



UNIVERSITAT
POLITÈCNICA
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THE DESIGN OF THE
SUPPORT BEAM OF
UNDULATOR WITH THE
USE OF AUTODESK
INVENTOR
PROFESSIONAL

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1. Introduction

This project intends to the design and dimensioning of the support beam of an undulator, taking into consideration beams with different cross-sections, subjected to the static loading.

The structural analysis of the beam was made with the use of the Autodesk Inventor Professional. The performed calculations allow for the selection of the optimal shape and cross-section of the beam.

Firstly, some preliminary calculations, to determinate analytically the optimal location for support were made in order to determine minimum deflections both in the centre as well as at both ends of the beam (the least favourable points). Such calculation was made with the use of the classical theoretical solutions. The detailed analysis of the beam deflection was performed in the Autodesk Inventor Professional. It allows for evaluate possibilities of the Autodesk software in the further design process and allows to calculate a more accurate behaviour of the designed structure.

Once that is done, the optimal moment of inertia for the beam was calculated. It allows for the selection of the typical and standardized cross-section of the beams. A few examples were selected, calculated, and finally compared in the project.

Once the optimal cross-section was determined, the beam was modelled in 3D and the corresponding 2D sketches were attached.

2. Main aim and assumptions

As established before, this project aims to optimally design the support beam of an undulator using Autodesk Inventor Professional.

To start with the analysis, some assumptions regarding the characteristics of the beam must be taken into consideration.

The beam is 2000 millimetres long and it is made of steel. The maximal deflection of the beam should not exceed 10 micrometres in any point of the beam. This value of the maximal admissible deflection will be used later to calculate the minimal required moment of inertia of the beam.

The beam will be subjected to external loading of 20 kN, which will be distributed evenly throughout the totality of its length. The own weight of the beam was also taken into consideration.

3. Software description

Autodesk Inventor Professional is a software that provides professional tools for mechanical design, 3D simulation of products and documentation.

For this project the functions used will be parametric model, which allows to create and edit 3D models, assembly modelling, which allows to assembly different components, specifying relations between them and movement restrictions, and creation of a drawing, which will be used at the end to obtain clear and detailed drawings suitable for the production of the product.

Using this software, every detail of the components can be determined, as well as the unions between them, such as welded unions in this case.

As for mechanical design, the software allows performing stress analysis specifying specific loadings, support, and materials. This will be used in the early stages of the project.

4. Preliminary calculations

In these preliminary calculations, the deflection on the beam under the static loading was performed. In order to include the beam weight, the initial loading was increased by the 20% and it was assumed that the loading is continuously distributed at the bottom of the beam. Such studies were made with the use of the analytical formulation, and later with the use of the Autodesk Inventor Professional. Both results were compared and summarized in the project.

After the calculations, a conclusion will be encountered on whether or not Inventor is a good tool to be used for engineering design basing on the accuracy of the results, and the optimal location for support in the beam will be determined.

The assumed loading and boundary condition of the beam is given in figure 1. The optimal value for the parameter a is the one to be found, to minimize the absolute values of deflection in the centre and at the both ends of the beam. For assumed configuration of the beam, loading and boundary condition, the maximal deflections may occur in these two points. Minimizing deflection in these points below 10 micrometres will ensure that the maximal deflection should not be larger than this admissible value.

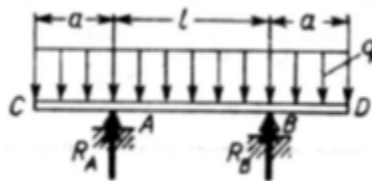
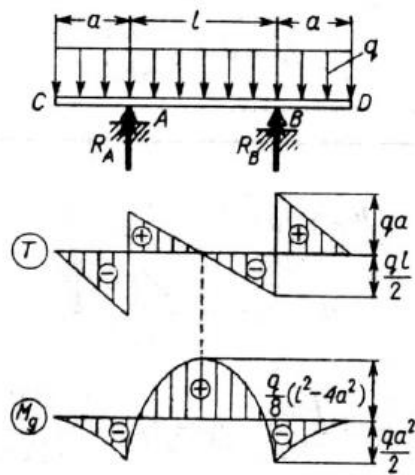


Figure 1. The assumed loading condition and support of the investigated beam

In figure 2, the formulae used in the studies are shown. They express the values of f_0 (deflection in the centre of the beam) and $f_c = f_D$ (deflection at the end of the beam) in function of the external loading (q), Young modulus of steel ($E = 206000$ MPa), the moment of inertia of the beam J , distance ' a ' and ' l ', which is known to be the total length of the beam (2000mm) minus two times ' a '.



$$R_A = R_B = q \left(a + \frac{1}{2} l \right),$$

$$M_{\max} = \begin{cases} \frac{q}{8} (l^2 - 4a^2) & \text{dla } a \leq \frac{l\sqrt{2}}{4}, \\ \frac{qa^2}{2} & \text{dla } a \geq \frac{l\sqrt{2}}{4}, \end{cases}$$

$$\theta_B = -\theta_A = \frac{ql}{24EJ} (l^2 - 6a^2),$$

$$\theta_D = -\theta_C = \frac{q}{24EJ} (l^3 - 6la^2 + 4a^3),$$

$$f_C = f_D = \frac{qa}{24EJ} (l^3 - 6la^2 - 3a^3),$$

$$\text{dla } x = a + \frac{1}{2} l \quad \theta_0 = 0, \quad f_0 = \frac{ql^2}{384EJ} (5l^2 - 24a^2)$$

Figure 2. The internal forces in the beam and theoretical solutions taken from references [1]

The optimal distance between supports was calculated assuming random initial values of the moment of inertia of the beam. It should be noted here, that in the investigated case the optimal position of the support does not depend on the value of the external load and the moment of the inertia. Now assigning random yet reasonable values for the external loading and the moment of inertia of the beam, such as $q = 20$ [N/mm] and $J = 5.5 \cdot 10^6$ (mm⁴) the values for both deflections f_0 and f_c (they are given in mm and μm) in function of the variable distance 'a' were calculated (table 1) and plotted (figure 3).

Taking values from 350 to 500 mm the results shown in figure 3 for f_0 and f_c are obtained, besides both plotted functions, as well as $|f_0| - |f_c|$ (figure 3). It can be seen that the minimal deflection in the centre and at both ends of the beam are for different values of the distance a . The selection of one of these points ($a = 430$ mm or $a = 475$ mm) results in the minimal deflection at one of these points but in the second the deflection achieves very high values. Because of this the optimal distance a is in point in which deflections in both points f_0 and f_c are the same and in which the $|f_0| - |f_c|$ is the smallest. This occurs for distance a in the range 445-450 mm (see table 1-marked rows by yellow colour).

Table 1. the results of the calculation for the initial configuration of the beam

a	l	q	J	E	fo	fc	fo	fc	fo - fc
(mm)	(mm)	(N/mm)	(mm ⁴)	(MPa)	(mm)	(mm)	(μm)	(μm)	(μm)
350	1300	20	5.50E+06	206000	0.42806	0.28649	428.06	286.49	141.58
355	1290	20	5.50E+06	206000	0.40512	0.27078	405.12	270.78	134.35
360	1280	20	5.50E+06	206000	0.38273	0.25468	382.73	254.68	128.04
365	1270	20	5.50E+06	206000	0.36087	0.23821	360.87	238.21	122.65
370	1260	20	5.50E+06	206000	0.33954	0.22137	339.54	221.37	118.16
375	1250	20	5.50E+06	206000	0.31873	0.20417	318.73	204.17	114.56
380	1240	20	5.50E+06	206000	0.29845	0.18661	298.45	186.61	111.84
385	1230	20	5.50E+06	206000	0.27868	0.16870	278.68	168.70	109.98
390	1220	20	5.50E+06	206000	0.25942	0.15046	259.42	150.46	108.97
395	1210	20	5.50E+06	206000	0.24067	0.13188	240.67	131.88	108.79
400	1200	20	5.50E+06	206000	0.22242	0.11297	222.42	112.97	109.44
405	1190	20	5.50E+06	206000	0.20466	0.09375	204.66	93.75	110.91
410	1180	20	5.50E+06	206000	0.18739	0.07422	187.39	74.22	113.17
415	1170	20	5.50E+06	206000	0.17060	0.05439	170.60	54.39	116.22
420	1160	20	5.50E+06	206000	0.15429	0.03425	154.29	34.25	120.04
425	1150	20	5.50E+06	206000	0.13846	0.01384	138.46	13.84	124.62
430	1140	20	5.50E+06	206000	0.12309	-0.00686	123.09	-6.86	116.23
435	1130	20	5.50E+06	206000	0.10819	-0.02783	108.19	-27.83	80.36
440	1120	20	5.50E+06	206000	0.09374	-0.04907	93.74	-49.07	44.67
445	1110	20	5.50E+06	206000	0.07974	-0.07056	79.74	-70.56	9.18
450	1100	20	5.50E+06	206000	0.06619	-0.09230	66.19	-92.30	-26.11
455	1090	20	5.50E+06	206000	0.05308	-0.11429	53.08	-114.29	-61.21
460	1080	20	5.50E+06	206000	0.04041	-0.13651	40.41	-136.51	-96.10
465	1070	20	5.50E+06	206000	0.02816	-0.15895	28.16	-158.95	-130.79
470	1060	20	5.50E+06	206000	0.01634	-0.18162	16.34	-181.62	-165.28
475	1050	20	5.50E+06	206000	0.00494	-0.20449	4.94	-204.49	-199.55
480	1040	20	5.50E+06	206000	-0.00605	-0.22758	-6.05	-227.58	-221.53
485	1030	20	5.50E+06	206000	-0.01663	-0.25085	-16.63	-250.85	-234.23
490	1020	20	5.50E+06	206000	-0.02680	-0.27432	-26.80	-274.32	-247.52
495	1010	20	5.50E+06	206000	-0.03658	-0.29797	-36.58	-297.97	-261.38
500	1000	20	5.50E+06	206000	-0.04597	-0.32179	-45.97	-321.79	-275.82

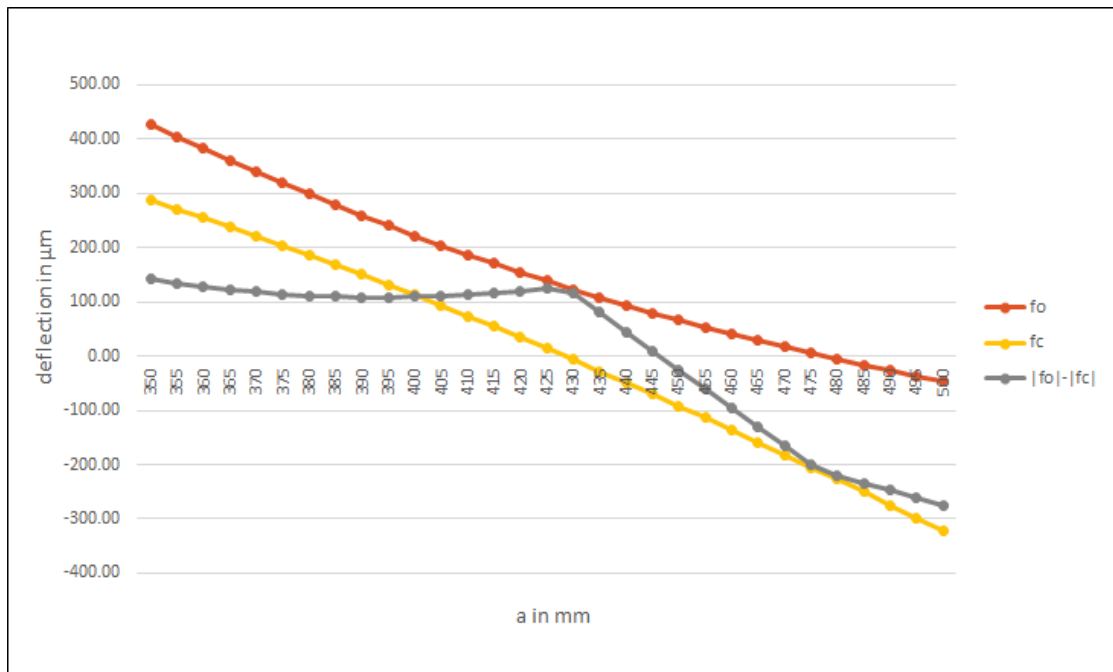


Figure 3. deflection of the beam (initial configuration) in function of the distance a

As it is shown in figure 3 the optimal value for 'a' is between 445 and 450, given it is where the maximal absolute values of both f_c and f_o are minimized.

Taking a closer look in that range, as displayed in figure 3, a more exact value for 'a' is determined, since it is now known to be between 446 and 447 mm.

Table 2. the results of the calculation for the initial configuration of the beam for the range 445-450 mm

a	l	q	J	E	f _o	f _c	f _o	f _c	f _o - f _c
(mm)	(mm)	(N/mm)	(mm ⁴)	(MPa)	(mm)	(mm)	(μm)	(μm)	(μm)
445	1110	20	5.50E+06	206000	0.07974	-0.07056	79.74	-70.56	9.18
446	1108	20	5.50E+06	206000	0.07700	-0.07489	77.00	-74.89	2.11
447	1106	20	5.50E+06	206000	0.07427	-0.07923	74.27	-79.23	-4.96
448	1104	20	5.50E+06	206000	0.07156	-0.08358	71.56	-83.58	-12.02
449	1102	20	5.50E+06	206000	0.06887	-0.08793	68.87	-87.93	-19.07
450	1100	20	5.50E+06	206000	0.06619	-0.09230	66.19	-92.30	-26.11

Considering that value for $a=446\text{mm}$, the deflection at the centre of the beam in the initial configuration should be equal to 0.077mm, and deflection at the end of the beam should be equal to 0.07489mm. That is, therefore, the optimal position for support, for which the further analysis in Inventor will be performed.

To make a general analysis of the beam, the beam was modelled simulating a rectangular structure with the required dimension of length (2000mm), and a square cross-section with the edge length equal to 90mm. The moment of the inertia of this cross-section is equal to $J=5.47\text{E}+6$ and is close to the value given in table 2. The calculations were performed in Inventor for the optimal position of the supports calculated with the use of the above theoretical calculations (446mm of distance from the end of the beam on each side). The external load was distributed continuously with a value of 20N/mm. The first calculation was made with omitting beam weight. Deflection of the beam, caused by an only external load, is presented in figure 4. These values can be compared with the values given in table 2 and it can be seen that a very good agreement was achieved.

Further calculations were made including beam weight. The using software (the Inventor) makes it possible to determine internal forces (i.e. cutting force – Figure 5) and moments (i.e. bending moment – Figure 6) in the beam.

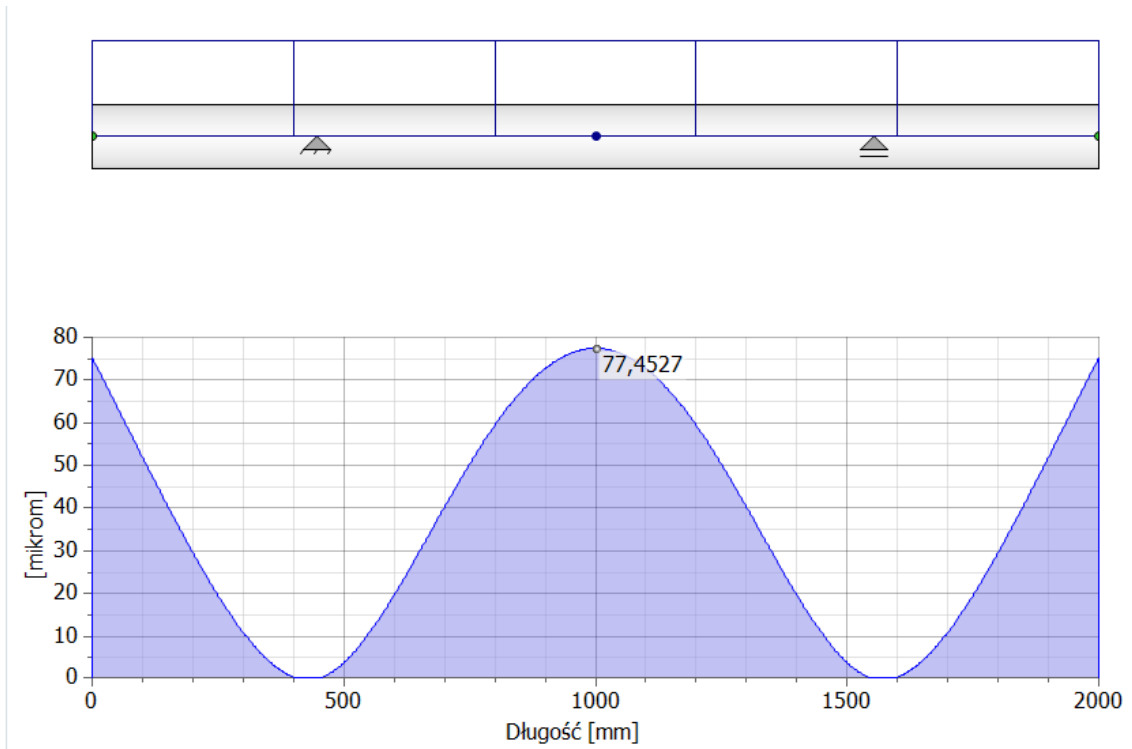


Figure 4. Loading and boundary condition and deflection of beam (beam weight is omitted)

Cutting force YZ

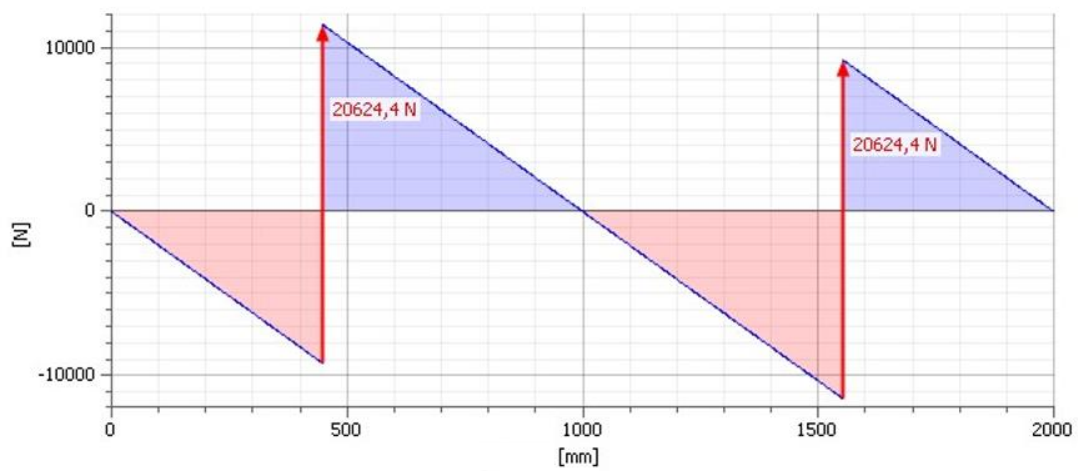


Figure 5. The forces in beam calculated by Autodesk Inventor Professional

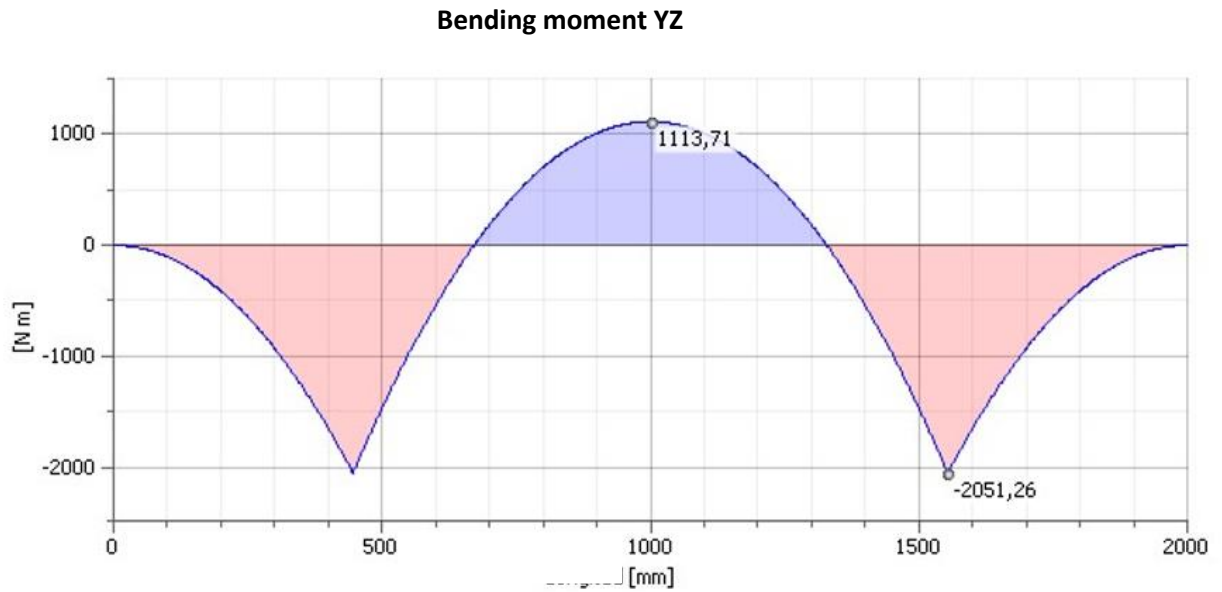


Figure 6. Bending moment calculated by Autodesk Inventor Professional

The deflection throughout the beam, including beam weight, is shown in figure 7. It can be seen that the maximal deflections are in the centre and at both ends of the beam. Figure 7 shows deflection at the centre of the beam is equal to 85.71 micrometres. Deflection at the centre of the beam in the preliminary calculations were 77 micrometres. Given the analysis with Inventor was based on an estimation of the geometry of the beam, it can be concluded that Autodesk Inventor Professional is an accurate tool to be used for this purpose.

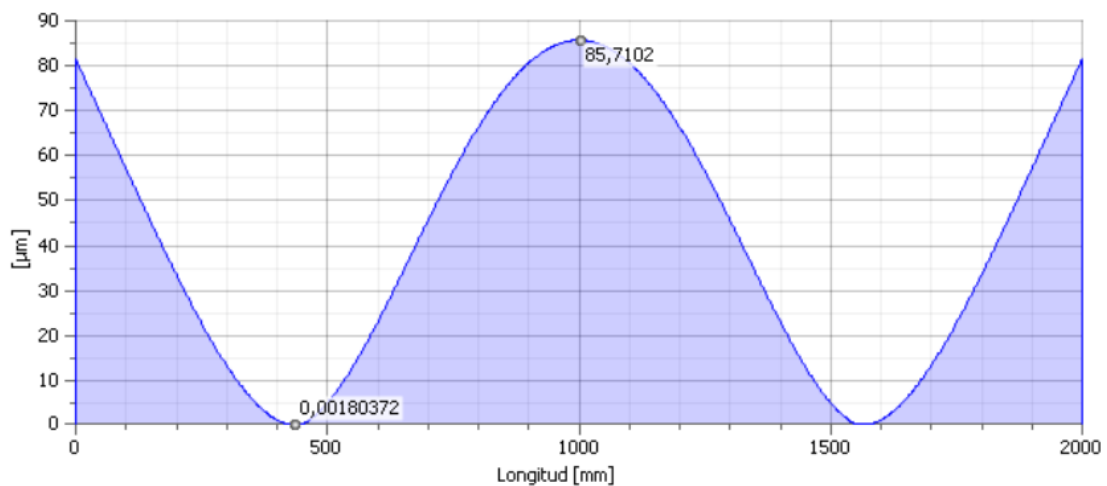


Figure 7. Deflection of the beam

5. Optimization of cross-section

Once the supports are located, the next step is to determine the optimal cross-section of the beam. Firstly, the minimal moment of inertia of the beam must be found. The value of this moment should provide the behaviour of the beam in such a way that the

deflection does not surpass the maximum of 10 micrometres. Using this minimal moment of inertia a few standardized cross-sections will be selected and compared. Finally, it allows for choosing the best one with respect to the beam dimensions and weight.

For determination of the minimal moment of inertia of the beam, a similar analysis than before was done, taking the already calculated position of supports ($a=446\text{mm}$), and the previous assumptions.

The weight of the beam was also taken into consideration. So considering the external loading of 20KN distributed throughout the beam of 2000mm, the external loading is equal to 10N/mm, and it was set, that the weight of the beam is equal approximately 20% of the external loading. The final loading (external and beam weight) is assumed as $q=10*1.2=12\text{N/mm}$.

The calculations were made with the given above theoretical formulas for a rectangular cross-section of the beam with the width of the beam set to 150mm and variable height (in a range 120-185 mm). Deflections at both the centre and at the ends of the beam were studied. The minimal height and resulting from it the minimal moment of inertia should be selected in such a way that both deflections do not surpass $10\mu\text{m}$.

The results of the performed calculations are shown in table 3.

Table 3. The results of the calculation of the deflection on the beam

Height (mm)	Width (mm)	J (mm ⁴)	a (mm)	I (mm)	E (Mpa)	q (N/mm)	fo (mm)	fo (μm)	fc (mm)	fc (μm)
120	150	21600000	446	1108	206000	12	0.0117633	11.76	-0.0114413	-11.44
125	150	24414063	446	1108	206000	12	0.0104074	10.41	-0.0101225	-10.12
130	150	27462500	446	1108	206000	12	0.0092522	9.25	-0.0089989	-9.00
135	150	30754688	446	1108	206000	12	0.0082618	8.26	-0.0080356	-8.04
140	150	34300000	446	1108	206000	12	0.0074078	7.41	-0.007205	-7.20
145	150	38107813	446	1108	206000	12	0.0066676	6.67	-0.006485	-6.49
150	150	42187500	446	1108	206000	12	0.0060228	6.02	-0.0058579	-5.86
155	150	46548438	446	1108	206000	12	0.0054586	5.46	-0.0053091	-5.31
160	150	51200000	446	1108	206000	12	0.0049627	4.96	-0.0048268	-4.83
165	150	56151563	446	1108	206000	12	0.004525	4.53	-0.0044011	-4.40
170	150	61412500	446	1108	206000	12	0.0041374	4.14	-0.0040241	-4.02
175	150	66992188	446	1108	206000	12	0.0037928	3.79	-0.003689	-3.69
180	150	72900000	446	1108	206000	12	0.0034854	3.49	-0.00339	-3.39
185	150	79145313	446	1108	206000	12	0.0032104	3.21	-0.0031225	-3.12

Looking at the results, it is deduced that the height of the beam that would suffer a minimum moment of inertia, without f_o and f_c surpassing $10\mu\text{m}$, is between 125 and 130mm. In table 4, a closer look at that range is taken, followed by an even closer look between 126.2 and 127, and an even closer look between 126.65 and 126.7.

Table 4. The results of the calculations of deflection on the beam in closer range

Height (mm)	Width (mm)	J (mm ⁴)	a (mm)	l (mm)	E (Mpa)	q (N/mm)	f _o (mm)	f _o (μm)	f _c (mm)	f _c (μm)
125	150	24414063	446	1108	206000	12	0.0104074	10.41	-0.0101225	-10.12
126	150	25004700	446	1108	206000	12	0.0101616	10.16	-0.0098834	-9.88
127	150	25604788	446	1108	206000	12	0.0099234	9.92	-0.0096518	-9.65
128	150	26214400	446	1108	206000	12	0.0096927	9.69	-0.0094273	-9.43
129	150	26833613	446	1108	206000	12	0.009469	9.47	-0.0092098	-9.21
130	150	27462500	446	1108	206000	12	0.0092522	9.25	-0.0089989	-9.00

Height (mm)	Width (mm)	J (mm ⁴)	a (mm)	l (mm)	E (Mpa)	q (N/mm)	f _o (mm)	f _o (μm)	f _c (mm)	f _c (μm)
126.2	150	25123959	446	1108	206000	12	0.0101134	10.11	-0.0098365	-9.84
126.4	150	25243597	446	1108	206000	12	0.0100654	10.07	-0.0097899	-9.79
126.6	150	25363614	446	1108	206000	12	0.0100178	10.02	-0.0097435	-9.74
126.8	150	25484010	446	1108	206000	12	0.0099705	9.97	-0.0096975	-9.70
127	150	25604788	446	1108	206000	12	0.0099234	9.92	-0.0096518	-9.65

Height (mm)	Width (mm)	J (mm ⁴)	a (mm)	l (mm)	E (Mpa)	q (N/mm)	f _o (mm)	f _o (μm)	f _c (mm)	f _c (μm)
126.65	150	25393677	446	1108	206000	12	0.0100059	10.0059	-0.009732	-9.73
126.66	150	25399693	446	1108	206000	12	0.0100036	10.0036	-0.0097297	-9.73
126.67	150	25405709	446	1108	206000	12	0.0100012	10.0012	-0.0097274	-9.73
126.68	150	25411727	446	1108	206000	12	0.0099988	9.9988	-0.0097251	-9.73
126.69	150	25417745	446	1108	206000	12	0.0099965	9.9965	-0.0097228	-9.72
126.7	150	25423765	446	1108	206000	12	0.0099941	9.9941	-0.0097205	-9.72

In order to provide both deflections f_o and f_c smaller than $10\mu\text{m}$ conclusion, the minimal moment of inertia should be not less than $J=25411727\text{mm}^4$, and height of beam should be larger or equal to 126.68mm. For these parameters, the following results were obtained: $f_o=9.9988\mu\text{m}$ and $f_c=-9.73\mu\text{m}$.

For the above geometry, the weight of the beam was equal to 298.33kg. This value was calculated, taking the average density of steel ($7850\text{kg}/\text{m}^3$), and volume of the beam $v=\text{height}*\text{width}*L=0.12668*0.15*2=0.038\text{m}^3$, which was multiplied by the density. This equals 2.9256 kN \approx 3kN which is a smaller weight for the beam than the one initially assumed, 20% of the external loading of 20kN (4kN). This guaranties a deflection smaller than 10 micrometres.

Now there is a lot of possibilities regarding the shape of the beam. To find the optimal one, different shapes must be compared.

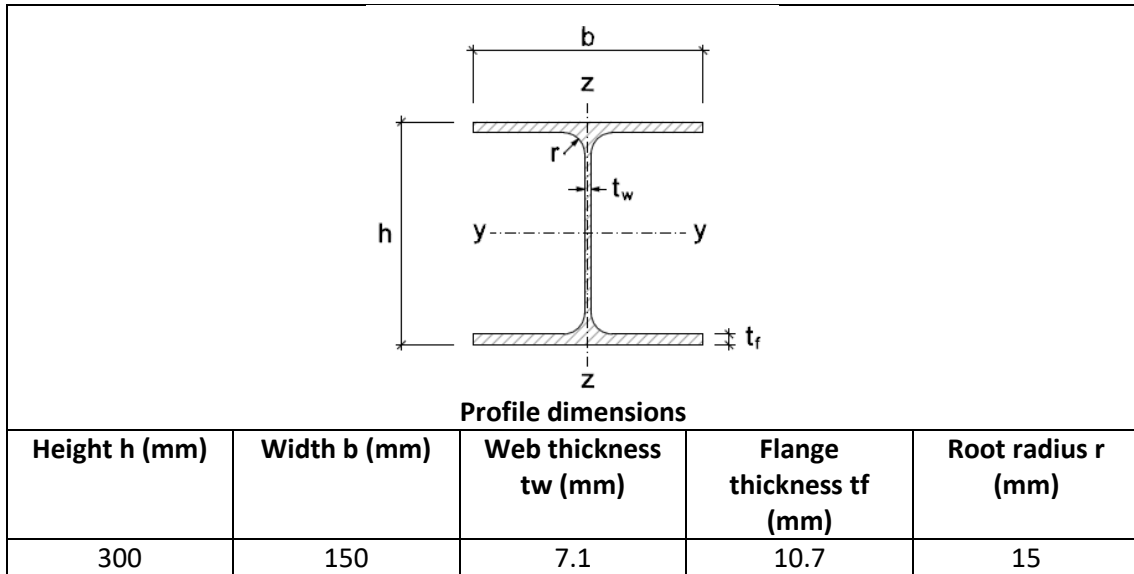
The values taken into consideration are the following:

1. the height of the beam (should be as small as it is possible),
2. the weight of the beam, which must be less than 4kN to ensure a deflection smaller than 10 micrometres,
3. and the smallest price.

Taking a minimal moment of inertia of 25411727mm^4 , and minimal width of the beam equal to 150mm, the following options found in different catalogues [2-4] are selected, presented, and compared.

- **IPE 300:** the most important properties of the profile are shown in figure 8. This shape provides the required moment of inertia and width, with a height of 300mm. The weight is significantly smaller than for the initial full square cross-

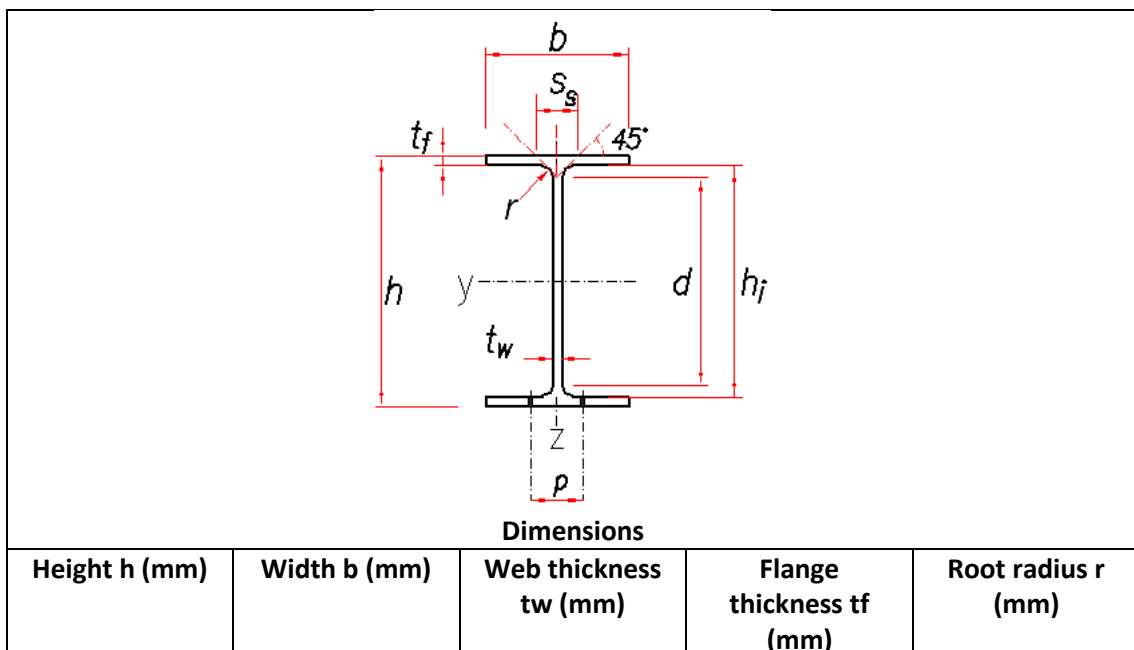
section. The rest of the dimensions are not of much relevance to the decision but will be used to model the beam if it were chosen.



Properties	
Weight m (kg/m)	Moment of inertia I_y ($\times 10^6$ mm ⁴)
42.2	83.56

Figure 8. Dimensions for profile IPE300

- **UB 305x165x40:** as shown in figure 9, the moment of inertia is provided this time by a larger width (165mm) and roughly the same height (303.4mm) as in the previous shape. The weight is again more optimal than for the initial full square cross-section.

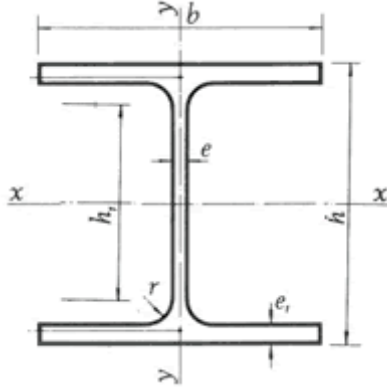


303.4	165	6	10.2	8.9
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Properties	
Weight (kg/m)	Moment of inertia I_y ($\times 10^6 \text{ mm}^4$)
40.3	85.03

Figure 9. Dimensions for profile UB305x165x40

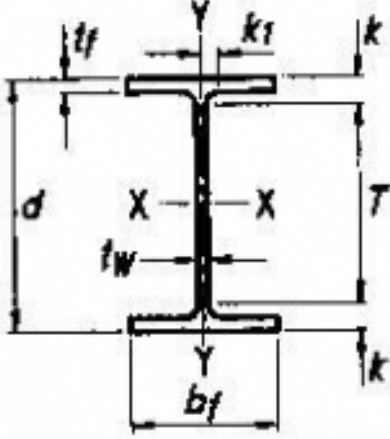
- **HE 180 B:** in the case of the shape shown in figure 10, width is slightly larger (180mm) as well as weight, but it is a rather small disadvantage, which translates in the height being reduced to 180mm.

				
Dimensions				
Height h (mm)	Width b (mm)	Web thickness e (mm)	Flange thickness e1 (mm)	Root radius r (mm)
180	180	8.5	14	15

Properties	
Weight (kg/m)	Moment of inertia I_y ($\times 10^6 \text{ mm}^4$)
51.2	38.31

Figure 10. Dimensions for profile HE 180B

- **W 200x165x35.9:** in this case, shown in figure 11, the weight is reduced, but both height and width have larger values than the last shape.



Dimensions				
Height d (mm)	Width bf (mm)	Web thickness tw (mm)	Flange thickness tf (mm)	Root radius r (mm)
201	165	6.2	10.2	10

Properties	
Weight (kg/m)	Moment of inertia Iy (x10 ⁶ mm ⁴)
35.90	34.38

Figure 11. Dimensions for profile W200x165x35.9

The catalogue provides weight in kg/m, so to compare the all above beam shapes with the square initial geometry, the calculated weight of 298.33 kg must be expressed in kg/m. The beam length is equal to 2000mm, so the weight of the initial beam with the full square cross-section per one meter is equal to 149.165 kg/m. In table 5 the most important values are put together.

It is concluded that the rectangular shape has better qualities (smaller height) but it is so much heavier than the rest of the shapes. Considering that with only 54mm more of height a much lighter beam such as HE 180 B could be used it should be considered as the optimal choice.

Table 5. General features for considered profiles.

Profile	Width (mm)	Moment of inertia (x10 ⁶ mm ⁴)	Height (mm)	Weight (Kg/m)
IPE 300	150	83.56	300	42.2
UB 305x165x40	165	85.03	303.4	40.3
HE 180 B	180	38.31	180	51.2
W 200x165x35.9	165	34.38	201	35.9
Rectangular shape	150	25.41	126.68	149.165

6. 3D modelling and 2D sketches

For the selected beam the model of the beam with joints was prepared using Autodesk Inventor Professional. Both joints were placed at the points on the beam calculated in the preliminary calculations (the distance from both ends of the beam is equal to 446mm). Each joint consists of three plates joined by welded connections, and then welded to the beam. The beam also needs to be modelled, using the dimensions provided by catalogues and given in the previous point, for HE 180 B. Using the assembly tool provided by Autodesk, movement can be restricted by setting relations between different sides of both components so that they must correspond. This way, by joining sides together and with the use of some auxiliary planes, both components can be joined properly. In figure 12, the complete assembling made as 3D model in Autodesk Inventor Professional is shown.

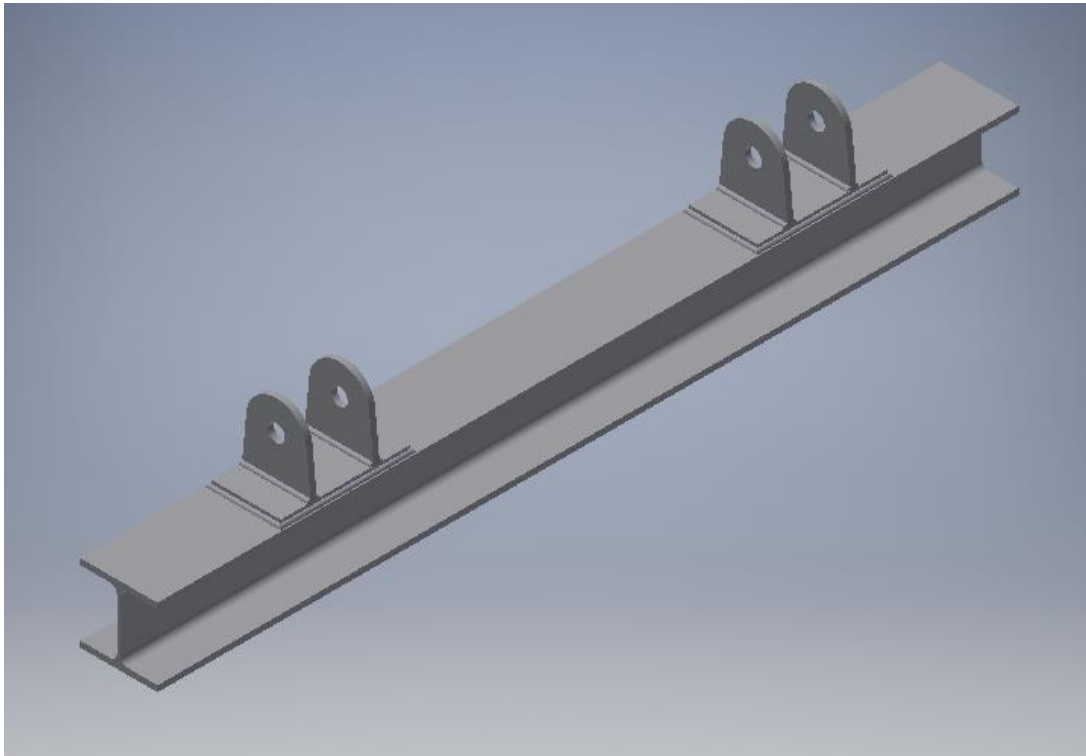
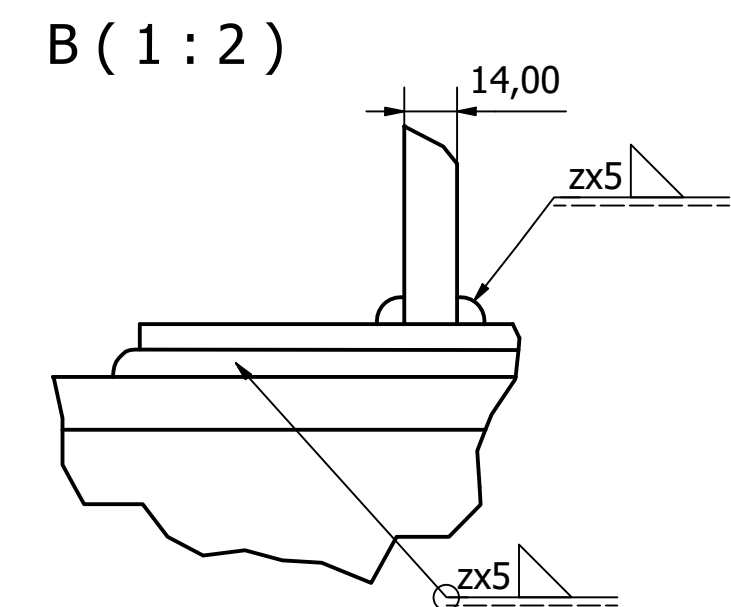
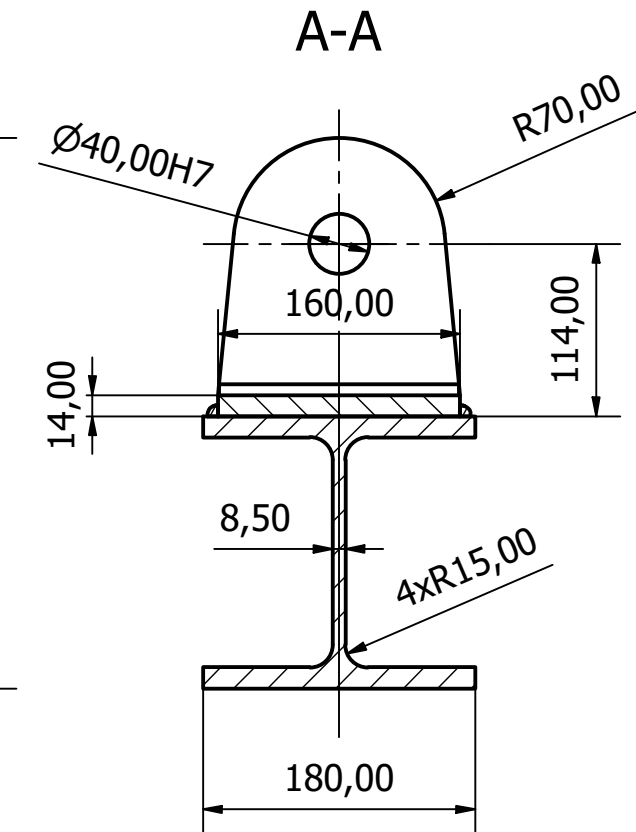
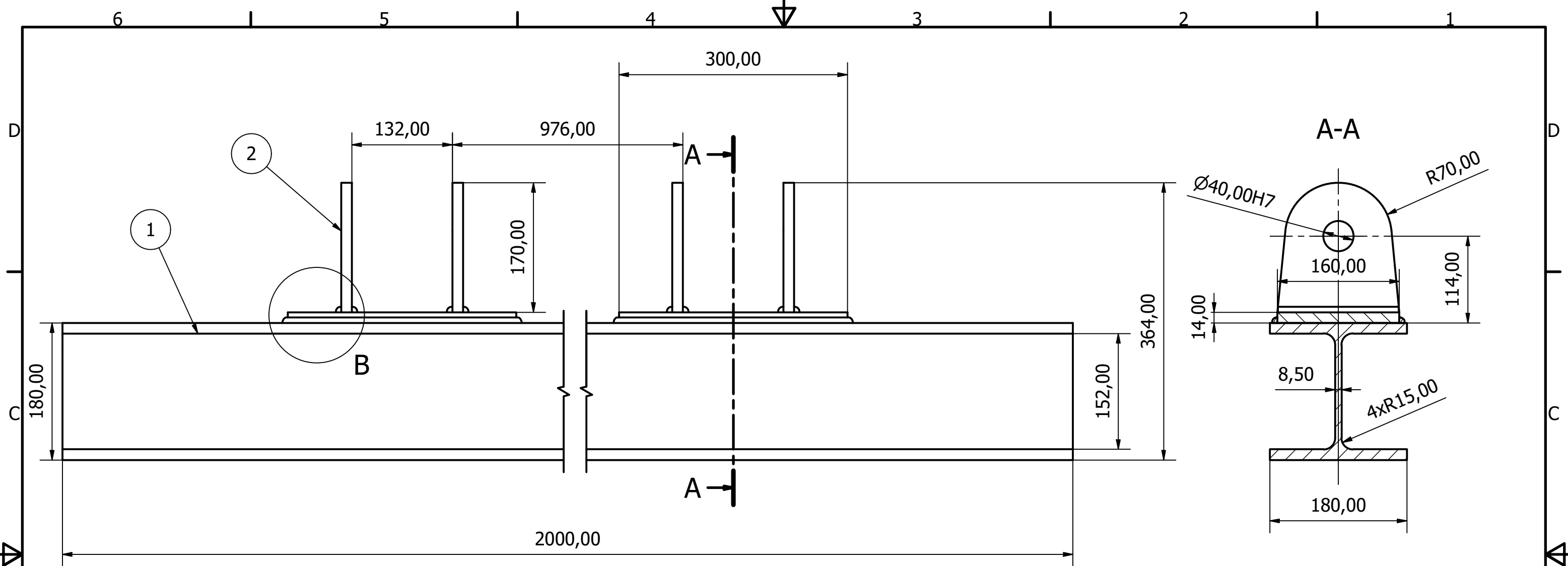


Figure 12. Complete assembly using Autodesk Inventor Professional

Further details of dimensions of the joint and the beam are shown in the form of 2D sketches, which can be obtained also from Inventor, using the corresponding tool, and making annotations so that every dimension of every component is determined.



LISTA DE PIEZAS			
ELEMENTO	CTDAD	Nº DE PIEZA	DESCRIPCIÓN
1	1	HE 180B	Beam
2	2	Plates	S235JR

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2D sketches			Edición	Hoja 1 / 1

7. Conclusions

In the project, the beam with the length 2000 mm and subjected to the external loading equal to 20 kN was calculated and modelled. The engineering calculations were made with the use of the analytical formulations taken from the literature as well as with the use Autodesk Inventor Professional. All assumptions were fulfilled and 2D technical drawing and 3D model was prepared in the project.

In conclusion, Autodesk Inventor Professional is found to be a reliable tool for both modelling and making structural calculations regarding deflection and stress. In this project it allows to analyse a general rectangular beam and to see how it would react to stress, showing the optimal points for placing the joints, which turned out to be 446mm from the edges of the beam.

The optimization of the beam cross-section was also made in the project. Comparison of the few standardized beams, considering the moment of inertia, the weight and the width, results in the selection of the optimal beam profile. It was proved that the profile HE 180B is the most favourable one, due to the small weight and comparable height to the initial configuration.

Autodesk Inventor Professional allowed for accurate modelling of the structure, consisting of the beam and the supports, as well as an assembly of both components, and the preparing of detailed 2D technical drawings of the designed structure.

8. References

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