

BUILDING THE CODE FOR DESIGN AND OPTIMIZATION OF MEMBERS AND JOINTS OF STEEL LATTICE STRUCTURES COMPOSED OF COLD-FORMED CIRCULAR HOLLOW SECTIONS, ALONG WITH A COMPARISON BETWEEN THE OLD AND THE NEW VERSION OF THE STANDARD EN 1993-1-8 - SUMMARY

PROJECT OBJECTIVES AND GOALS

This Thesis covers two main topics:

- Modifications made in prEN 1993-1-8: 2021 (Technical Committee CEN/TC 250 “Structural Eurocodes”, 2021) in comparison with EN 1993-1-8: 2005 (Technical Committee CEN/TC 250 “Structural Eurocodes”, 2005)
- Building the code for the design and optimization of K gap joints composed of (cold-formed) circular hollow sections,

with an accent on the second topic.

The Thesis is divided into two parts, according to the group of joints in question. The first part, therefore, deals with the modifications made in the first 8 chapters and Annexes of prEN 1993-1-8: 2021. The second part deals with the modifications made in the general part of chapter 9 of prEN 1993-1-8: 2021, *Hollow section joints*, and shortly indicates the possibility of applying the component method for the verification of these types of joints. The second part also shows the changes made in the resistance formulas for K gap joints composed of circular hollow sections, after which the approach taken while building the code for the design and optimization of these types of joints (and their particular members) in accordance with prEN 1993-1-1: 2020 and prEN 1993-1-8: 2021 is described.

One of the goals while working on this Thesis was to make the changes made in the latest version of EN 1993-1-8 available to the users of the current version, and so to facilitate the transition from the first to the second generation of EN 1993-1-8.

The main motive for making this Thesis was to review the research concerning design resistance formulas for K gap joints made of circular hollow sections in order to present the theoretical background for building the code for the design and optimization of these types of joints. That brings us to the second (and main) goal of this Thesis: to make a code in MS Excel that enables the adoption of members of the joint in question only on the basis of the internal forces and the general geometry of the joint. Afterwards, by applying the optimization procedure, this combination will be swapped with an economically more viable combination (if it exists). The basic idea for building this code can be found in (Đuričić, et. al, 2021). This paper considers a direct adoption of sections in an axially loaded K joint by using nomograms. Suppose we made all the necessary nomograms; we could also seek for the most rational combination of sections. Building a code instead of nomograms was meant to “simplify” the procedure of both making and using nomograms. Also, by building codes, we can take into consideration much more complex solutions for the joint (for example, reinforced joint) when we want to adopt the most rational solution, while the simplicity of use of the program remains the same.

Considering the above said, there were two main tasks while building the code:

- 1) To avoid any previous adoption of sections. The program should itself adopt a combination of sections based on the input data. It was good enough to make this first part of the Excel file work on the principle of adopting a combination of members which has a minimum total area, that is, a minimum mass.
- 2) To optimize this adopted combination. Here an accent is put on the price as a function for which a minimum value is sought. Additional conditions should, of course, take into consideration the utilization of the sections, i.e., the joint: for a combination of sections (for a particular joint) to be acceptable, the utilization ratios of the sections, both individually and as parts of the joint, must be ≤ 1 for the relevant values of internal forces (and bending moments).

DESCRIPTION OF METHODS AND RESULTS

A comparison was made in order to determine the differences between EN 1993-1-8: 2005 and prEN 1993-1-8: 2021. Clauses where some kind of modification was done (supplemented, changed, added, removed clauses...) are shown and a short summary of modifications was also given in the conclusion of the Thesis. Due to the

limitations given on the Thesis' scope, Annex C of prEN 1993-1-8: 2021, which is a new chapter for EN 1993-1-8, was left out.

In order to make the code for the design and optimization of the subject joint, MS Excel with its add-ins was used. While building the code for the design of the joint, it had to be kept in mind that this code is “read” by the solver when we want to optimize the joint. In this respect, it was recommendable, at every step of the calculation, to consider the complexity of the calculation for our problem and the possibility of our solver to understand that model. If there is a part of the calculation that does not depend on the variables of the optimization problem, then this part will not influence the complexity of the optimization problem, no matter how “complicated” the calculation formulas are. If the variables of the optimization problem are a part of complex calculation formulas, which complicates the optimization problem, it needed to be considered if that is the only way in which we can formulate our problem or if we should take a different approach.

For that reason, the code for calculation, i.e., for the adoption of the first combination of sections, was built so that it is entirely independent of the optimization variables. That brought the calculation down to a consideration of a vast number of combinations of sections. The program looks up and explicitly shows, in a large table, all the relevant combinations for the subject joint. A binary representation is then joined to each one of these combinations. These binary representations are the variables of the optimization problem. Thanks to this, the optimization problem is classified as a linear problem with discrete variables, for which a solver connected with MS Excel can be applied. The first combination of sections the program adopts will be represented with 1 and all the others with 0. After the optimization, binary representation 1 will shift to an appropriate combination of sections with the lowest price.

After building the code in MS Excel, the design and optimization procedure by using the Excel file made for one joint was checked on particular examples of joint and roof truss. In this summary, the example of the joint will be shown as it is more accurate. Along with it, some aspects of building the code will additionally be explained. General data such as lengths of members, angles of inclination of members, forces in members, etc., represent the input data. Figure 1 shows the general data for our joint. All the general data are input in the orange-coloured cells in the Excel file.

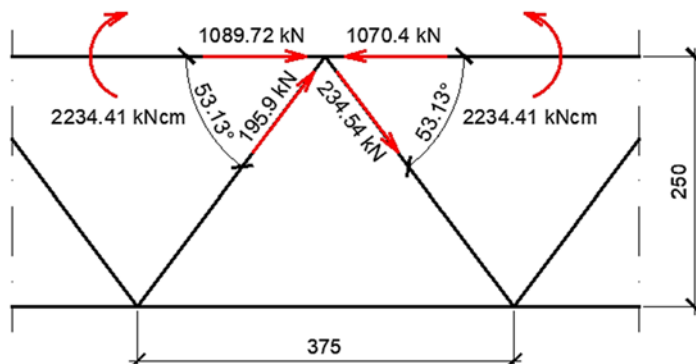


Figure 1: Geometry and forces in the joint

As it can be seen from the Excel file, there are two tables for defining the grade of the material: one for the chord, and the other one for the braces. Next to these tables, you can note tables that show one lower and one higher steel grade compared to the chosen one. We made the program purposely vary the steel grade in order to have some parameters other than mass that would influence the price of the product. It was assumed that higher steel grades have higher prices. The actual steel price wasn't checked (this can be easily rectified in the Excel file). It was not necessary nor realistic to make the program vary between all the seven classes given in Eurocode. For that reason, the program considers only one higher and one lower class compared to the one the user chose for the first combination of sections (Table 1).

Table 1: Selection of steel grade for chord

Select steel grade for chord	Steel grade for chord	fy2 kN_per_cm2	fy1 kN_per_cm2	fy3 kN_per_cm2
S275	S275	23.5	27.5	35.5

It must be highlighted that here the original idea was not to vary only the material. In order to widen the range of possible solutions for the joint before applying the optimization procedure, it would be very interesting to enable the change of shape of sections, add the possibility of reinforcing the joint, vary the material, etc. However, the code was built using Power Query. Power Query is an MS Excel (Office 365) add-in for which MS Excel serves only for writing

the input data and reading off the results. In that sense, the connection between Power Query and MS Excel is not interactive enough and it limits the building of the code only to the possibilities of Power Query. Certain queries¹ inside Power Query, for example, functions written for determining the utilization ratio of the individual members and the joint, had to be copied several times. The big table with all the relevant combinations of sections was also made in several steps. All that slowed down the work of Power Query significantly, so for this first version of the Excel file only the variation of material was assumed.

After writing the general data, it is necessary to click on *Data* → *Refresh All* and wait for the results to load. The results show the first combination of sections for the subject joint - a combination of sections that has a minimum mass, and for which the utilization ratio both of separate members and the joint is ≤ 1 . Also, this combination of sections refers to only those steel grades which the user chooses. (If the user is determined to apply only those steel grades he chose, the relevant combination of sections is the first combination, i.e., he doesn't have to optimize the joint). For our example, a combination of sections was obtained as is shown in Table 2. The adopted steel grade for all the members was S275.

Table 2: Section obtained before optimization (0 – chord; 1 – compression brace; 2 – tension brace)

Outside diameter d0 mm	Thickness t0 mm	Outside diameter d1 mm	Thickness t1 mm	Outside diameter d2 mm	Thickness t2 mm
219.1	10	114.3	3.5	76.1	4

The aforementioned large table with combinations of sections for the joint considers also the other two steel grades from Table 1. The maximum possible number of combinations of materials is 3×3 , so eight more columns were added in this table for the variables, i.e., the binary representations of those other combinations. The number of optimization variables that were considered for this example was $9 \times 13718 = 123462$. Since the maximum number of variables that the solver add-in for MS Excel takes into consideration is 200, an add-in called OpenSolver was installed. This add-in enables assigning the objective function, variables, as well as constraints in the same way as the MS Excel solver add-in. However, this add-in has more efficient solvers than MS Excel's add-in. Using the CBC solver, our problem was successfully solved.

The following tables show the objective function - the price of the joint before and after optimization of the joint - and the combination of sections after optimization. The steel grade for all the members is now S235. It can be noted that the original price is reduced for 53.49€, i.e., for 17.4%.

Table 3: Objective function before optimization

Objective function (cost):	306.95
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Table 4: Objective function after optimization

Objective function (cost):	253.46
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Table 5: Sections obtained after optimization

Outside diameter d0 mm	Thickness t0 mm	Outside diameter d1 mm	Thickness t1 mm	Outside diameter d2 mm	Thickness t2 mm
273	8	139.7	3	114.3	3

POTENTIAL FOR APPLICATION OF RESULTS

The users of the current version of EN 1993-1-8 can use the first part of this paper to keep up to date with the modifications made in the newest draft of EN 1993-1-8.

The code for the design and optimization of the joint, with a few corrections, can be used for the subject joint. However, the design takes up a lot of time – the dynamic change of tables using Power Query is relatively slow. The code in Power Query also loads slowly. For that reason, a more complex code that would take into consideration a change in cross-section shape of joint members, reinforcing the joint, etc. could not be made for now. The easiest way around was to vary steel grades in order to widen the range of viable solutions. The other problem with this code was that everything was considered on the level of the joint, so the change of internal forces (and bending moments) due to the change in self-weight could not be taken into consideration.

¹ The term query refers to any Power Query unit: table, list, function...

The code can be enhanced if verifying the resistance of members and joints was entrusted to other programs. The other enhancement would be to consider the design and optimization problem on the level of the whole structure.

To solve a great part of this problem it would be convenient to connect MS Excel and SAP2000. SAP2000 could use for the analysis of the whole structure and for checking the utilization ratio of members according to EN 1993-1-1. That would enable us to remove the part of the code in Power Query which calculates the utilization ratio of the members and thus significantly speed up the work of Power Query. The main issue here would be to determine the way to filter the data on the level of a structure. The simplest approach would be filtering the combination of sections according to a realistic main geometry of the structure, but it should further be examined what is the usual extent of data that would be gained in this way and how much time would it take for SAP2000 to analyze all the relevant solutions. For joints, it should be determined if it would be more appropriate to use commercial software or if making codes would be simpler and better. The workflow between software and capabilities of the software, in general, should be analyzed in order to propose a good and new solution. In this respect, of great significance is to go through previous research done on this topic to obtain an overview of the latest achievements. For example, in (Baldissera dos Santos and Palomino-Tamayo, 2020) a connection between MS Excel and SAP2000 was made. The structure is optimized using an optimization algorithm, but everything is considered on the level of members, i.e., joints aren't taken into account. Also, this paper considers only lattice structures. However, in our case, the first step would be to expand the code to any members and joints, i.e., any steel structure at all. If we can accomplish this, the complete calculation can be reduced only to the input of the general geometry of the structure and its loads. The second step would be to include certain preferences so that users can optimize the structure not only on the basis of the lowest price. Since this would become an interdisciplinary problem and much more work and research is needed than for the previously explained example, it is important to estimate the time and resources available before making any further alterations to the code.

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