and this means that the joint stiffness is automatically present in the structural analysis of the entire skeleton. The resistance checks of all the components of the joint can be integrated into the product modeling software widely used by the engineers. This means a large enhancement to the structural design practice, because joint detailing and analysis are the most time consuming tasks in the design of steel structures.
The study presented is theoretical and no tests are so far available to evaluate the results. The same enlargement including the software implementation can be done for the fire cases. The reliability studies (numerical and experimental) dealing with the results including bending in two directions, axial force and shear forces and warping should also be done. However, the method is fully consistent with EN 1993-1-8 for planar cases. The method seems to have a great potential to enhance the design of steel structures.

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REFERENCES

EN 1993-1-8. (2005). Eurocode 3: Design of steel structures, Part 1-8: Design of joints, CEN, Brussels.

Heinisuo M. (1989). Exact finite element method for layered beams, Tampere University of Technology, *Publications* 56, Tampere.

Heinisuo M. (2001). Product modeling of steel structures, Proceedings of NSCC 2001, 9th Nordic Steel Construction Conference, Mäkeläinen P., Kesti J., Jutila A., Kaitila O. (Eds), Helsinki, Finland, 18-20 June 2001, pp. 41-53.

Heinisuo M., Liukkonen V.-P., Tuomala M. (1995). New beam element including distortion, Nordic Steel Construction Conference 95, Malmö, Sweden, June 19-21, Swedish Institute of Steel Construction, *Publication* 150, Vol I, pp. 65-72.

Heinisuo M., Rautakorpi J. (1998). Teräsrungon rakenneanalyysin tuotemallin generointi geometrian tuotemallista, *Report* 25, Tampere University of Technology, Department of Civil Engineering, Structural Mechanics, Tampere (in Finnish).

Heinisuo M., Rautakorpi J., Haapio J. (1999). Cost Estimation of Steel Structures in FST-EXPERT System, Artificial Intelligence in Engineering, *Information Technology for Design, Manufacturing, Maintenance, and Monitoring*, Borkowski A. (Ed), Wydawnictwa Naukowo Techniczne, Warszawa, pp. 223-224.

Heinisuo M., Saikkonen M., Haapio J., Miles J. (2007). Welded steel beam design using particle swarm analysis, Proceedings of 14th EG-ICE Workshop, Maribor.

Johansson B. (2005). Buckling resistance of structures of high strength steel, in Use and Application of High-Performance Steel for Steel Structures, *Structural Engineering Documents* 8, IABSE.

Laine V. (2008). *Teräsrungon liitosten jouston huomioon ottaminen integroidussa suunnittelujärjestelmässä*, Ms Sci Thesis, Tampere University of Technology, Tampere. (in Finnish).

Lehtimäki E. (2009). *Peruspulttiliitoksen jouston huomioon ottavan laskentamallin muodostaminen ohjelmallisesti liitoksen tietomallista*, B Sci Thesis, Tampere University of Technology, Tampere. (in Finnish).

Leston-Jones L. (1997). *The influence of semi-rigid connections on the performance of steel framed structures in fire*, PhD Thesis, University of Sheffield.

Simões da Silva L. (2008). Towards a consistent design approach for steel joints under generalized loading, *Journal of Constructional Steel Research* 64. pp. 1059-1075.

Tschemmernegg F., Tautschnig A., Klein H., Braun Ch., Humer Ch. (1987). Zur Nachgiebigkeit von Rahmen-knoten – Teil 1, *Stahlbau* 5, Heft 10: pp. 299-306.