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Computer Aided Engineering in Structural Design:

trends and challanges in data processing

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The purpose of this thesis was to study the impact of Computer Aided Engineering (CAE) methods, which substantially grew in significance over the last several decades, on structural design process. The goal of this study was to evaluate degree of the impacts using data processing issues as an example.

The methods used in this study included literature review and performance assessment of such computational tools used in structural design as Autodesk Revit and Robot Structural Analysis. The studied literature covered sources on conventional structural design, as well as papers on the latest advancements in computational structural engineering. The performance assessment involved the steel frame structures analysed with the programs mentioned above.

As a result, it could be seen that smooth data transfer and integration of the computer programs in the design process substantially facilitated delivery of the structural design for the construction project. The same statement is true for such computer-facilitated tools as modeling, analysis and optimization.

Nonetheless, the minor issues that were discovered in the use of the programs suggested that many improvements should be made. Open modeling and optimization of transferred data in particular seemed like relevant topics to consider.

Keywords	Computer Aided Engineering, Structural Modelling, Data Processing

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1 Introduction

Over the last decades computational techniques have become a significant tool in many fields of engineering including structural engineering. It is hard to ignore the impact of Computer Aided Engineering (CAE) on structural design practices and changes caused by it.

Traditionally, structural design is defined as a set of actions that aim to produce a function-oriented design of a structure, while complying with a number of requirements and limitations. Today one of the primary ways to handle structural design process, taking into account its complexity and large number of parameters, involves the use of Computer Aided Engineering. At the moment, in addition to its evident benefits, this approach has certain issues, placing new challenges for the industry. However, it promises, eventually, to shape a reformed construction process, where all subsystems, including structural design, function efficiently and in coherence with each other, making sure to deliver an optimal result. [1,2.]

This thesis aims to evaluate and classify the changes caused by the growing importance of computational methods in structural design, with data processing being the main focus area. The aims are achieved through the analysis of existing practices and supported by the assessment of the computer programs commonly used for structural design. Autodesk Revit and Robot Structural Analysis serve as platforms for the assessment, assuring the practical validity of the conclusions.

The assessment is based on 2 case studies, where steel frames are analysed with Autodesk Revit and Robot. The modeled steel structures are sent from one program to another several times, in order to assess the quality of data processing. The results of the tests help to evaluate to what extent information exchange can impact the final results of the design.

2 Traditional and Computer Aided Structural Design

In order to describe and evaluate the applications of CAE in structural design in a comprehensible way, first, it is essential to analyze structural design itself. Taking a closer look at the concept of structural design, its workflow and technical aspects allows the formulation of fundamental questions that arise in course of any project. By doing so, elaborate design process can be condensed to a finer model. Hence, the areas that require the use of computational techniques become easier to detect. The next logical step is to link these areas with available solutions offered by computer software. [3.]

As a final outcome, this chapter presents the most common computer aided (CA) structural engineering techniques together with development trends. The obtained information is used as a frame of reference for performance tests of Autodesk Revit and Robot Structural Analysis described in chapter 3.

2.1 Traditional Structural Design

This section describes structural design, which is carried out from three points of view: as a stage in a construction design process, as an independent process and, finally, as a mathematical problem. During the analysis of each of the three points of view possible technical issues become apparent. In short, the issues include communication and data exchange difficulties between involved parties, as well as the delivery of a timely and precise solution of the design problem. The solution of the design problem usually means solving systems of simultaneous partial differential equations (PDE). [2,4.]

2.1.1 Construction Engineering Process

Construction engineering is a multidisciplinary area of expertise, which requires diverse knowledge and skills. A workflow of a construction project is subject to certain variation, yet there are a number of typical stages, as can be seen in figure 1. [5.]

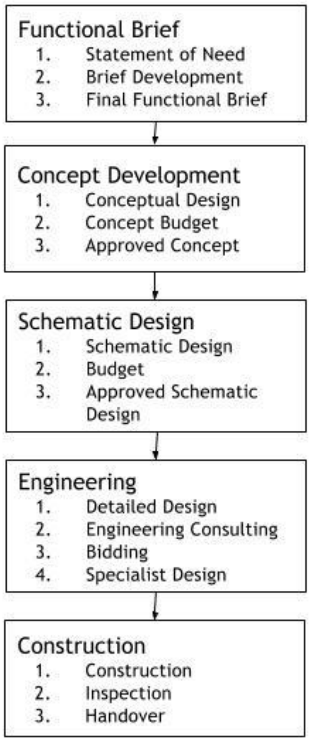

Figure 1. Construction Engineering Process

Initially, a client develops a brief that states the main functions, which is then transferred to a design team for conceptual, or schematic, design. This stage utilizes simplified tools, in order to investigate a wide range of possibilities. The main goal here is to outline the appearance of the building, major design solutions and methods for structure erection, along with specifications and restrictions. [1,5.]

As soon as the client approves the design, the team starts to work on a detailed building model which refines the existing design through editing and by encompassing new details. Simultaneously, the manager can start procurement, which in turn strongly influences the design of the details. After the project information is complete, the actual construction can commence. In order to assure sufficient quality, inspections by the design team and authorities take place during this stage. [6,7,8.]

Despite the brevity of the description given above, it is clear that the number of parties involved in a building project is fairly large. Therefore, apart from technical considerations, which are discussed in section 2.1.1, timely and efficient communication is another issue worth looking at. To a large extent interactions between the participants of the project are carried out using computers. Therefore communication is strongly connected with data exchange. Hence, efficient data processing and interoperability need to be ensured during any design project. [2,5,7.]

2.1.2 Structural Engineering Process

By decomposing the process described above, structural design can be viewed as a separate system. Schematic and detail design constitute the largest part of a structural designer's work, yet certain level of involvement is required during the whole construction project. As a matter of fact, structural design cannot be described as a continuous uninterrupted process. To be more precise, the design team produces several solutions, which are then edited and improved by maintaining a constant feedback loop with the other involved parties including the architect, client, consultants etc. [5,9,10.]

As can be seen in figure 2, the design process starts with functional design, where the topology, shape and size of the structures are established. It also includes an estimation of a sufficient area, the preliminary design of staircases and elevators, any atypical structural requirements and building code limitations. [5,9.]

The next step is to select trial structure systems. Primary concerns here are material selection, load resisting system and structural configuration. The trial systems are then designed and analysed with some basic structural analysis methods meant for estimation of approximate loads, member sizes and connections. [5,11.]

Based on the results of the preliminary analysis a system for detailed design is chosen. This phase is typically carried out with computer programs and includes structural modeling and load definition, followed by the computation of forces and deflections. [12,13.]

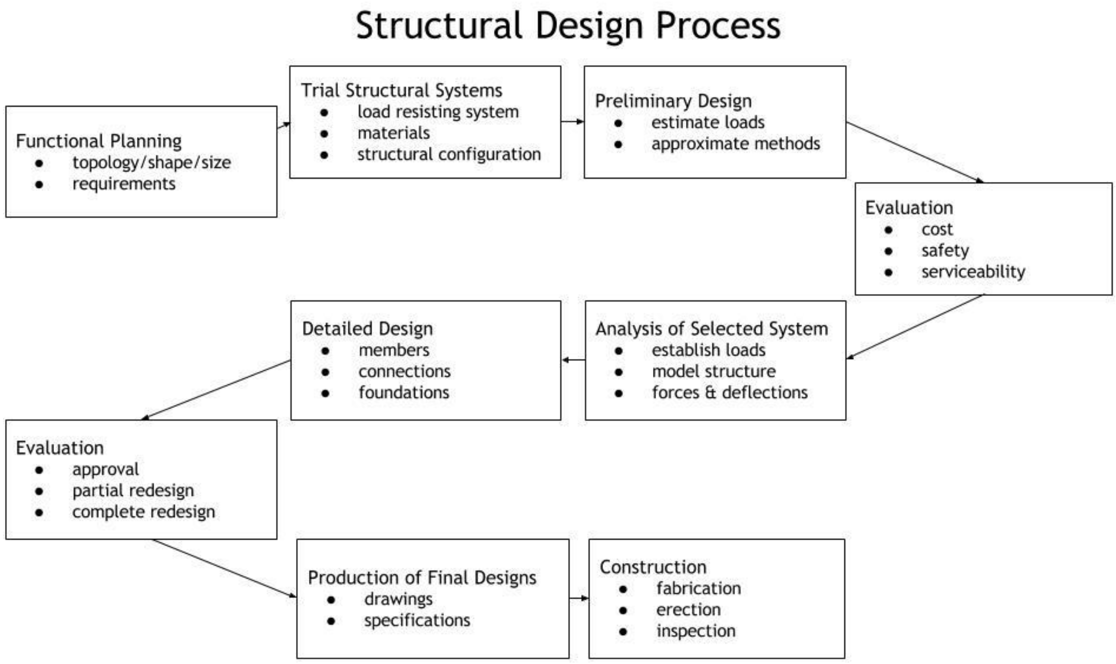

Figure 2. Structural Design Process

The final detailed design is then evaluated against the criteria set during the initial functional design. If the results are unsatisfactory, the project must be redesigned. Depending on the situation, the redesign could be either complete, which starts with a selection of new trial systems and the repetition of all further steps, or partial, which consists of reworking existing detailed designs. As soon as the desired optimum is achieved, the drawings and specifications can be produced and the project moves to construction phase. [10,14,15.]

Structural design is strongly interconnected with architectural design as well as with procurement. Thus, it can be altered at any given stage of the construction process. Apart from redesign during early stages, it is not uncommon for the architect or the manager to request some changes to the finalized structural model during later stages of the project. The reasons for this can be constructability problems, detection of collision and so on. These situations prove that flexibility is an essential characteristic of a successful structural engineering process, yet in practice it is not always the case. [2,4,16.]

Structural design process poses many technical challenges, which result in multiple redesigns. This way the main goal of the structural design is to deliver satisfactory solution with as few redesigns, or iteration loops, as possible. In terms of CAE it means implementation of more effective optimization techniques. [17.]

2.1.3 Structural Design Method

The final outcome of a structural design process is an arrangement of structural elements that optimally suits the set requirements. Most design problems are formulated and solved with the analysis procedure. It is often necessary to carry out the analysis repeatedly in the course of the design process. This approach allows the designer to pinpoint better design solutions considering the budget and performance. [4,14.]

The intent of a structural analysis is to identify forces, stresses and displacements that occur as a result of working loads. To assess the abovementioned reactions, it is crucial to set up a model imitating the behaviour of the structure under assumed loads. The main criterion for the adequate model is the relation between its accuracy and simplicity. [4,17.]

From a theoretical point of view, parameters that influence structural responses are well defined and can be solved with numerical methods. Its simplified procedure is shown on figure 3. However, a growing complexity of designed systems, naturally, leads to structural solutions becoming more complicated as well. As a result, in order to find the problem solution more sophisticated computational procedures and higher level of expertise are required. Another essential steps are verification and interpretation of numerical output. [14,18,19.]

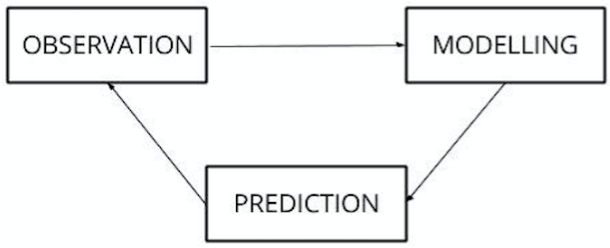

Figure 3. Modelling process

An analytical model is created in order to calculate the displacements in the structure and usually processed in a standard way. First, a structure is idealized to such level of abstraction, where it can be solved. Typically, a real structure is reformulated into an assembly of interconnected elements. Next, a model is generated, as local requirements for equilibrium are defined. Then the set of simultaneous equations which are used for displacement calculation is formulated through requirements for interconnection of elements. Finally, the solution of simultaneous equations provides values of unknown displacements, which are required for the final model. Then internal stresses and forces are computed by solving local equilibrium requirements. [16, 20,21]

The quality of the analysis predominantly relies upon the computational techniques utilized for the solution of the equilibrium equations. A higher precision can be achieved by using better-defined models which approximate real structures to a very high extent. [22,23.]

2.2 Computer Aided Structural Design

After outlining the issues that typically occur in the structural design, available corresponding CA solutions are outlined. Even though the division suggested below is conditional and implies substantial simplification, it can be accepted that each of the issues is tackled with a certain computational tool or family of tools. The first group of problems is related to communication, including data exchange. They are supposed to be eliminated by modeling tools. The second group of problems is caused by difficulties with the mathematical formulation of the design problem. Such tools as computational structural analysis and optimisation are expected to resolve these problems. [20,24.]

2.2.1 Implementation of CAE in Construction Industry

BIM and its implementation are typically expected to improve productivity and quality of deliverables. However, there is still no uniform strategy for the incorporation of BIM methodology in a construction process. Naturally, this fact causes some implementation issues. Yet despite possible complications at the early stages, information modeling brings certain benefits to the design procedure, including a lower number of interdisciplinary conflicts and a higher quality of the final output. [25,26,27.]

A universal definition of BIM is yet to be given. Nevertheless, it can be interpreted as a multidimensional, historically evolving and complex concept. To begin with, it is a digital representation of a building in 3D. It can also be perceived as the information library of a project, as well as a communication and cooperation tool. The main trend is for BIM to refine a construction project workflow and to strengthen the relationship between design and construction. Along with all existing branches of building industry, structural design is impacted by BIM and by the changes that it brings to the construction process. [25,28.]

As stated above, the implementation of BIM could at times be challenging due to its novelty. In spite of the lack of comprehensive research on the subject and limited experimental data, some modeling practices are more successful and some have proven to be fruitless. For instance, for quite some time the concept of single software solution for the whole construction process was dominant in the industry. However as it became obvious that this paradigm is not feasible practically, distributed modeling started to gain more attention and eventually proved to be a more successful approach. A comparison of these two approaches is summarized in Figure 4. [29,30.]

Hypothetically, integrated design offers multiple advantages. Still little progress has been made to bring it to the industry. Currently there is no existing or developing application that could store all the information for a construction project in a form that would be understandable to all participants. Moreover, none is likely to appear at all. [20,30.]

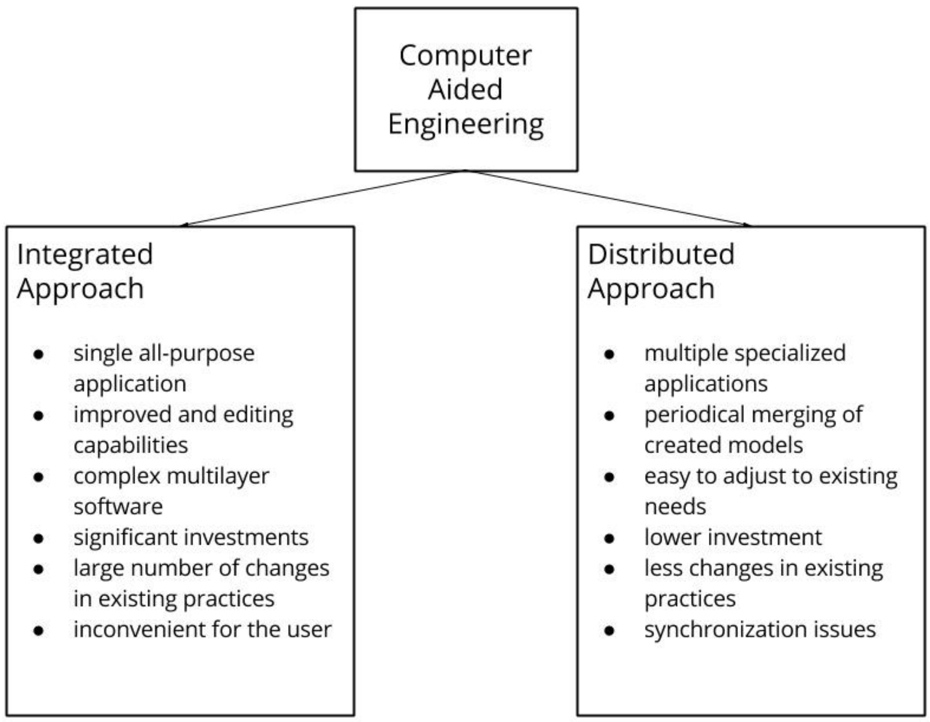

Figure 4. Comparison of Integrated and Differentiated Approaches in Construction Industry

Development of a program with multiple environments for the different specialists is rather complicated and would require an extremely high investment. Financial costs of that size would turn the project unprofitable for the developer. Businesses would face the need to disintegrate current operation practices and establish new ones, and users would be exposed to a complicated interface, with a majority of functions that are never used. Overall, financial, intellectual and social investments required for the success of this paradigm along with the high risks undermine the possible benefits, making integrated approach unattractive for the industry. [28,30.]

The distributed modeling paradigm, on the other hand, has shown more signs of success. Such positive results can be attributed to the high flexibility of this approach. As opposed to various experts working with the same software, distributed modeling promotes highly specialized programs, where the created models are merged periodically, in order to provide a platform for collaboration and comparison. [25,30.]

Changes caused by the introduction of such software in a company would be of a moderate scale, keeping the existing practices intact. Additionally, there remains a possibility to modify and experiment with available functions, crafting the most suitable implementation pattern for a given company and allowing the company to develop in the most organic way. Considering the wide range of businesses involved in construction, adaptability plays an important role. Lastly, a large number of vendors with a relatively low market share should put the issue of interoperability forward. At the moment, data processing with several software products within the same project considered to be one of the most problematic areas. [30.]

2.2.2 BIM-enabled Structural Engineering

As it is now clear from section 2.2.1 which direction modeling in building industry is headed to, impacts of computer modeling on the development of computer aided structural design in particular can be spotted as well. Some of the major trends of modeling in structural design include an increase in data sharing, ever-growing iteration capabilities of software products and the development of parametric design. [2,31.]

A constant exchange of information is an adjustment that affects all levels of a project. These adjustments influence all specialists, including the structural designers, in a similar manner. First, increased transparency leads to a higher awareness of current situation, changing the approach to decision making. Different teams, such as structural, electrical, HVAC and others who traditionally work separately and do not share almost any facts regarding their progress, now get an opportunity to get familiar with the solutions of the remaining specialists, thus making better-informed decisions in their own domain. [32,33.]

Additionally, with growing information flows every piece of data is exposed to a larger number of viewers within the same design team as well, which can be beneficial in a number of ways. Importantly, the exposure of the design details to a larger number of people can reduce errors and inconsistencies. If tracked at early stages, these issues can be resolved with a minimal negative effect. Then, a higher level of exposure brings a higher sense of responsibility, resulting in a better quality of the output. [31,32.]

The development of computational methods supports the advancement of modeling software too, making it more efficient and productive. With a higher automation level and a lower time required for a single operation, iterative capabilities of structural design programs increase significantly. Hence, the higher productivity means a larger variety of possible options to be considered and evaluated, which leads to a more refined solution. [34.]

Parametric modeling is another important development in CAE area. The ability to use an object library, where the geometry of an object is related to its properties, could advance many procedures. For example, the use of object-oriented software can facilitate design, as individual components can be queried for material and performance data, as well as for cost. [28,35.]

The development of the parametric modeling is also supported by the fact that manufacturers create open libraries with models of their products. This way, a parametric relationship between form and components of a building can be established right after initial sizing and form organization, resulting in a better overall optimization of the structure. [27,20.]

2.2.3 Analysis and Optimisation in Structural Design

As mentioned above in section 2.2.2, advancements in operational speed and output data quality of computational methods strongly encouraged, among many things, the incorporation of computer-aided structural design techniques in construction engineering process. The most prominent tools used to increase the operational speed and data quality include finite element analysis (FEA) along with multiple optimisation methods. With the development of computational engineering, especially finite element method calculations, processes of optimisation were integrated into design activities, in order to save the time required for obtaining a satisfactory result. [29,36.]

The technical procedure of computational structural analysis is not in the scope of this study, yet a basic interpretation of the issue could help to gain better understanding of the subject. One of the ways to look at a structural analysis is by dividing it into three major parts. [27,29.]

As can also be seen in figure 5, a model created by architects should be pre-processed. In other words, the project needs to be reformulated using simple structural elements, such as beams and columns. [37.]

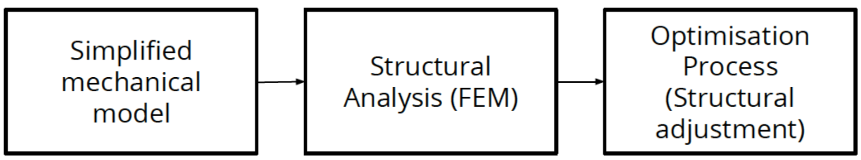

Figure 5. Computational Structural Analysis Process

When the model is assembled, the analysis is carried out with computer programs. The finite element method (FEM) is the most widely used form of analysis, as it provides solutions to complex problems while maintaining a high level of automation. The finite element method for structural analysis is based on substitution of a real continuous structure with a model that consists of finite number of elements. These assumed elements possess known material properties, including elasticity and inertia, which are expressed in a matrix form. Assembled according to the rules derived from elasticity theory, matrices describe the responses of the actual structure. The major concept to keep in mind, when discussing FEM, is that once the size of the defined elements becomes small enough, the model's behaviour converges to that of the real structure and it is possible to determine the deformations with sufficient accuracy. [29,30.]

After the analysis, engineers should interpret the results. Furthermore, they introduce adjustments to an existing design. Even though structural analysis is predominantly used to evaluate the quality of the suggested design, more appropriate structural solutions can be offered. One of the ways to find more suitable solutions supposes the use of certain patterns and search mechanisms. This process denotes the shift from analysis to optimization. [37.]

Optimization in structural design deals with three aspects, the size, shape and topology. Optimizing the shape and area is typically less complicated and allows for the control of such factors as fabrication costs and structural reliability. Topology, on the other hand, can be more challenging to optimize. It deals with the connectivity of the elements, and when optimizing it, the design should be viewed from a more global perspective. Nonetheless, the latest studies indicate that the best possible results come from the simultaneous optimization of all three aspects. [2,37.]

From a technical point of view, structural design can be said to significantly benefit from implementation of computational tools which handle sophisticated calculations with a higher accuracy in a shorter period of time, decreasing the overall cost. The development of computer optimization tools and FEM serve as major examples for that.

3 Analysis of Steel Frames with Autodesk Revit and Robot

The practical part of this thesis aims to assess the level of data transfer quality offered by Autodesk Revit and Robot. Problems, which are analysed with the method described below, are used to demonstrate capabilities of the computer programs and to draw conclusions regarding performance and possible future developments of the programs.

As it was stated in chapter 2, distributed design showed to be rather successful. However, the use of distributed deign approach in CAE development places certain challenges on the industry. For instance, any software is now supposed to accommodate an ever-increasing number of model and data transfers in the course of a construction project. Results of the tests carried out in this chapter give the basis for the evaluation of the current situation in the computer-aided structural design. [9,10.]

The tests carried out in this final project clarify how compatible different computer programs are and how much their repetitive synchronization can affect the quality of a structural model. Structural models used in the case studies are all steel hyperstatic structures under a uniformly distributed load. The moment diagrams for the structures need to be determined. In order to ensure the reliability of the results, the problems were preliminary solved manually with Excel. There were two pieces of structural analysis software used in the practical part, Autodesk Revit and Robot, both of which are developed by the same company and widely used in the industry. [38,39.]

As a final outcome, the test results are supposed to provide sufficient information for software evaluation. Based on the case studies, the current synchronization procedure is assessed and any possible drawbacks and development suggestions are outlined.

3.1 General method of analysis

The tests carried out in this study are based on several cases, the main goal of which is to determine the quality of data transfer and, if possible, distinguish areas worth improving. The general analysis procedure adopted for the tests is described in this section and schematically shown in figure 6. Case-specific details are elaborated further in corresponding sections.

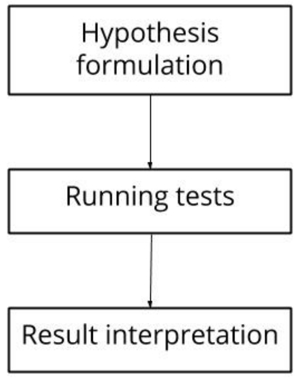

Figure 6. General test procedure

In order to answer the questions posed in section 2 above, tests on different structures are carried out. Every test procedure is performed in a similar manner and can be divided into three steps: hypothesis construction, testing and analysis of results. [7,17.]

For each case, certain unknowns should be calculated with both Autodesk Revit and Robot Structural Analysis. The outputs of each program are expected to be coherent and, additionally, stay within the same order of magnitude as preliminary calculated results. The results are obtained through manual calculations with Excel for repetitive operations. As it can be understood, the availability of preliminary results and their accuracy are significant for the overall assessment. For this reason, the test structures are chosen with a view to obtaining unambiguous results which can be checked manually. [9.]

Once the hypothesis is formulated, tests are carried out, and their results are recorded and stored. The main areas of focus here are the consistency of the calculation results on one hand, and their accuracy after multiple conversions from one format to another, on another hand. Derived results are then compared with each other, as well as with the preliminary manual calculations. This provides sufficient background for the evaluation of the used software products. [25.]

3.1.1 Employed software applications

The programs used for the study were Autodesk Revit and Robot Structural Analysis Professional. Both programs are developed by Autodesk, which ensures a high level of compatibility during the simulations. In addition to this, the fact that Autodesk is one of the leaders in the industry means that both programs are widely used in construction projects. [38,39.]

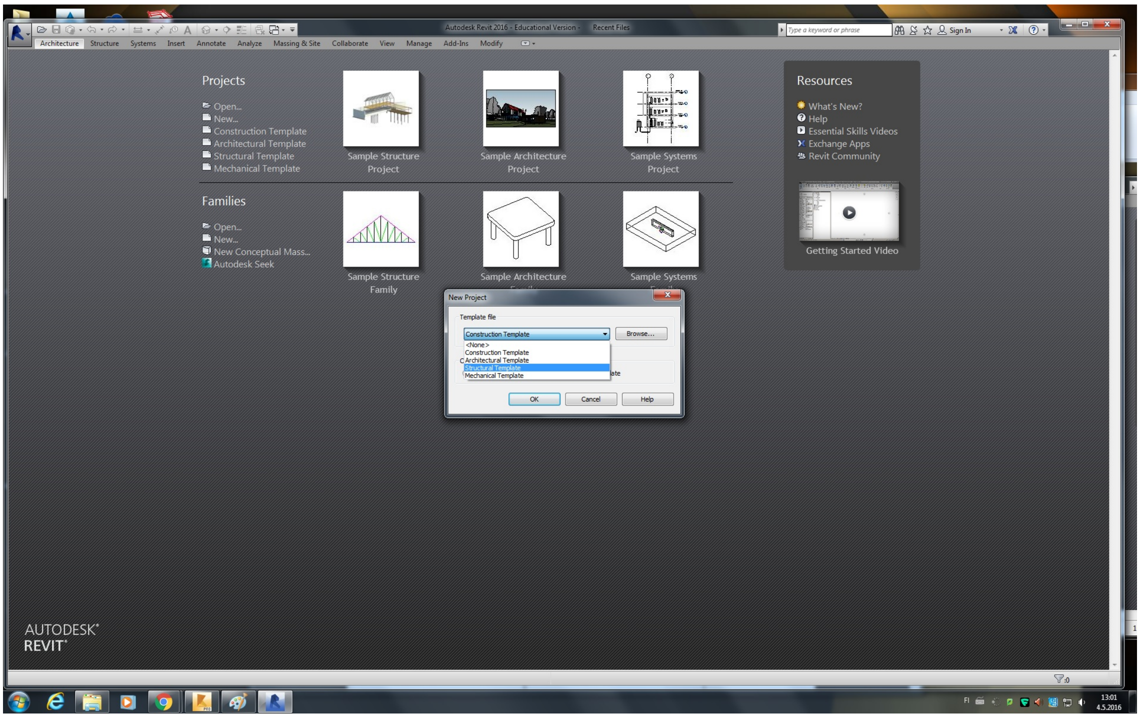

Figure 7. Interface of Autodesk Revit

Autodesk Revit, work environment of which is presented in figure 7, is a design and construction program, which supports implementation of BIM at all stages of a construction project. It promises, among other features, to provide precise models, facilitate optimisation processes and give a platform for effective communication. [39.]

Autodesk Robot Structural Analysis is a structural analysis program based on FEA. It allows engineers to carry out design, simulation and analysis procedures, as well as code checking for any type of structures. It also has a link to Autodesk Revit, assuring sufficient interoperability. [38.]

3.1.2 Computer procedure

Based on sections 3.1 and 3.1.1 the test procedure is described. Its schematic representation can be seen in figure 8.

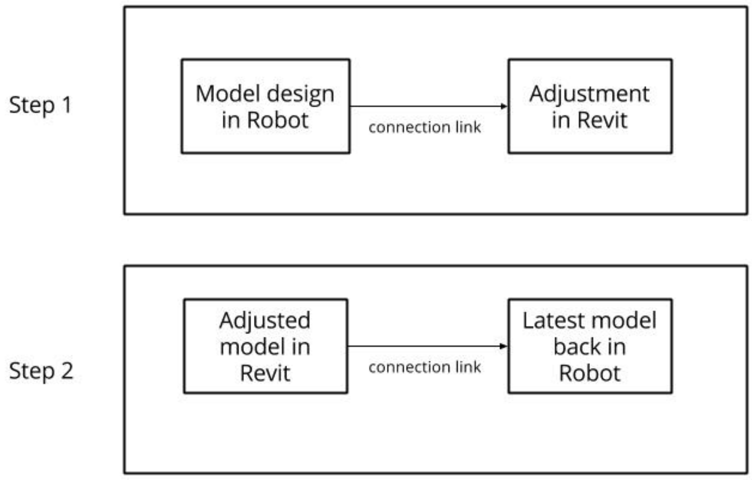

Figure 8. Procedure of computer simulation

Initial modelling and analysis are performed with Autodesk Robot Structural Analysis Professional. The created model is then transferred to Autodesk Revit, where it can be modified if necessary. The updated model can then be delivered back to Autodesk Robot with all adjustments intact. The produced results are studied and summarized, in order to assess the level of data processing.

3.2 Case Study 1

A structure displayed in Figure 9 is chosen for analysis in the first case. It is a hyperstatic homogenous structure, meaning that the bending stiffness, or a product of the elastic modulus (E) and the area moment of inertia (I), is a constant. Its horizontal element is uniformly loaded with p=25kN/m. More relevant dimensions can be seen in figure 9.

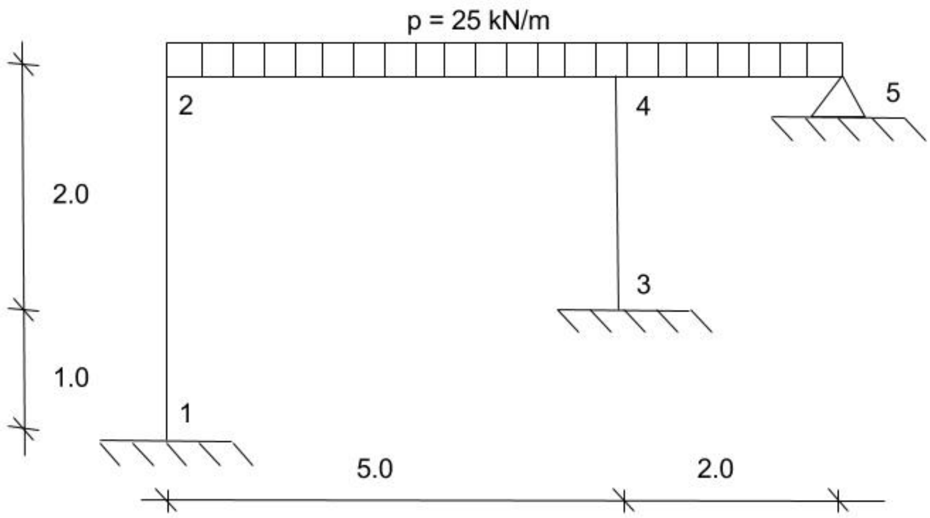

Figure 9. Case 1: Structure diagram

The task is to identify reaction forces and sketch a moment diagram for the structure. A detailed solution of this problem can be found in Appendix 1. For the purposes of this study, a manually derived moment diagram with denoted extreme values is presented below in figure 10. The values serve as a reference point for computer calculations, performed next.

When the preparatory calculations for case 1 are ready, the problem can be reformulated and solved with Autodesk Robot. The proceedings of the process can be checked in Appendix 3.

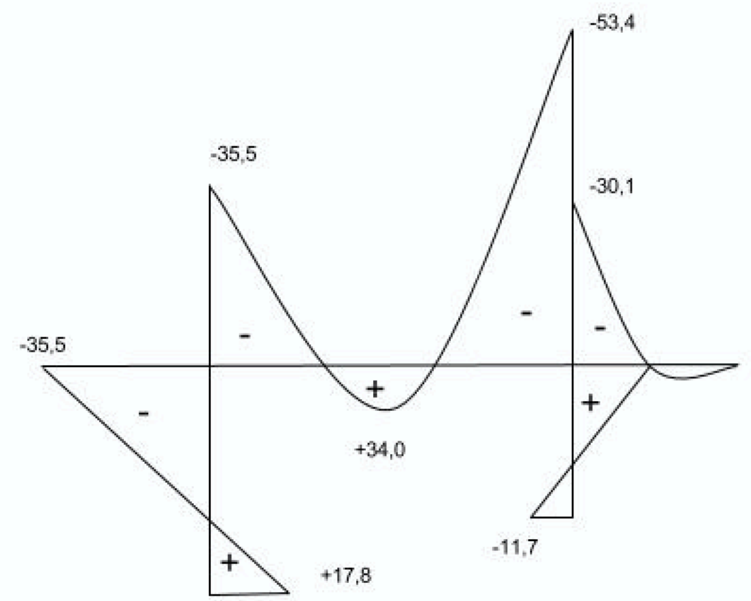

Figure 10. Case 1: Moment diagram

The shaped curves show that that the obtained solution is fairly close to the expected one (see figure 10). Upon further examination, also the extreme values for moments appear to be sufficiently close. For example, the maximal moment value of the horizontal element, bar 2-4-5 in figure 8, is 33,96 kNm with manual calculations against 33,98 kNm offered by Autodesk Revit. The remaining critical values vary in the same range. With this result it can be concluded that the input of data was performed successfully and further simulations have a solid point of reference.

The complete Autodesk Robot model is then sent to Revit via built-in link. The function offers multiple options regarding the objects and properties of the object's properties that will be transferred to Revit. The final moment diagram can be seen in figure 11.

Further, once the program processes the model, the examined structure can be viewed in Revit. The properties of the model, including the materials, dimensions and topology, remain unchanged, as well as the assumed loads, keeping the moment diagram identical to the one in Robot.

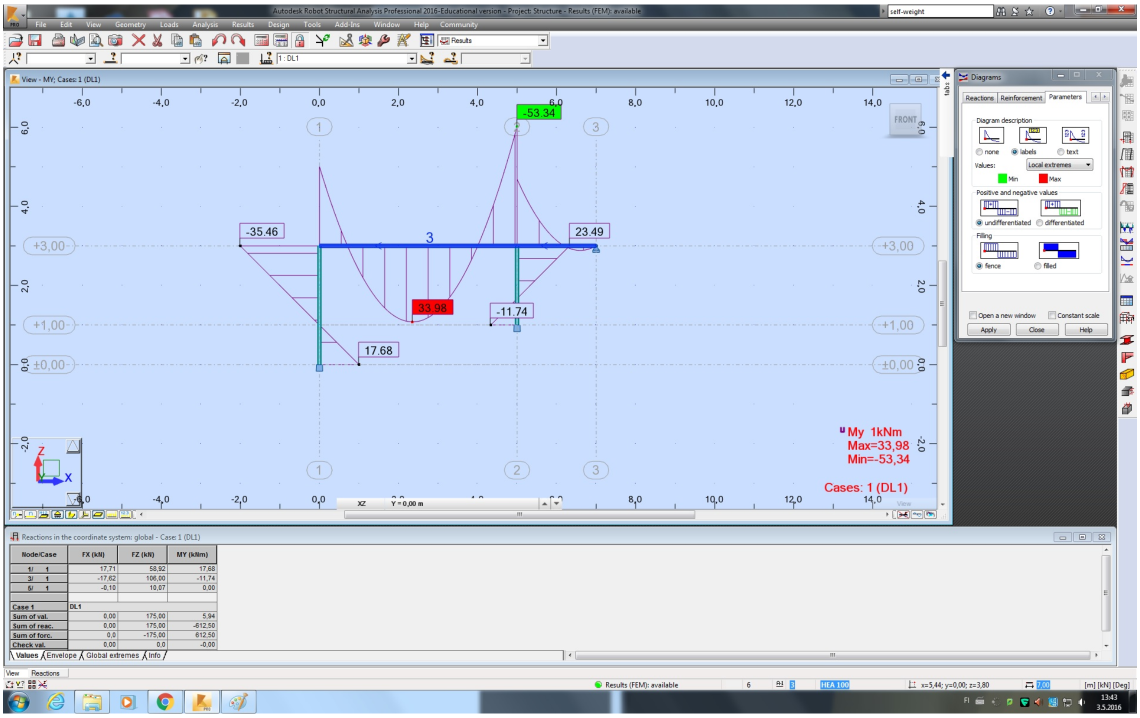

Figure 11. Case 1: Moment diagram generated with Autodesk Robot

Revit also allows the designer to modify the loads. In Case 1, uniform 25 kN/m load was reduced to 15 kN/m. The updated model is then sent to Robot via the built-in link for a new analysis. When the model is viewed in Robot the loads are reduced from 25 kN/m to 15 kN/m, proving compatibility of the programs. Finally, after the analysis it can be stated that the latest model of the structure, which is displayed in figure 12, is no longer stable.

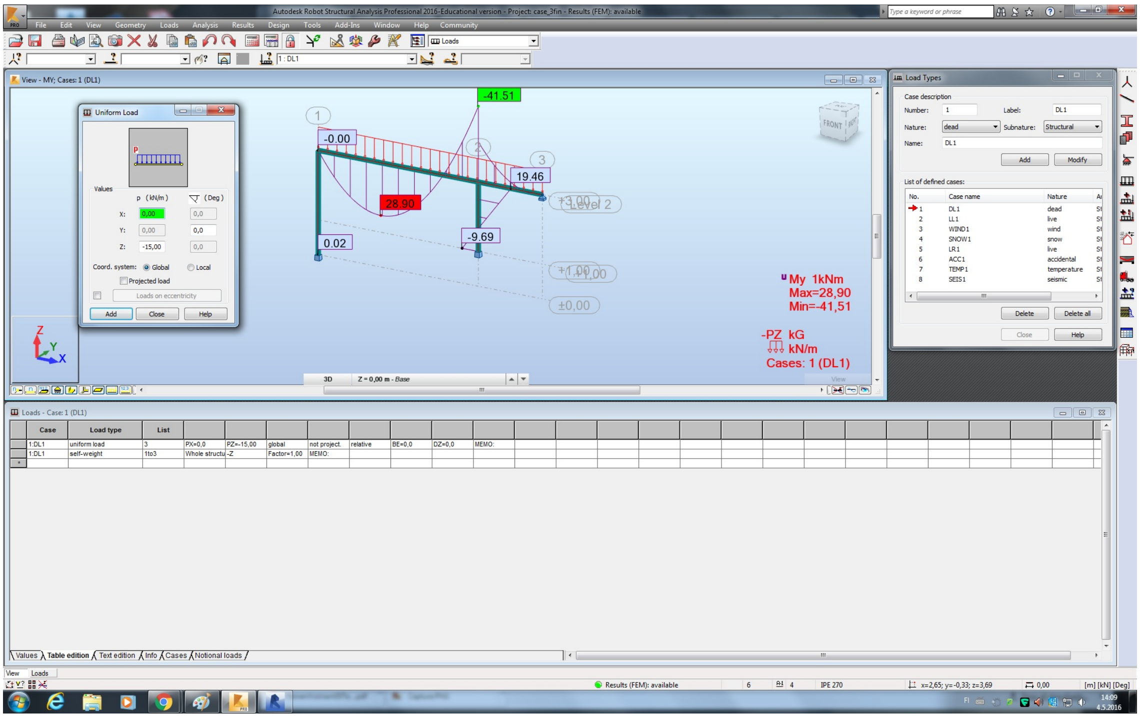

Figure 12. Updated Robot model

As a result, it is possible to say that the data transfer between Revit and Robot in this case study was quite successful and smooth. Both programs retained the essential information and the results of the analysis stayed coherent with the expected values.

3.3 Case Study 2

The second case to be analysed is the structure shown in figure 13. It is a hyperstatic homogenous structure, meaning that the bending stiffness, or a product of the elastic modulus (E) and the area moment of inertia (I), is a constant. Its horizontal element is uniformly loaded with p=42kN/m. More relevant dimensions can be seen in the figure 13.

Similarly to the 1st case, the task is to identify the reaction forces and sketch a moment diagram for the structure. Appendix 2 offers a full solution to the problem. A moment diagram with denoted extreme values, drawn from the calculations in Appendix 2. Further computations with Autodesk Robot and Revit are compared to these results for the reference.

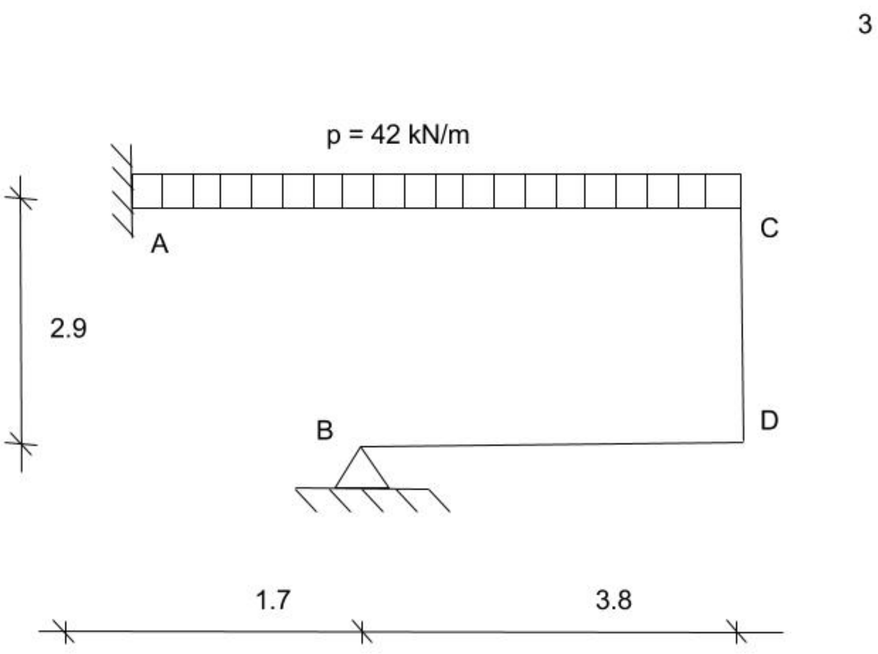

Figure 13. Case 2: Structure diagram

When the preparatory calculations for the Case 2 and the moment diagram are ready, the problem can be reformulated and solved with Autodesk Robot. The proceedings of the process can be checked in Appendix 4.

It can be seen from the similarly shaped curves that the obtained solution is fairly close to the expected one (figure 14). Upon further examination the extreme values for moments appear to be sufficiently close also. For example, the manually calculated moment value at the fixed support, point A on Figure 11 is -317,65 kNm against -317,77 kNm offered by Autodesk Revit. The remaining critical values vary in the same range. Consequently, it can be concluded that the input of data was performed successfully and further simulations have a solid point of reference.

The complete Autodesk Robot model is then sent to Revit using the built-in link. The link allows the engineer to specify which objects and properties should be transferred.

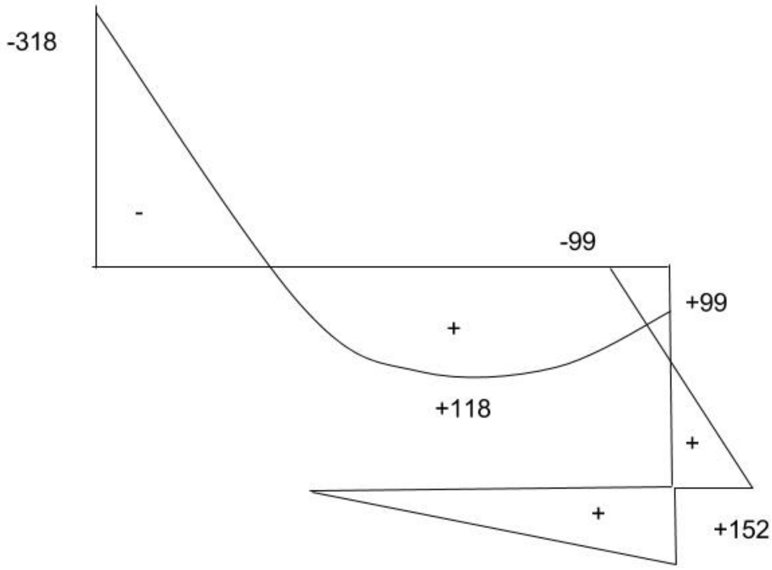

Figure 14. Case 2: Moment diagram

Further, once processed by the software, the examined structure can be viewed in Revit. The properties, including materials, dimensions and topology of the structure remain unchanged, as do the assumed loads, keeping the moment diagram identical to the one in Robot.

In this case two changes to the initial model were made: one element was changed and the magnitude of load was increased. First, The changes were begun with modifying properties of the lower horizontal bar, element B-D in figure 13. Its section was changed from HE100 to HE320, while the remaining elements were not changed. Then the load introduced to the structure was increased from 42 kN/m to 100 kN/m. [38.]

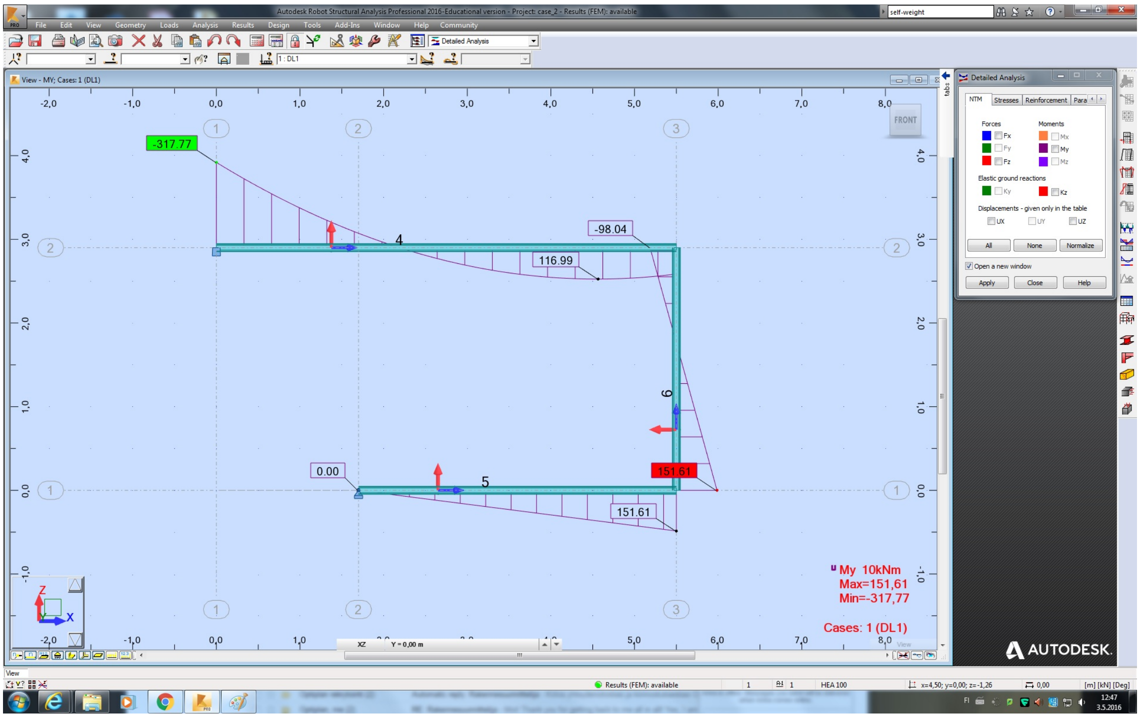

Figure 15. Case 1: moment diagram generated with Autodesk Robot

The updated model is then sent back to Robot, figure 15, and analysed. In figure 16 it can be seen that the modified bar is also updated in Autodesk Robot. The section properties and loads are updated as well. Lastly, an analysis on the structure is performed for the second time. The analysis states that the frame is no longer stable due to the introduced changes.

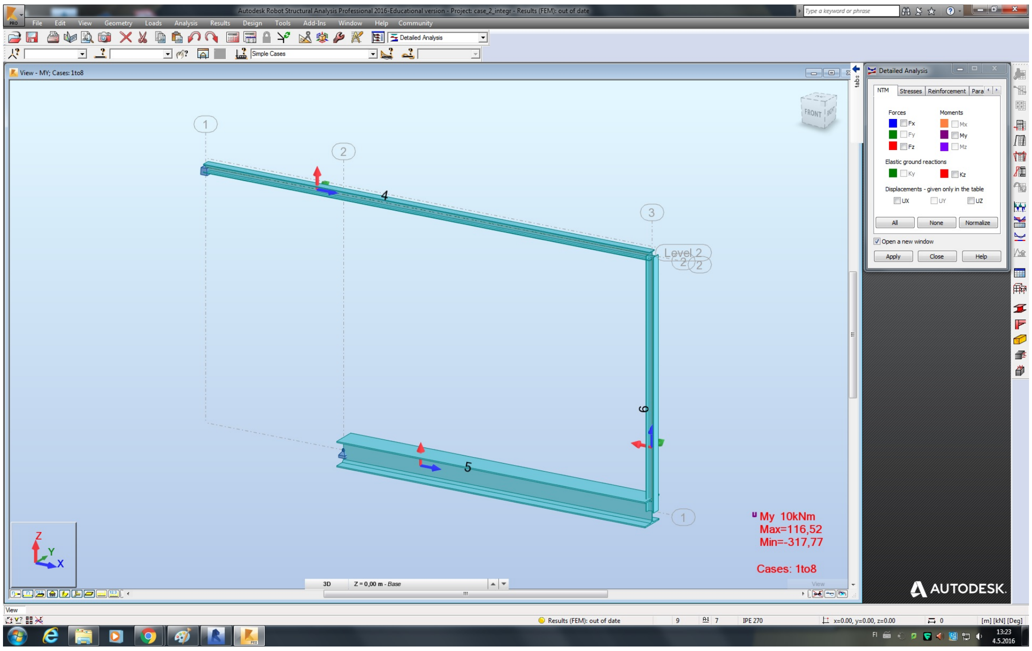

Figure 16. Case 2: updated Robot model

The tests showed that the data transfer between Revit and Robot was quite successful and smooth in this case. Both programs retained the essential information and the results of the analyses stayed coherent with the expected values.

3.4 Test Results

After considering the output produced during the tests, models designed in Autodesk Robot can be transferred to Revit and back with minor to none distortion. However that is true in the cases with conventional structures and loads within typically expected range. Load cases described by Eurocode can be used as an example. [38,39]

Moreover, changes introduced in Revit are also displayed in Autodesk Robot after synchronisation. Nonetheless, in order to avoid inconsistencies in the calculation the software-specific rules for definition of geometrical surfaces and loads should be followed accurately. Average construction projects can use Autodesk Robot and Revit and expect the high level of synchronization and data exchange. Aside from that, the tests show that distributed design becomes more common and is recognized by larger software developers, such as Autodesk, who also provide a link that ensures smooth information exchange between users of different products. Still data exchange properties of any program are strongly dependant on parameters determined by the developer and can at times serve as limitations. [35,38,39.]

Talking about special requirements during a design process in Autodesk Robot and Revit, it is essential to pay close attention to two instances. Firstly, a clear and consistent definition of the coordinate system and sign convention plays a significant role in achieving accurate results. Furthermore, units and their scale should be double-checked as well for the same reason.

Secondly, during the synchronization of Revit and Autodesk Robot, the definition of loads needs to be traced carefully, as their listing in Revit is slightly different from that in Autodesk Robot. Input values do not get altered after the integration of the model, though the load groups might be automatically re-named in Robot to match the groups in Revit, as the latter is typically serves as a primary software application in construction projects. All in all, this feature does not cause any significant disruption to the process.

Synchronization of the two programs provides a reliable tool for distributed design of a structure. Certain difficulties may arise when working with pieces of software developed by different companies. While the transition between Autodesk Robot and Revit is uncomplicated, similar procedure between Autodesk Robot and Tekla Structures might require more effort due to installation technicalities and more time consuming configuration of the parameters of a transferred model.

To sum up, a distributed approach to the design of structures becomes more common and developers of software, such as Autodesk, have already acknowledged this fact. Nevertheless, interoperability is still quite far from being as all-encompassing as stated in official papers. Despite certain challenges that may arise while working with products of different vendors, tests with Revit and Autodesk Robot Structural Analysis showed that project models can be synchronized and updated while maintaining most of the model information, which allows different design teams in a project relatively independently.

4 Discussion

Overall, the test results in Chapter 3 supported by the theoretical research in Chapter 2 help to distinguish the ways in which structural design is impacted by CAE. It can be also seen that Autodesk Revit and Robot provide the design functions adequate for the analysis purposes in majority of projects. Use of the programs facilitates both technical calculations and communication process. Nevertheless, a number of challenges is still to be overcome. Most importantly, it is crucial to understand that the contents and definition of structural design have changed, as well as the skills required to perform it. [10,27.]

Models used for the simulations in chapter 3 contain information that is typically relevant in the structural design phase of a construction project. This way, despite their relative simplicity, tests can be used to extrapolate the performance of CA functions in a large-scale project. Evidently, a structural model developed in Autodesk Revit and Robot can be sent back and forth several times without any significant disturbance to the overall quality of the model. Alterations can also be performed and retained after transfer, if some details, such as geometric parameters and load definition process, are performed carefully. [20.]

However, timing can be an issue worth considering. Even for the studied simple structures analysis process with Autodesk Robot took some time. Naturally, a project with thousands of details and multiple load combinations require a lot more time. This may lead to project extensions and delays. Consequentially, studying the relation of output, processing speed and amount of transferred information should be studied further.

Also, the practical implications of distributed design adoption should be noticed. The approach taken in the practical part of this study, where a model created with one program is then edited or analysed with another, is typical for a structural design process today. Architects, managers and consultants merge models from specialized applications to achieve better communication. [25,27.]

This system works well enough, provided that the synchronization of models is properly organized. Such distributed design simplifies the delegation of tasks, which naturally occurs in any construction project. As an outcome, deliverables are presented within shorter period of time and their quality is typically better. The reason for that is the fact that engineers work with narrowly targeted programs that offer exceptional results for a limited number of tasks. An example of this is Autodesk Robot and its use for finite element analysis. [28,38,39.]

Distributed design still has some issues, mainly related to the openness and compatibility of design and its outputs. With Autodesk Revit and Robot, the integration process takes place quickly and smoothly. Such results are expected from applications developed by the same company. However, many issues arise when applications were created by different companies. A direct link is not always available and manual transfer of a model requires high level of expertise in a number of areas: structural design, construction management and programming. The transfer issue can currently be considered as pressing, and an express solution would be highly beneficial to many companies. [30.]

Finally, the roles of the structural engineer and designer are getting redefined, as new skills become more and more essential and old ones are now looked at from a different perspective. The main idea is that massive computations, which used to constitute the body of structural engineer's work, are now done by of a machine. Constantly developing mechanisms of analysis and optimisation handle extremely complicated problems better than humans could ever do. In turn, the ability to communicate the designer's intent to a program and derive conclusions from numerical output provided by a computer becomes invaluable, in order to successfully solve any structural design problem. [27,31.]

At the same time, traditional skills and practices cannot be abandoned. The ability to predict results and evaluate computations carried out by a computer application is essential as well. In the case studies, the solutions to the problems were also calculated normally and served as a reference point for the rest of the process. Yet in real projects this scenario is impossible, so the reference point needs to be produced with approximate calculations in a very short time. This sort of proficiency requires exceptional knowledge of traditional methods and an understanding of structures, setting high requirements for future specialists. [31.]

Research performed in the course of writing this thesis shows that structural design primarily benefits from the use of CAE methods. With the adoption of a distributed approach to design, facilitated by software applications that can be recurrently synchronised, more precise and economical solutions become available. Although problems with data exchange between computer programs of different developers are still to be solved, the general impact of CAE can be considered positive both for the field and for its specialists.

5 Conclusion

The intent of this paper is to identify those areas within structural design in construction process that are most affected by the introduction of computational methods, and then assesses the scale and consequences of these new developments. Data exchange is one of the more obvious and, at the same time vital implications of CA structural design, thus it was studied particularly closely. [27.]

After defining structural design as part of a construction project, independent discipline and technical approach to problem, it appears that CAE can be tied to structural design in two major ways. First, computer software solves the problem of complex analysis and optimization. FEA-based programs for structural analysis, such as Autodesk Robot, are an example of this. Second, since structural design serves as a part of a construction project, developments in construction engineering typically affect the workflow of a structural design process as well. Computer-enhanced modeling capabilities are a relevant example for that, as they allow the design team to work more efficiently and new ways of communication, presenting visuals and exchanging data. [13,25,31.]

The data exchange was studied more closely and showed to be worth the attention. The quality of data transfer strongly affects the quality of final outputs and the time frame of structural design. Some software applications, such as Autodesk Revit and Robot, provide sufficient functions in that area. Their integration ensures a smooth information exchange and shows that a distributed design approach is developing in a positive direction. Yet for other programs it may not be the case, as the synchronization of products from different developers is typically more cumbersome. For this reason, further investigation in data-processing issues, for instance, the manual definition of transferred model may be pursued in future, becoming another fascinating area of research. [38,39.]

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Appendix 1. Case 1: Problem solution

In this Appendix solution of the problem used for the 1st case study is presented.

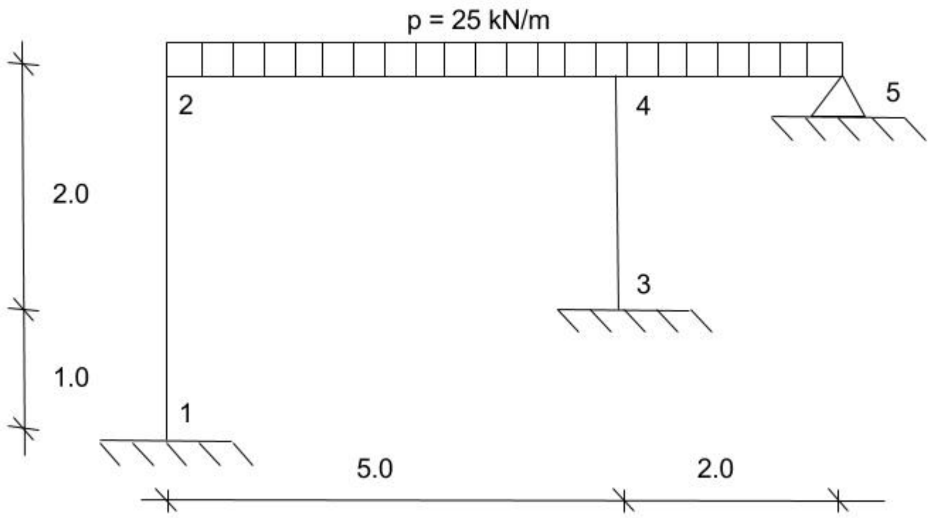


Figure 17. Case 1: Schematic drawing of a frame

The first structure is a hyperstatic frame showed above. It is uniformly loaded (p= 25kN/m) and EI is constant, which means that the material is homogeneous.

Moment diagram and steps preceding its deduction are provided below.

$k_{12} = \frac{1}{3}$

$k_{24} = \frac{1}{5}$

$k_{34} = \frac{1}{2}$

$$k_{24} = \frac{3}{4} * \frac{1}{2} = \frac{3}{8}$$

$$\mu_{21} = \frac{1/3}{1/3 + 1/5} = \frac{5}{8}$$

$$\mu_{24} = \frac{1/5}{1/3 + 1/5} = \frac{3}{8}$$

$$\mu_{42} = \frac{1/5}{1/5 + 1/2 + 3/8} = 0{,}18605$$

$$\mu_{43} = \frac{1/2}{1/5 + 1/2 + 3/8} = 0{,}46512$$

$$\mu_{45} = \frac{3/8}{1/5 + 1/2 + 3/8} = 0{,}34883$$

$$MK_{24} = -\frac{pL^2}{12} = -\frac{25*25}{12} = -52{,}084\ Knm = -MK_{42}$$

$$MK_{45} = \frac{pL^2}{8} = -12{,}5\ kNm$$

1		2				4			3
		0,625	0,375		0,18605	0,46512	0,34884		
			-52,084		52,084		-12,5		
16,27625		32,5525	19,5315		9,76575				
			-4,59076		-9,181521	-22,95356	-17,21517		-11,47678
1,434613		2,869225	1,721535		0,860768				
			-0,080073		-0,160146	-0,40036	-0,30027		-0,20018
0,025023		0,050046	0,030027		0,015014				
					-0,002793	-0,006983	-0,005237		
17,73589		35,47177	-35,47177		53,38107	-23,3609	-30,02067		-11,67696
M12		M21	M24		M42	M43	M45		M34

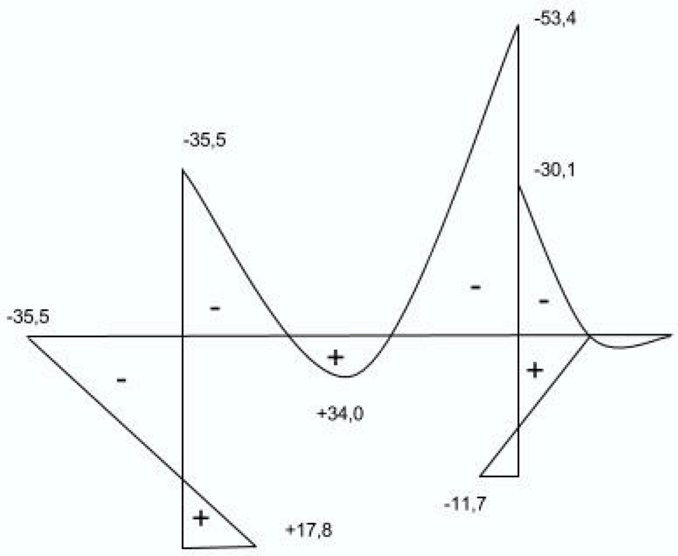
$$Q_{24} = \frac{1}{2}pL - \frac{M_{24}+M_{42}}{L} = \frac{1}{2}25 * 5 - \frac{-35{,}47+53{,}38}{5} = 58{,}92\ kN$$

$$x_0 = \frac{Q_{24}}{p} = 2{,}357\ m$$

$$M_{max} = M_{24} + Q_{24}x_0 - \frac{1}{2}px_0^2 = 33{,}962\ kNm$$

$$Q_{45} = \frac{1}{2}pL - \frac{-M_{45}}{L} = \frac{1}{2}25 * 2 - \frac{-30{,}02}{2} = 40{,}01\ kN$$

$$M_{max} = 1{,}98\ kNm$$


-53,4
-35,5
-30,1
-35,5
-
-
-
-
+
+
+34,0
-11,7
+
+17,8

Appendix 2. Case 1: Steel frame design and analysis in Autodesk Robot Structural Analysis

In this Appendix detailed procedure of the design and analysis via Autodesk Robot for the 1st case study is presented.

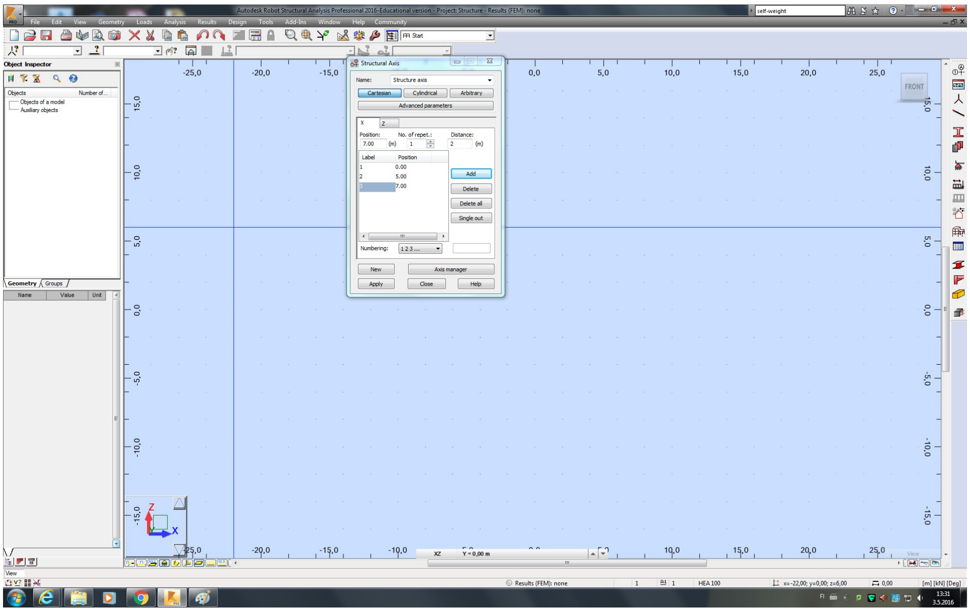


Figure 18. Case 1, Autodesk Robot: Definition of axis 1

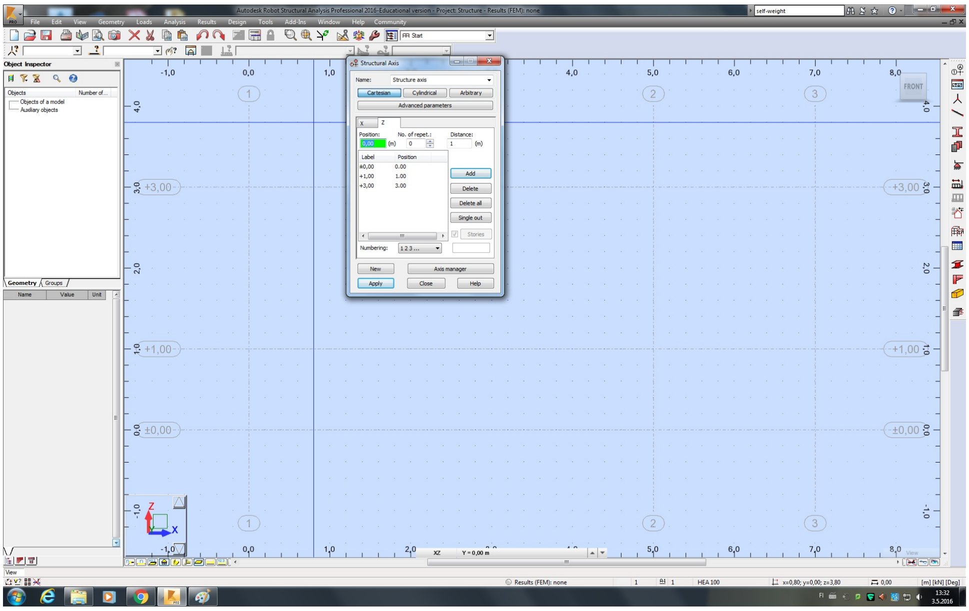


Figure 19. Case 1, Autodesk Robot: Definition of axis 2

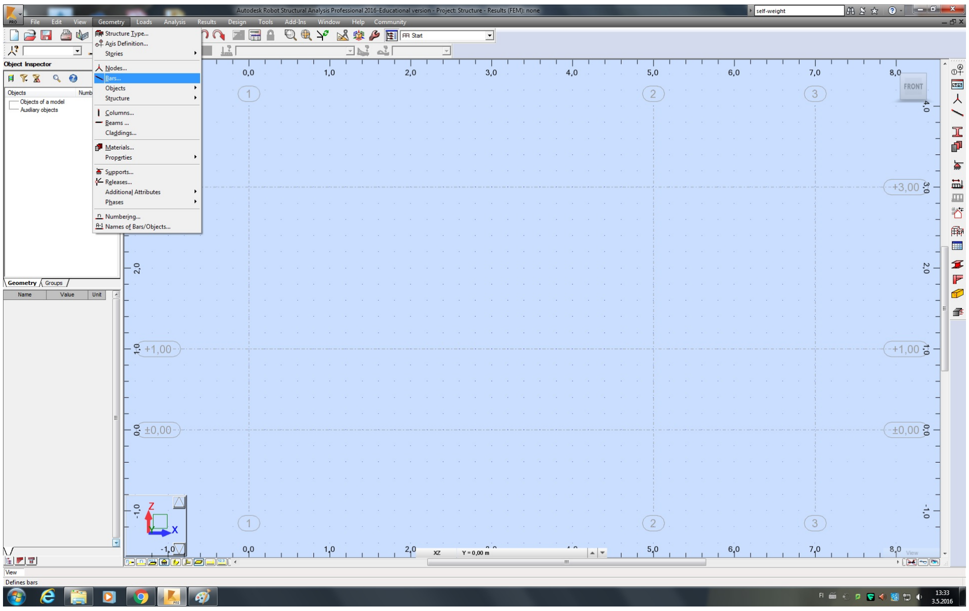


Figure 20. Case 1, Autodesk Robot: Definition of elements 1

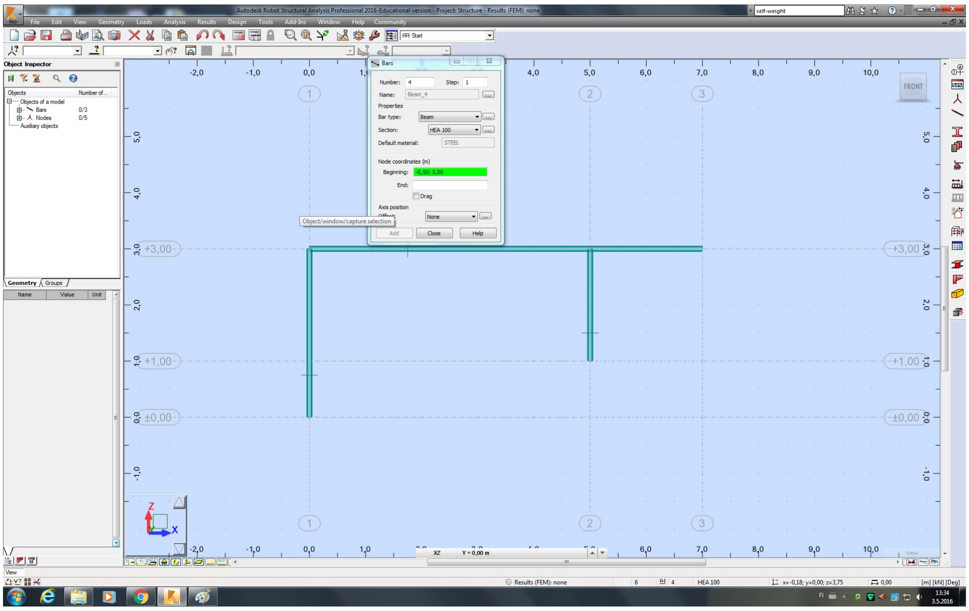


Figure 21. Case 1, Autodesk Robot: Definition of elements 2

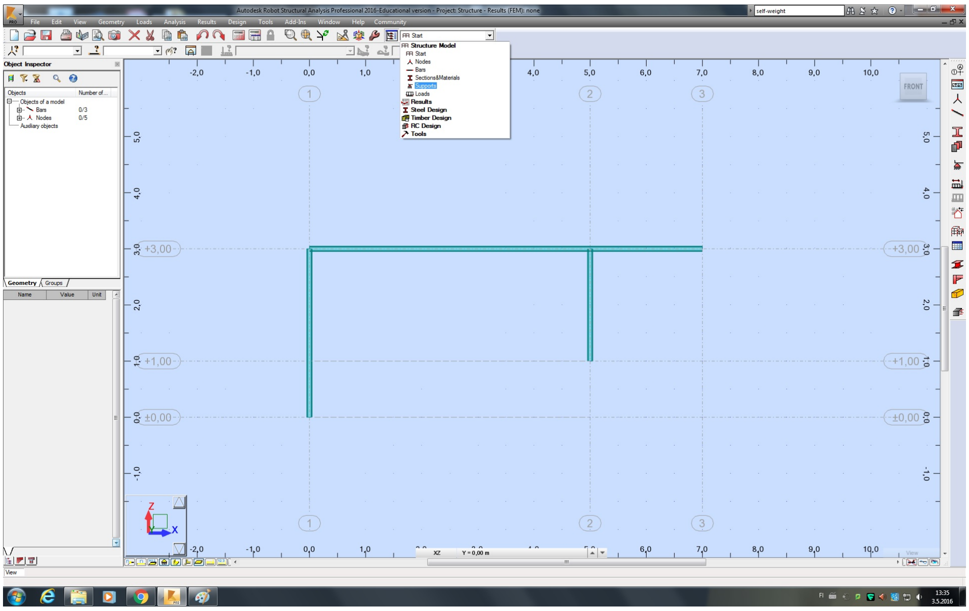


Figure 22. Case 1, Autodesk Robot: Definition of supports 1

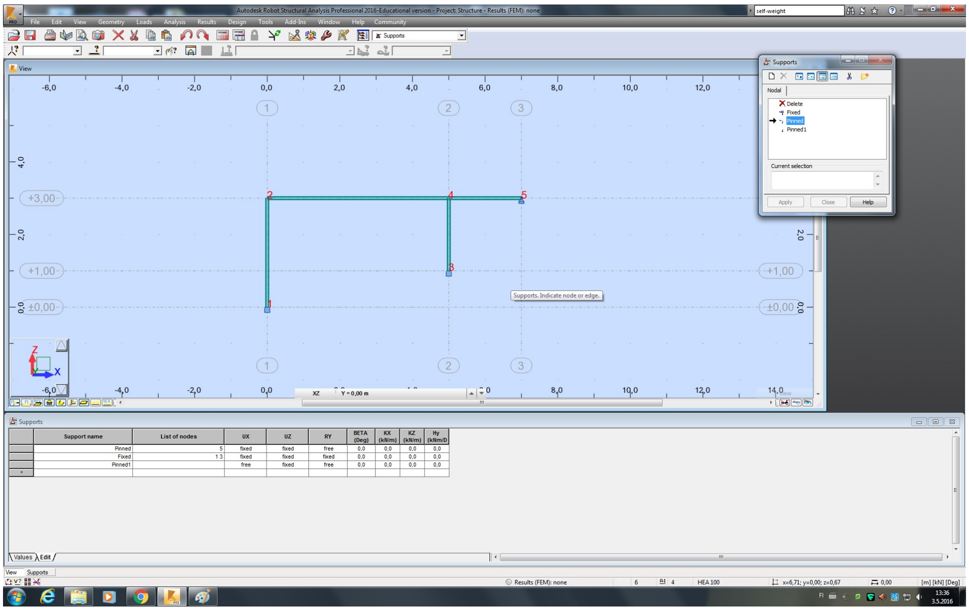


Figure 23. Case 1, Autodesk Robot: Definition of supports 2

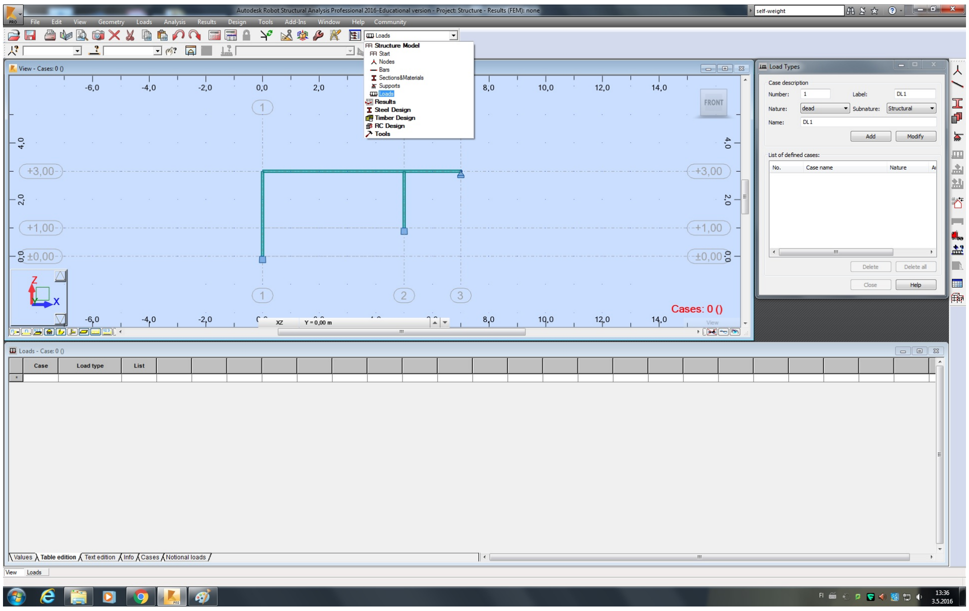


Figure 24. Case 1, Autodesk Robot: Definition of loads 1

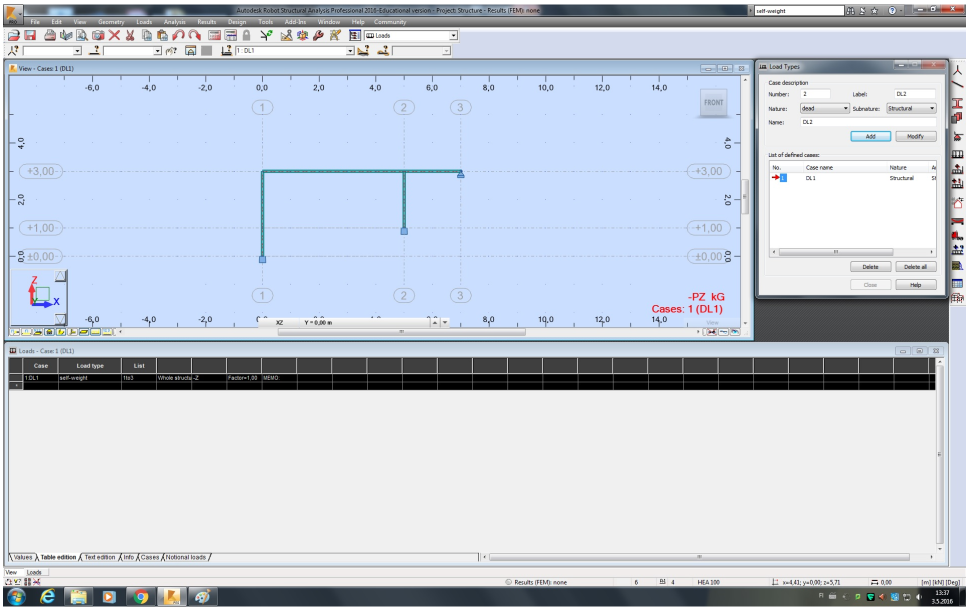


Figure 25. Case 1, Autodesk Robot: Definition of loads 2, load case selection

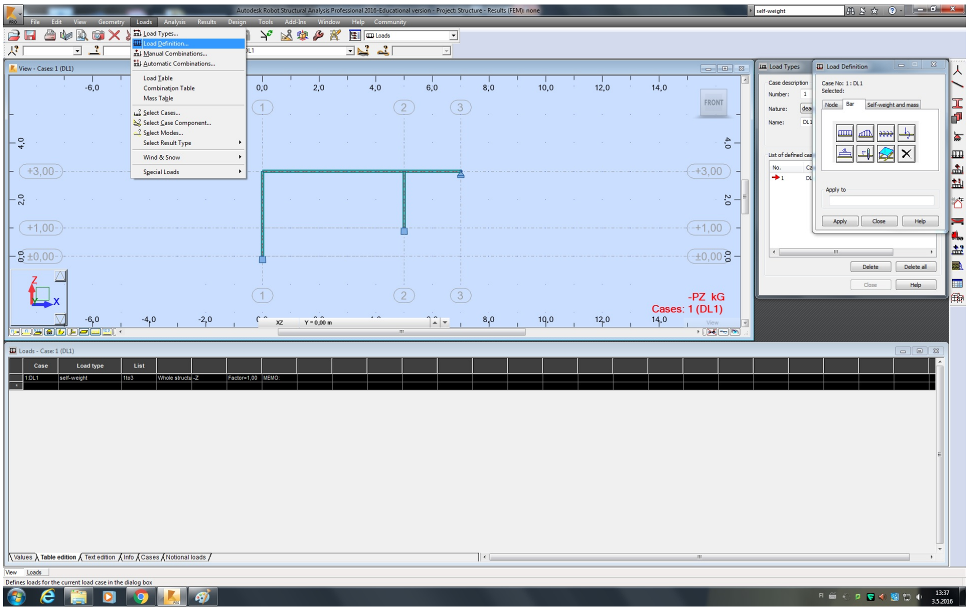


Figure 26. Case 1, Autodesk Robot: Definition of loads 3, load type

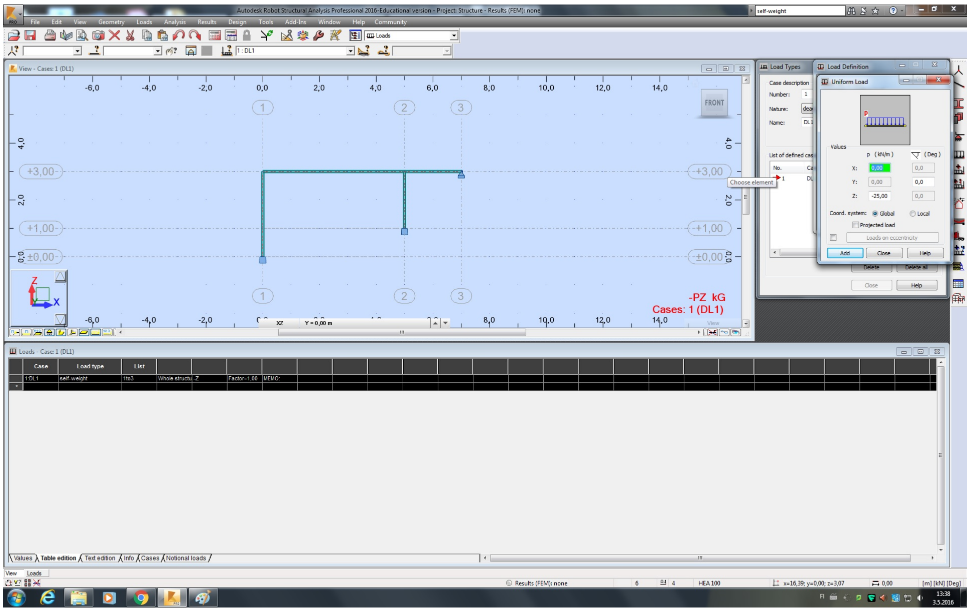


Figure 27. Case 1, Autodesk Robot: Definition of loads 4, magnitude and direction of a load

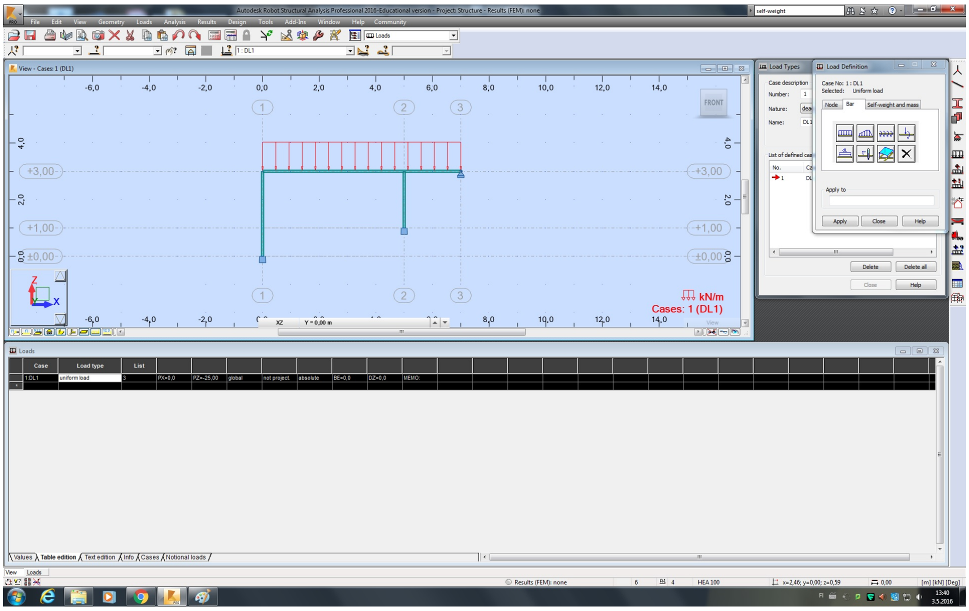


Figure 28. Case 1, Autodesk Robot: Definition of loads 5

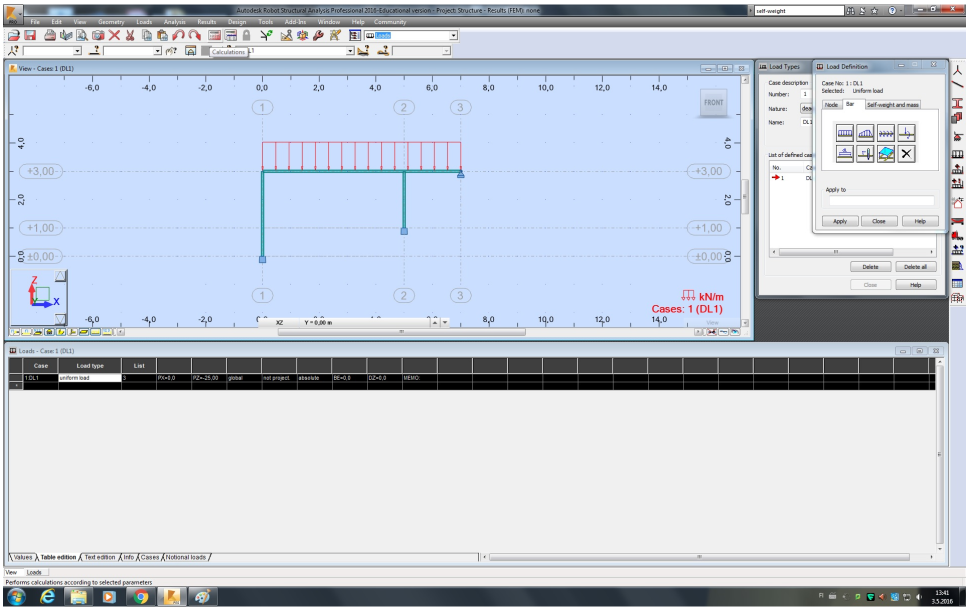


Figure 29. Case 1, Autodesk Robot: running calculations 1

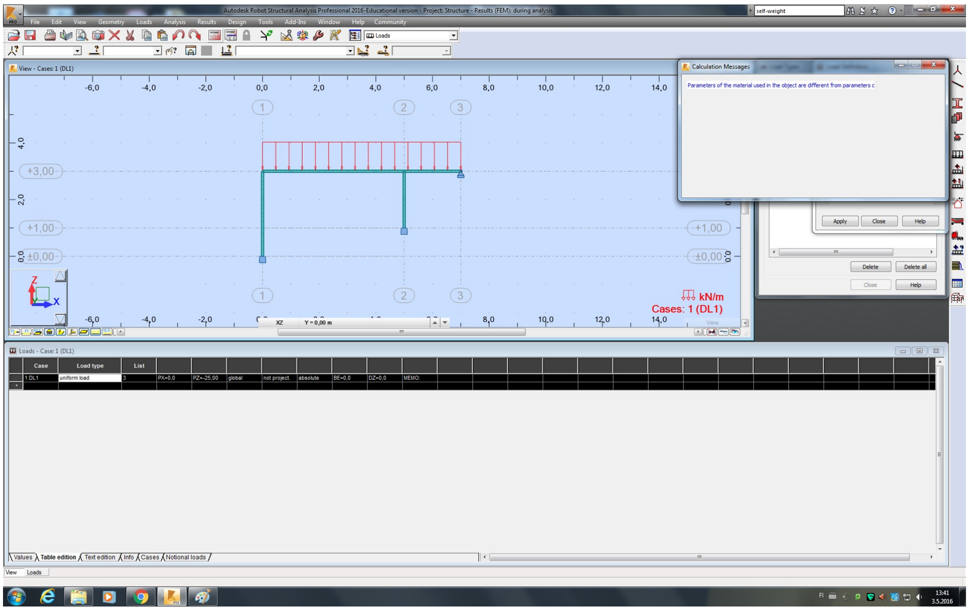


Figure 30. Case 1, Autodesk Robot: running calculations 2

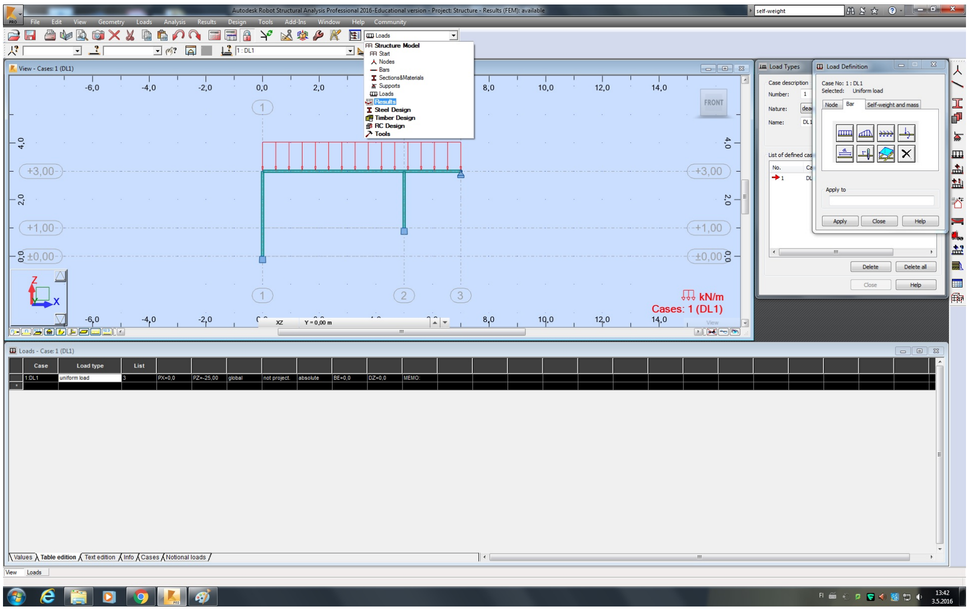


Figure 31. Case 1, Autodesk Robot: presentation of results 1

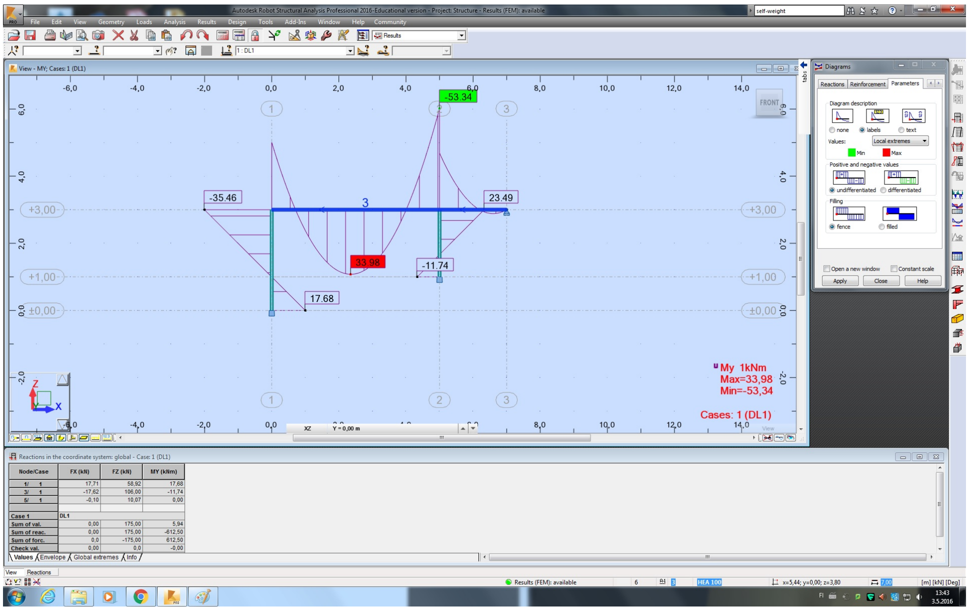


Figure 32. Case 1, Autodesk Robot: presentation of results 1, moment diagram

Appendix 3. Case 1: Steel frame model integration between Revit and Robot

In this Appendix detailed procedure of model integration between Autodesk Robot and Revit or the 1st case study is presented.

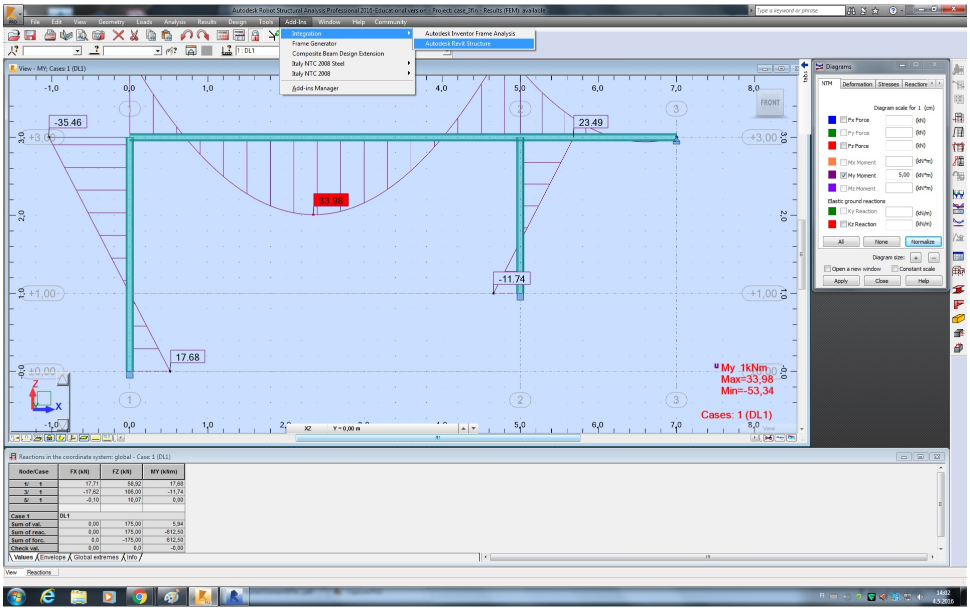


Figure 33. Case 1, Autodesk Robot: establishing the link with Revit 1

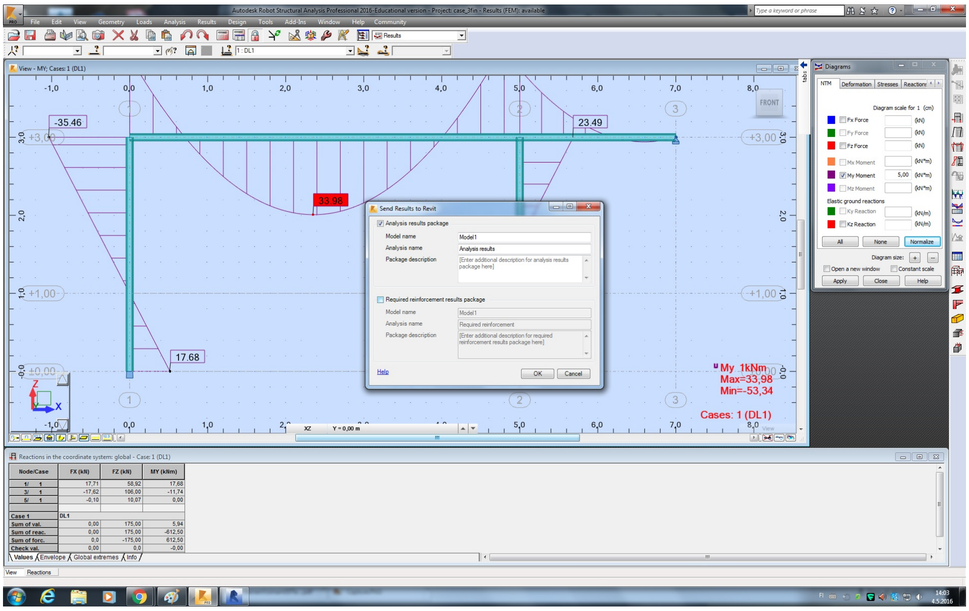


Figure 34. Case 1, Autodesk Robot: establishing the link with Revit 2, properties selection

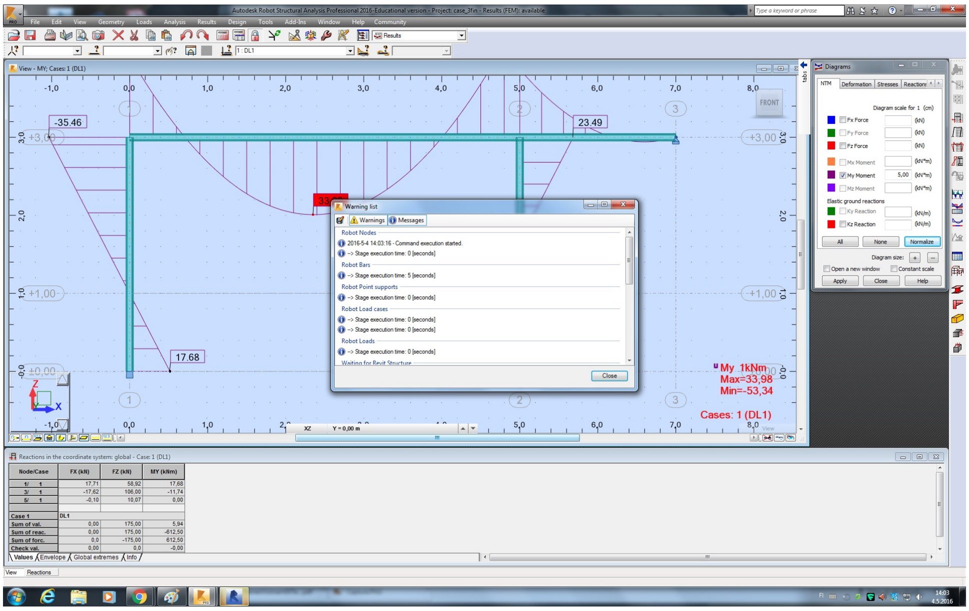


Figure 35. Case 1, Autodesk Robot: establishing the link with Revit 3

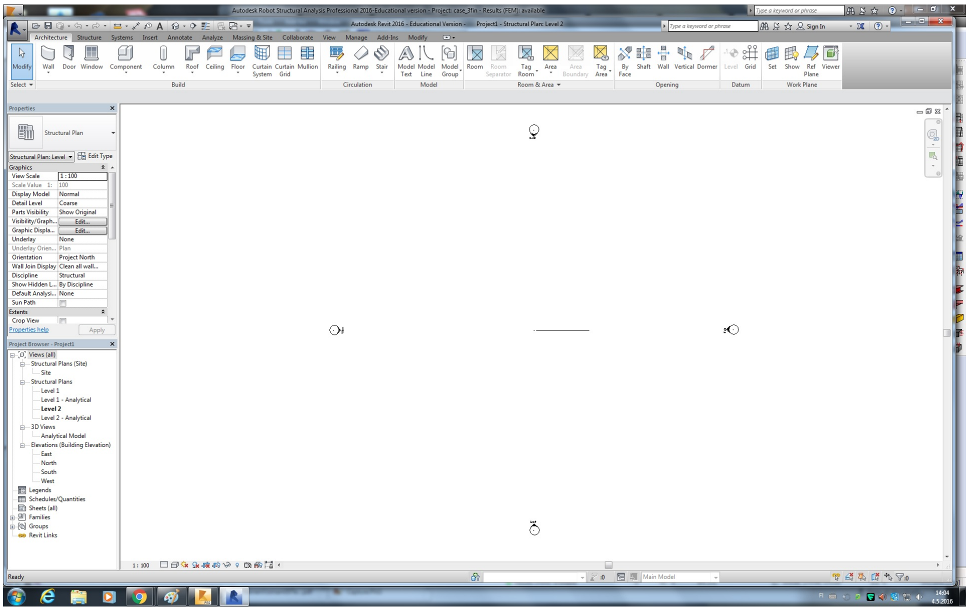


Figure 36. Case 1, Revit: model received from Autodesk Robot, plan view

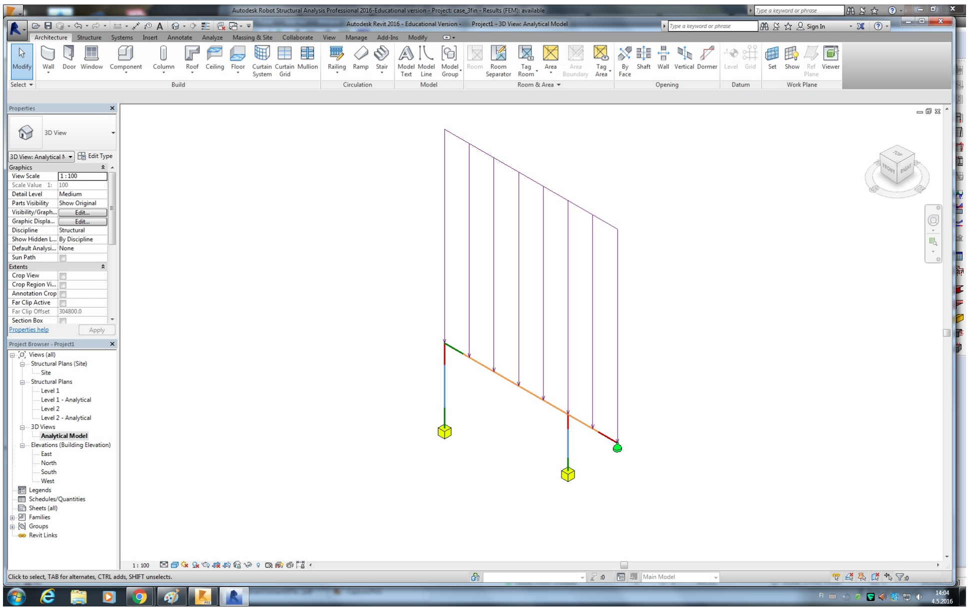


Figure 37. Case 1, Revit: model received from Autodesk Robot, analytical model

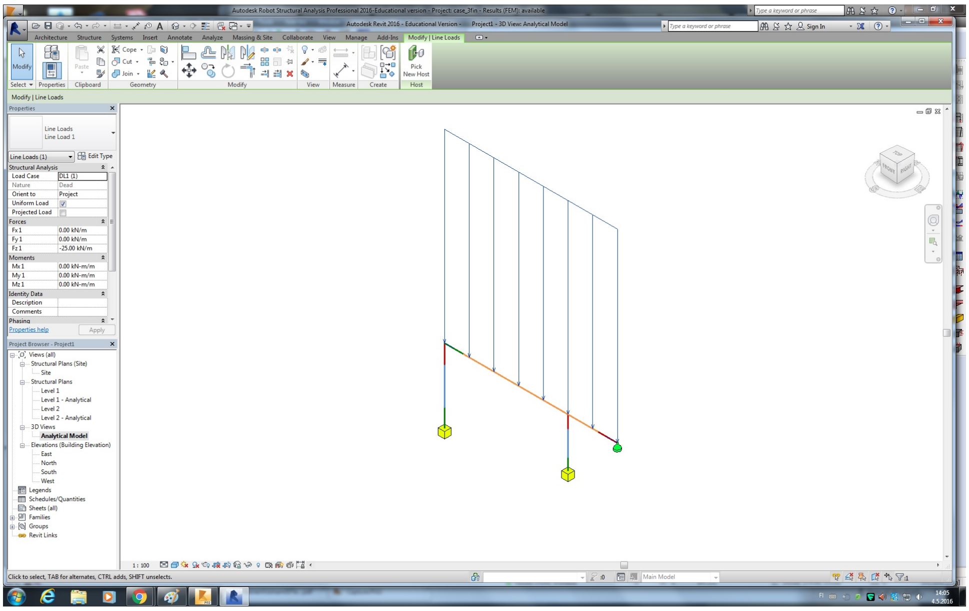


Figure 38. Case 1, Revit: modification of the model 1

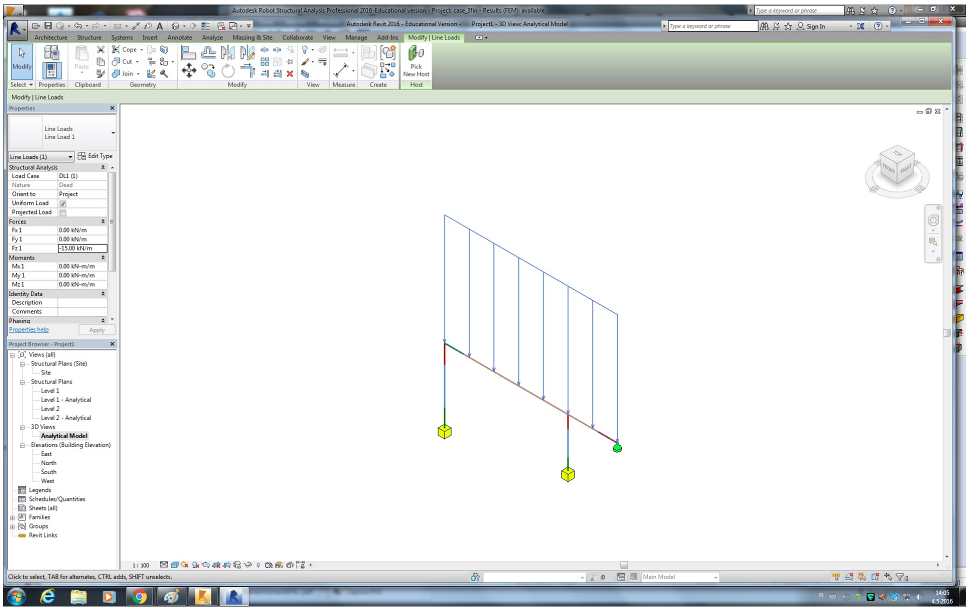


Figure 39. Case 1, Revit: modification of the model 2, reduction of the load

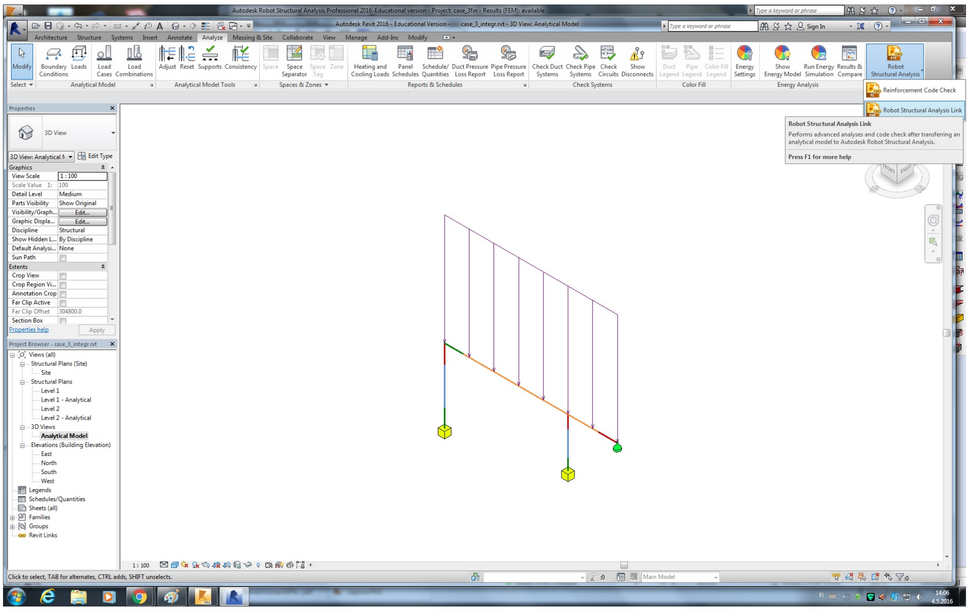


Figure 40. Case 1, Revit: establishing the link with Autodesk Robot

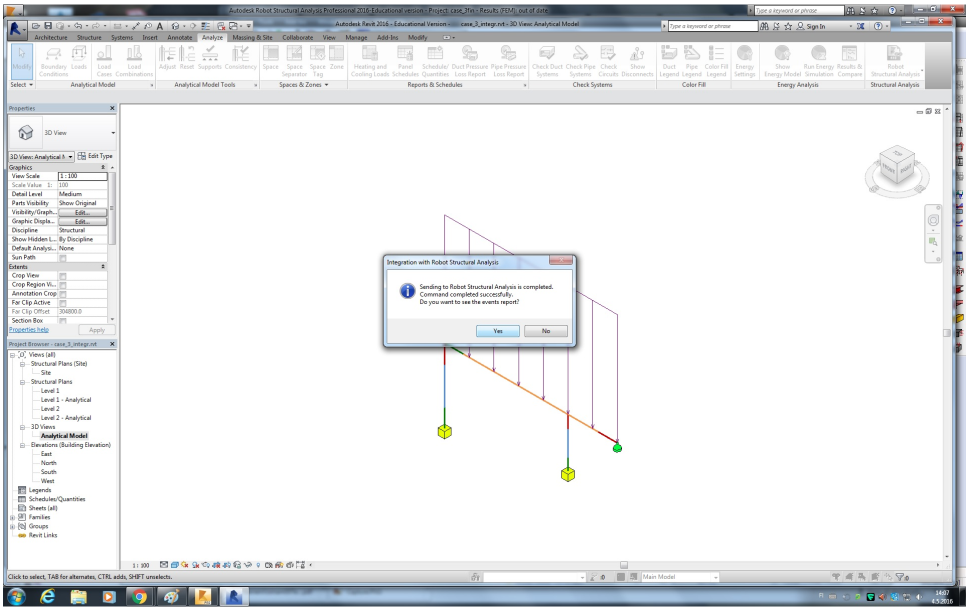


Figure 41. Case 1, Revit: integration process with Autodesk Robot 1

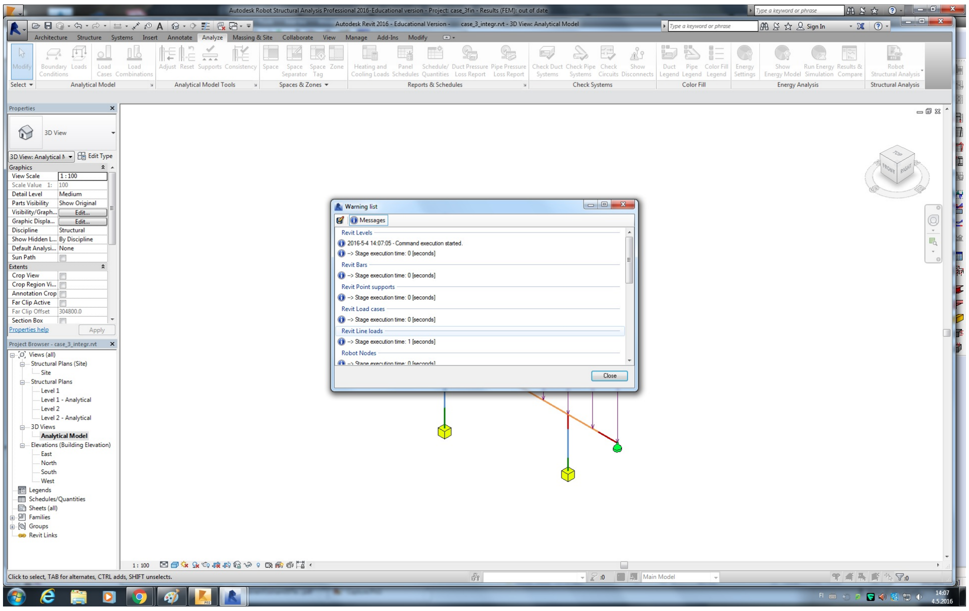


Figure 42. Case 1, Revit: integration process with Autodesk Robot 2

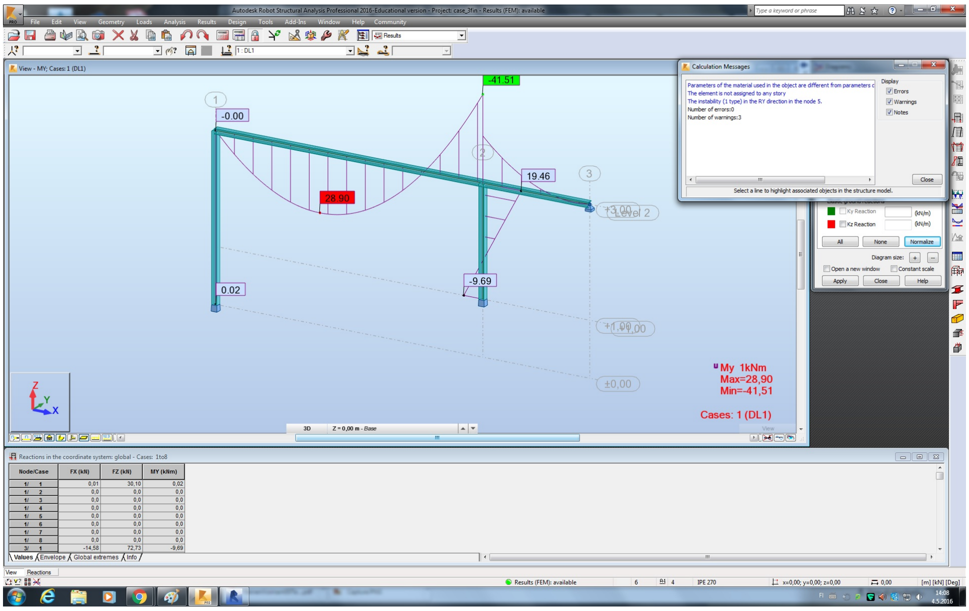


Figure 43. Case 1, Autodesk Robot: updated model with calculation messages

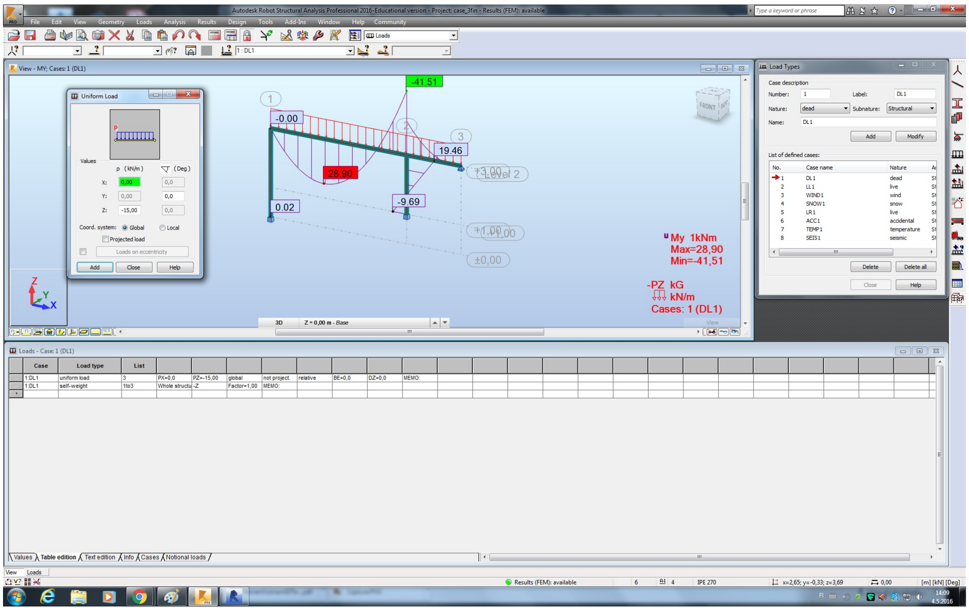


Figure 44. Case 1, Autodesk Robot: check of changes of updated model

Appendix 4. Case 2: Problem solution

In this Appendix solution of the problem used for the 2nd case study is presented.

3

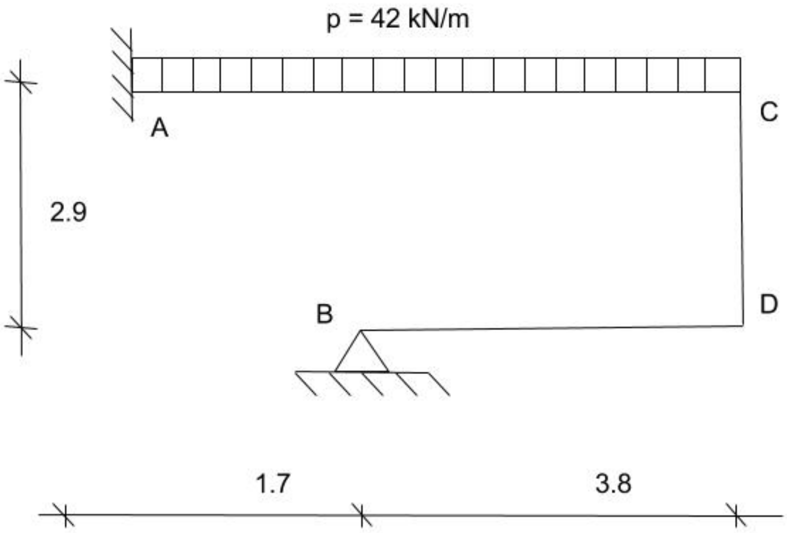
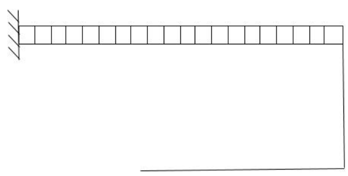
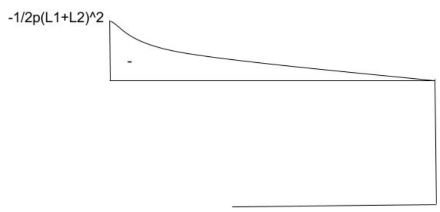


Figure 45. Case 2: Schematic drawing of a frame

0)





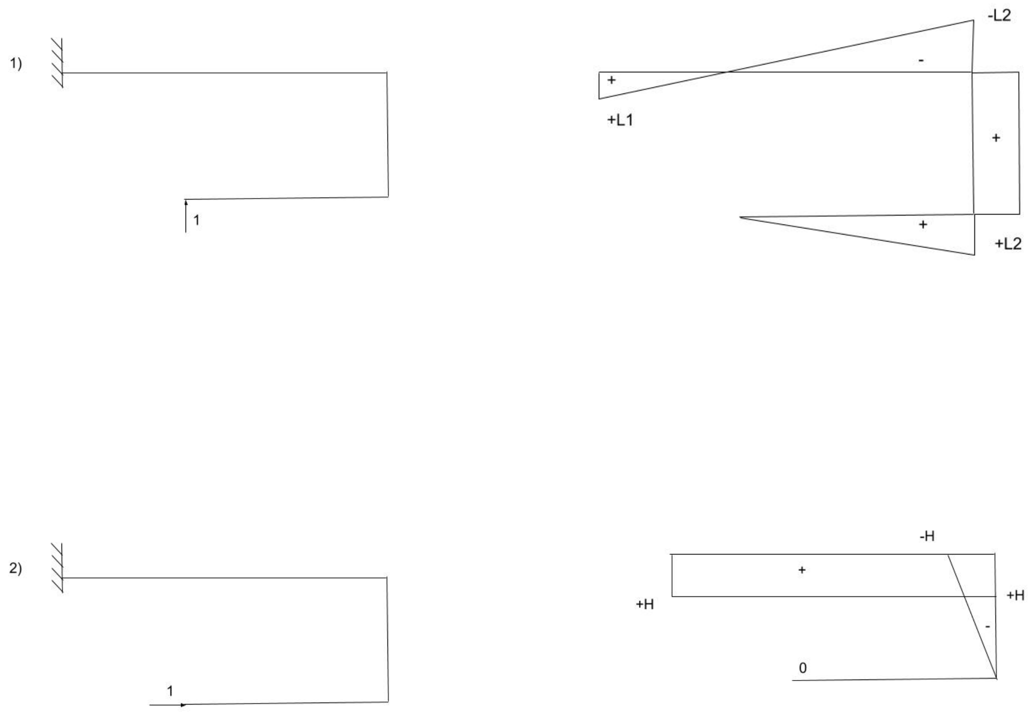


Figure 46. Case 2: force method solution

$$\delta_{10} = \frac{1}{EI}\int M_0 M_1 ds = \frac{1}{EI}\frac{sy_2}{12}\left(\overline{y_1} + 3\overline{y_2}\right) = \frac{1}{EI}\frac{(L_1+L_2)\left(-\frac{1}{2}p(L_1+L_2)^2\right)}{12}(-L_2 + 3L_1) = -\frac{p(L_1+L_2)^3}{24EI}(-L_2 + 3L_1)$$

$$\delta_{11} = \frac{1}{EI}\int {M_1}^2 ds = \frac{1}{EI}\left(\frac{1}{3}s\left(\overline{{y_1}^2} + \overline{y_1 y_2} + \overline{{y_2}^2}\right) + s\overline{y_2^2} + \frac{1}{3}s\overline{y_2^2}\right) = \frac{1}{EI}\frac{(L_1+L_2)\left(L_1^2+L_1L_2+L_2^2\right)+HL_2^2+\frac{1}{3}L_1L_2^2}{3} = \frac{\left(L_1^3+2L_2^3+3HL_2^2\right)}{3EI}$$

$$\delta_{20} = \frac{1}{EI}\int M_0 M_2 ds = \frac{1}{EI}\frac{sy_1\bar{y}}{3}\left(\overline{y_1} + 3\overline{y_2}\right) = \frac{1}{EI}\frac{(L_1+L_2)\left(-\frac{1}{2}p(L_1+L_2)^2\right)}{3}H = \frac{p(L_1+L_2)^3}{6EI}H$$

$$\delta_{22} = \frac{1}{EI}\int {M_2}^2 ds = \frac{1}{EI}\left(\overline{y^2} + \frac{1}{3}\overline{y^2}\right) = \frac{1}{EI}\left((L_1+L_2) * H^2 + \frac{1}{3}H(-H)^2\right) = \frac{1}{EI}\left((L_1+L_2) * H^2 + \frac{1}{3}H^3\right)$$

$\delta_{12} = \delta_{21} = \frac{1}{EI}\int M_1 M_2 ds = \frac{1}{EI}(\frac{s}{2}\ (y_1 + y_2)\bar{y} + \frac{1}{2}sy\overline{y)} = \frac{1}{EI}\left(\frac{1}{2}(L_1 + L_2)(L_1 - L_2)H +\right.$

$\left.\frac{1}{2}HL_2(-H)\right) = \frac{1}{2EI}((L_1^2 - L_2^2)H - L_2H^2)$

$\delta_{10} + X_1\delta_{11} + X_2\delta_{12} = 0$

$\delta_{20} + X_1\delta_{21} + X_2\delta_{22} = 0$

$\begin{vmatrix}\delta_{11} & \delta_{12}\\ \delta_{21} & \delta_{22}\end{vmatrix}\begin{vmatrix}X_1\\ X_2\end{vmatrix} = \begin{vmatrix}-\delta_{10}\\ -\delta_{20}\end{vmatrix}$

$\begin{vmatrix}\frac{(L_1^3+2L_2^3+3HL_2^2)}{3EI} & \delta_{12}\,\frac{1}{2EI}((L_1^2 - L_2^2)H - L_2H^2)\\ \delta_{21}\,\frac{1}{2EI}((L_1^2 - L_2^2)H - L_2H^2) & \frac{1}{EI}\left((L_1 + L_2) * H^2 + \frac{1}{3}H^3\right)\end{vmatrix}\begin{vmatrix}X_1\\ X_2\end{vmatrix} = \begin{vmatrix}\frac{p(L_1+L_2)^3}{24EI}(-L_2 + 3L_1)\\ \frac{p(L_1+L_2)^3}{6EI}H\end{vmatrix}$

$X_1 = 39{,}9\ kN$

$X_2 = 86{,}1\ kN$

$B_y = 39.914\ kN$

$B_x = 86.121\ kN$

$M_D = B_y * L_2 = 151.67\ kNm$

$M_{CD} = B_y * L_2 - B_X * L_2 = -98{,}08\ kNm \quad M_{CA} = 98{,}08\ kNm$

$M_A = B_y * L_1 + B_X * L_2 - \frac{1}{2}p(L_1 + L_2)^2 = -317.645\ kNm$

$Q_A = \frac{1}{2}p(L_1 + L_2) - \frac{M_A - M_c}{L_1 + L_2} = \frac{1}{2} * 42 * 5{,}5 — \frac{-317{,}645-98{,}08}{5{,}5} = 191{,}086\ kN$

$x_0 = \frac{Q_A}{p} = 4{,}55\ m$

$M_{max} = M_A + Q_A x_0 - \frac{1}{2}px_0^2 = 117{,}04\ kNm$

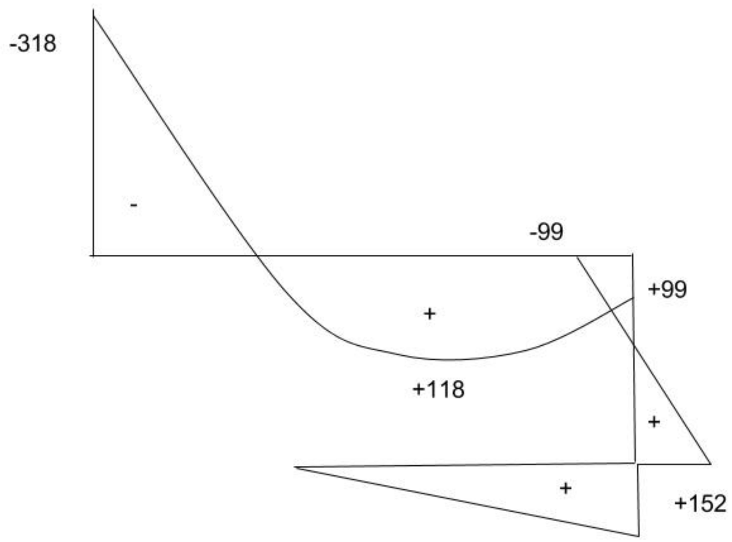


Figure 47. Case 2: Moment diagram

Appendix 5. Case 2: Steel frame design and analysis in Autodesk Robot Structural Analysis

In this Appendix detailed procedure of the design and analysis via Autodesk Robot for the 2nd case study is presented.

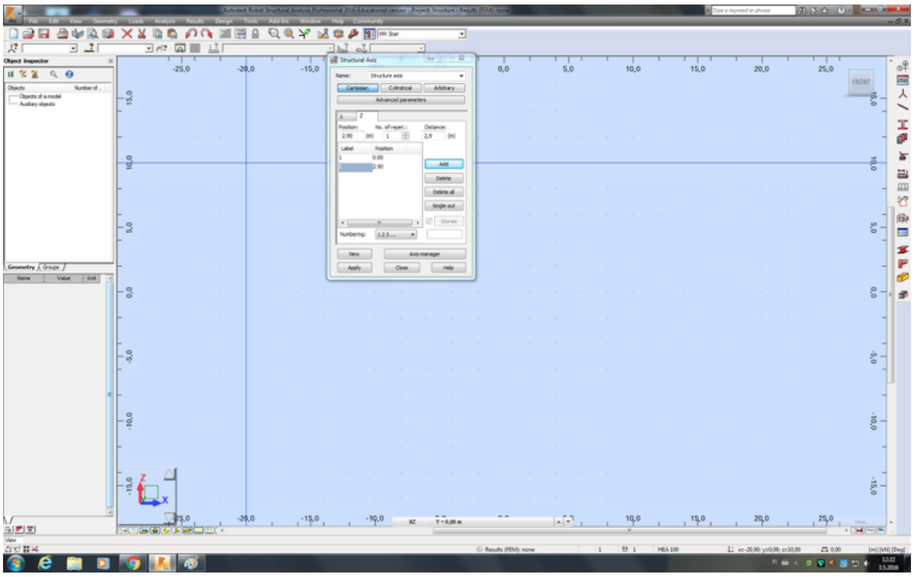


Figure 48. Case 2, Autodesk Robot: definition of axis

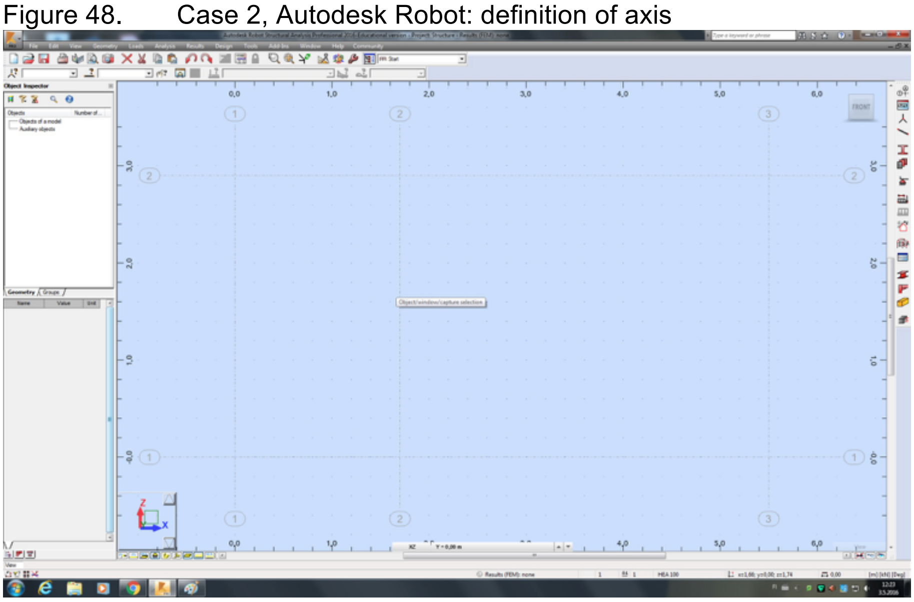


Figure 49. Case 2, Autodesk Robot: prepared grid

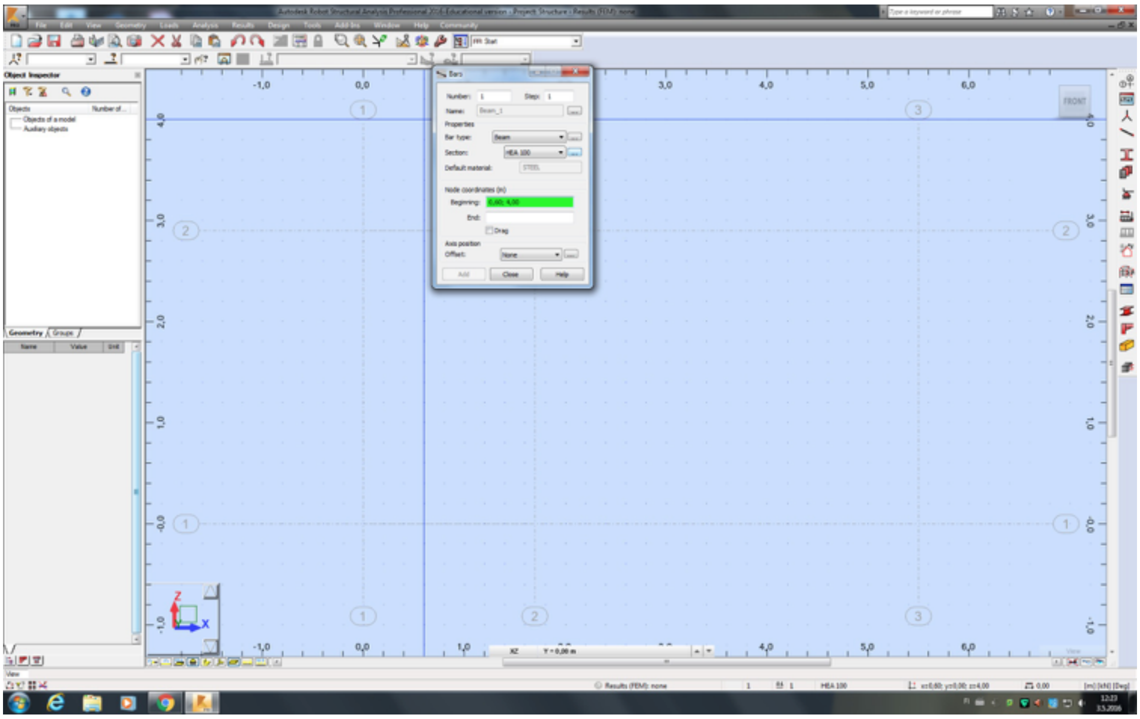


Figure 50. Case 2, Autodesk Robot: definition of elements 1

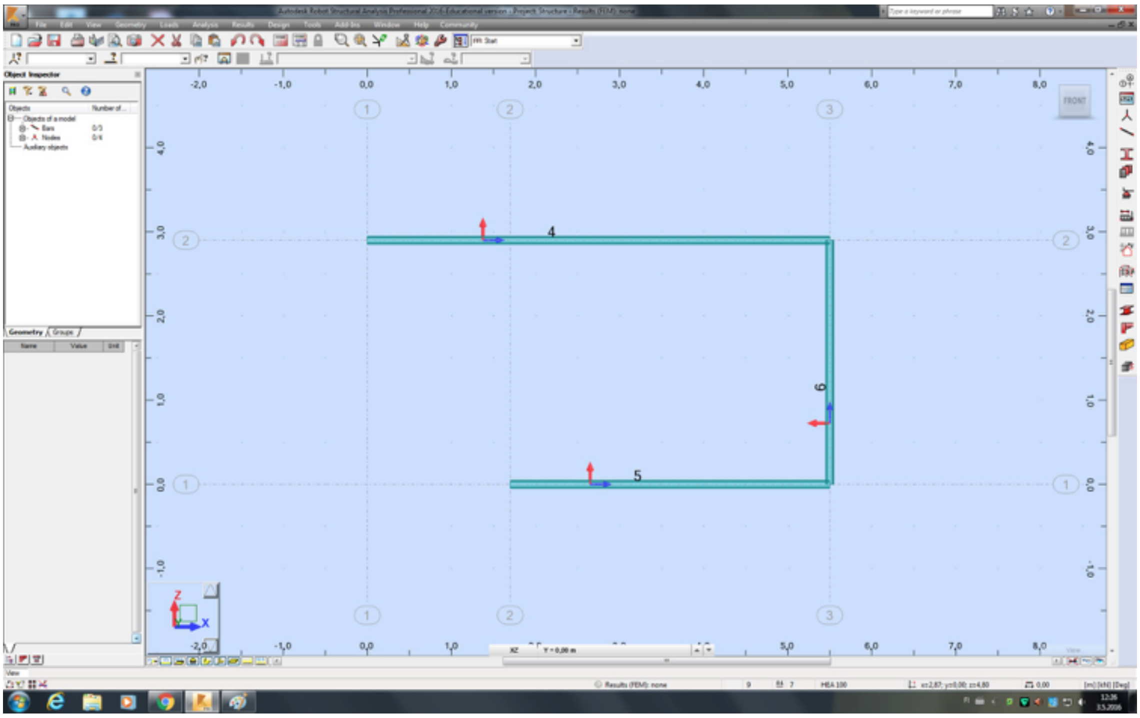


Figure 51. Case 2, Autodesk Robot: definition of elements 2

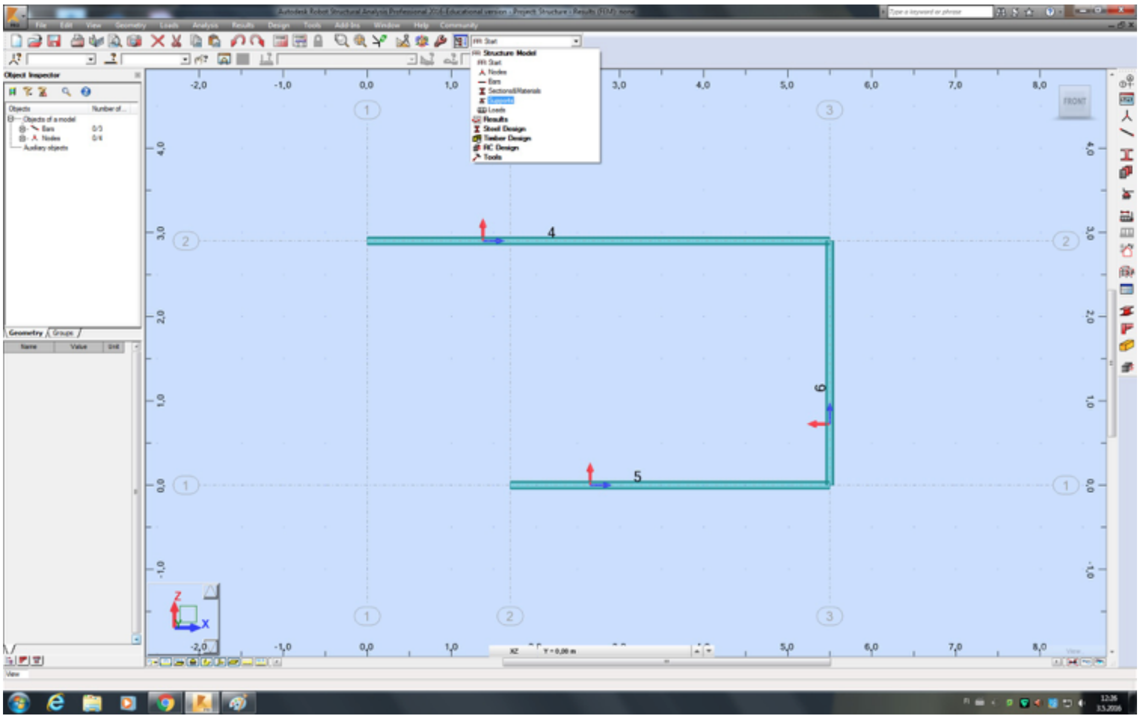


Figure 52. Case 2, Autodesk Robot: definition of supports 1

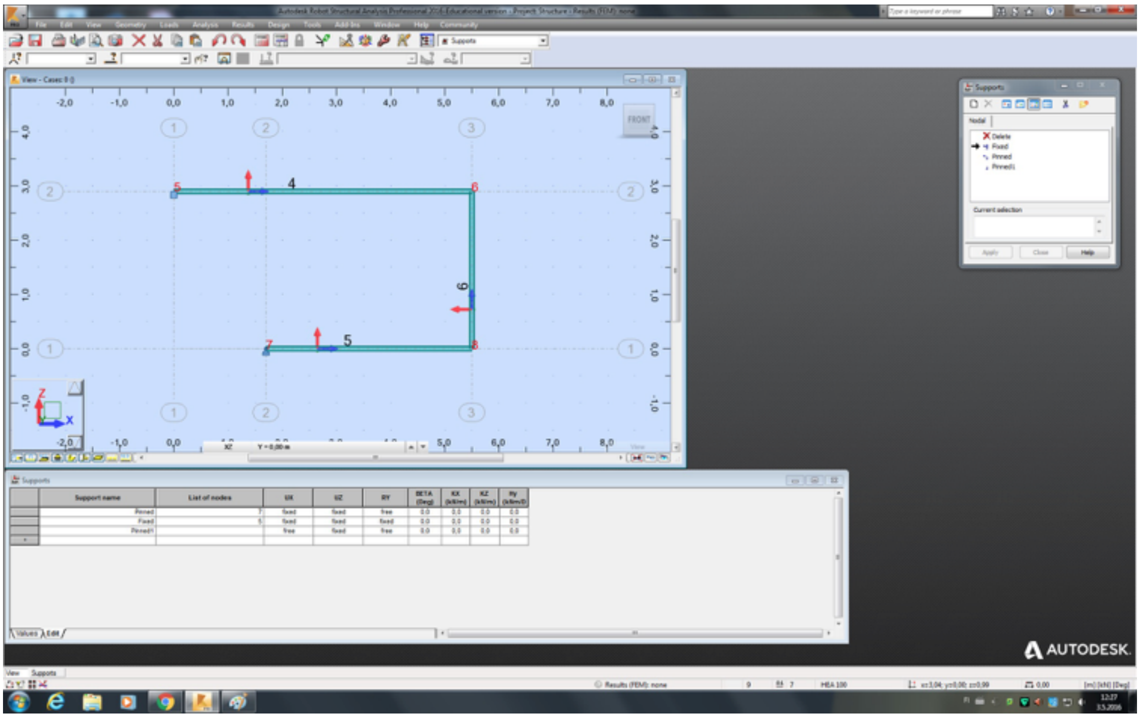


Figure 53. Case 2, Autodesk Robot: definition of supports 1

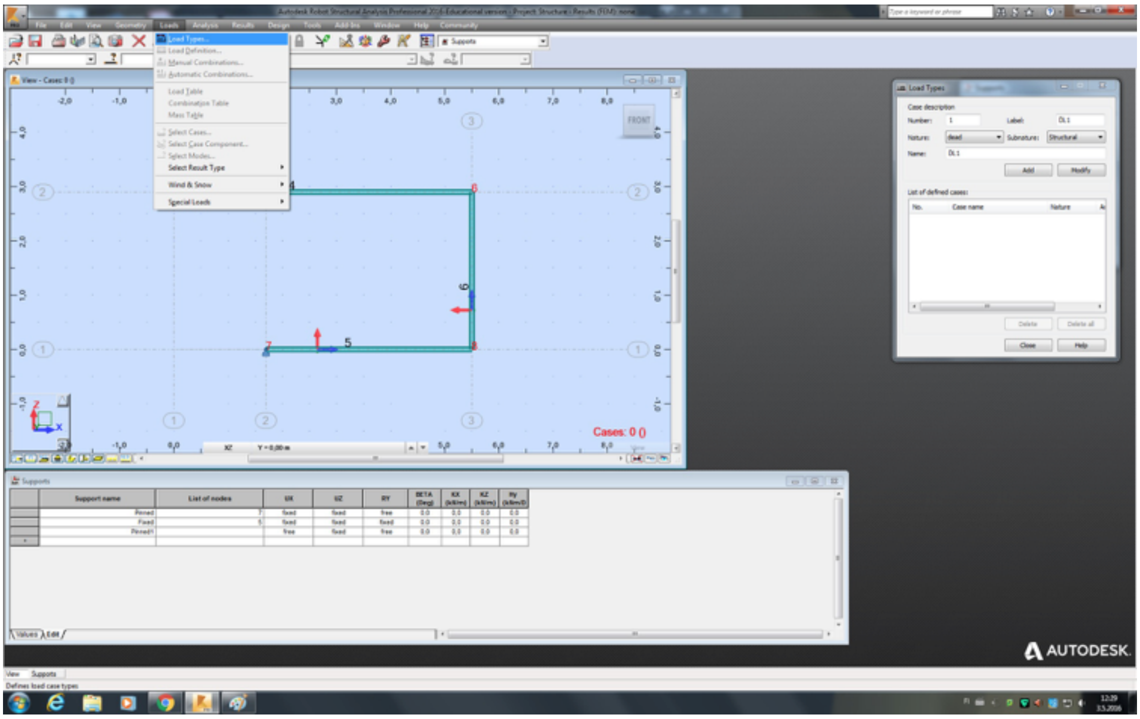


Figure 54. Case 2, Autodesk Robot: definition of loads 1, load case selection

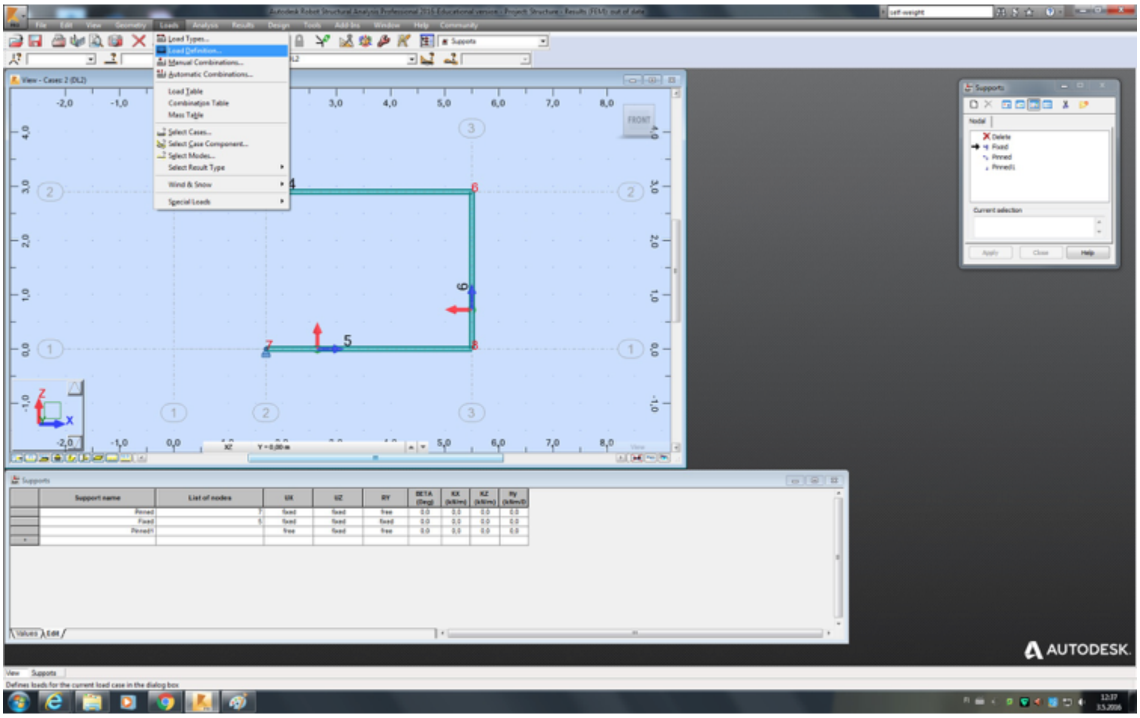


Figure 55. Case 2, Autodesk Robot: definition of loads 1, load type selection

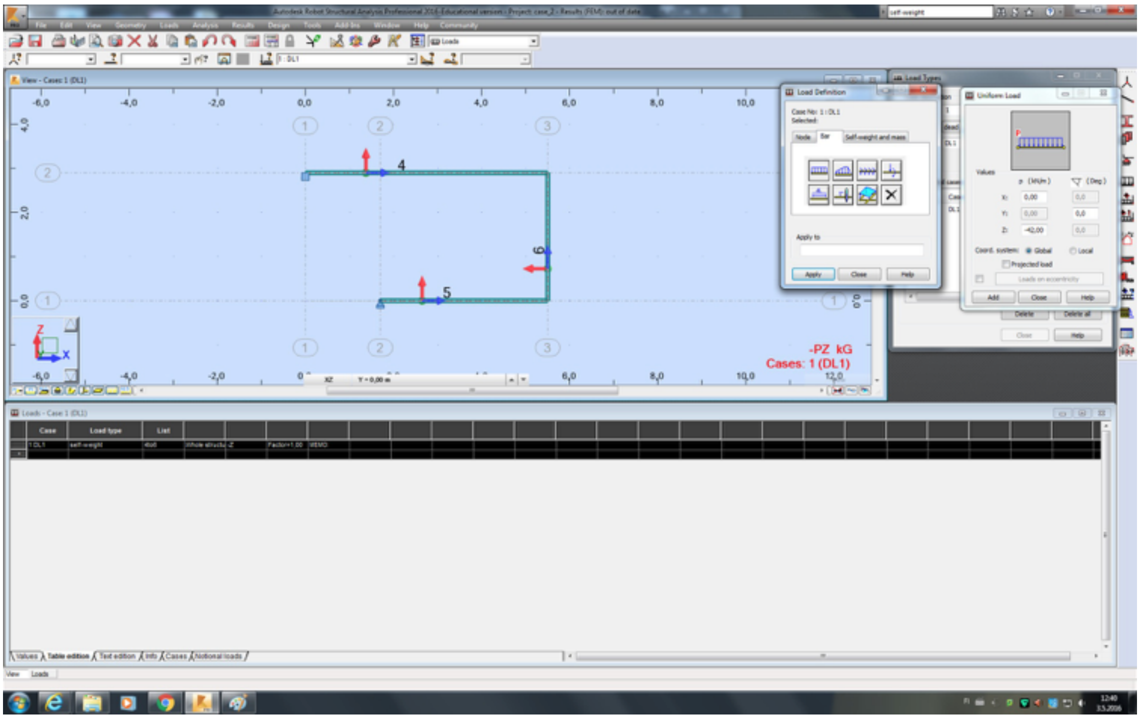


Figure 56. Case 2, Autodesk Robot: definition of loads 1, uniformly distributed load

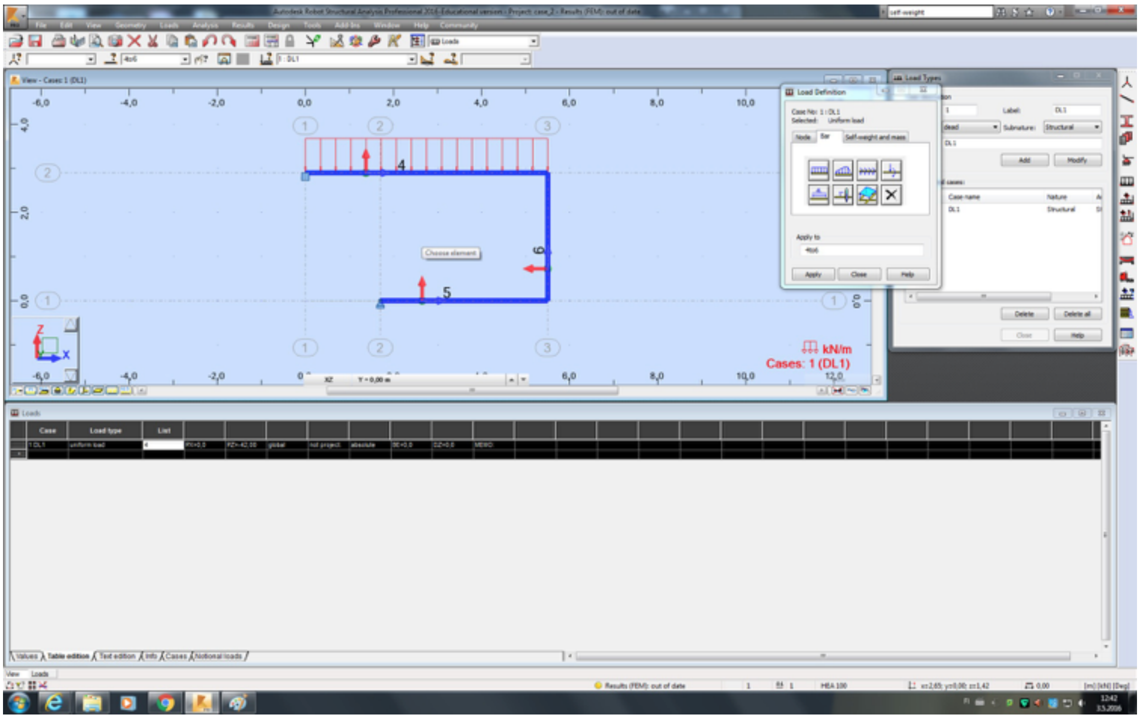


Figure 57. Case 2, Autodesk Robot, steel frame with assigned loads

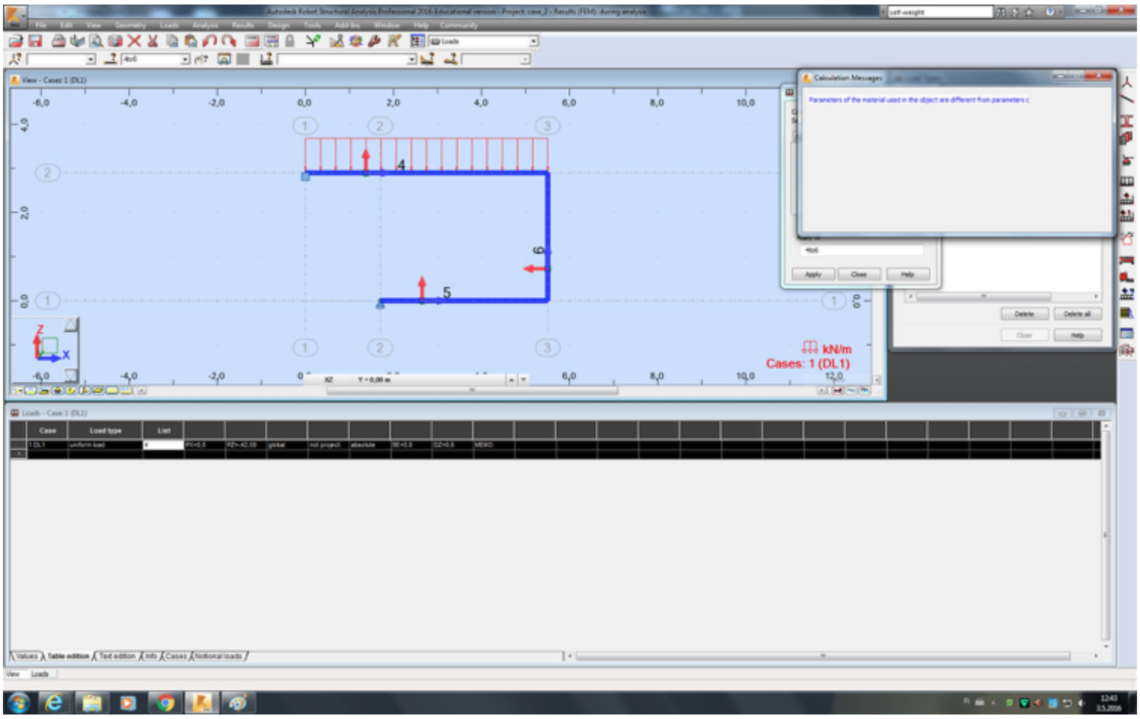


Figure 58. Case 2, Autodesk Robot: analysis

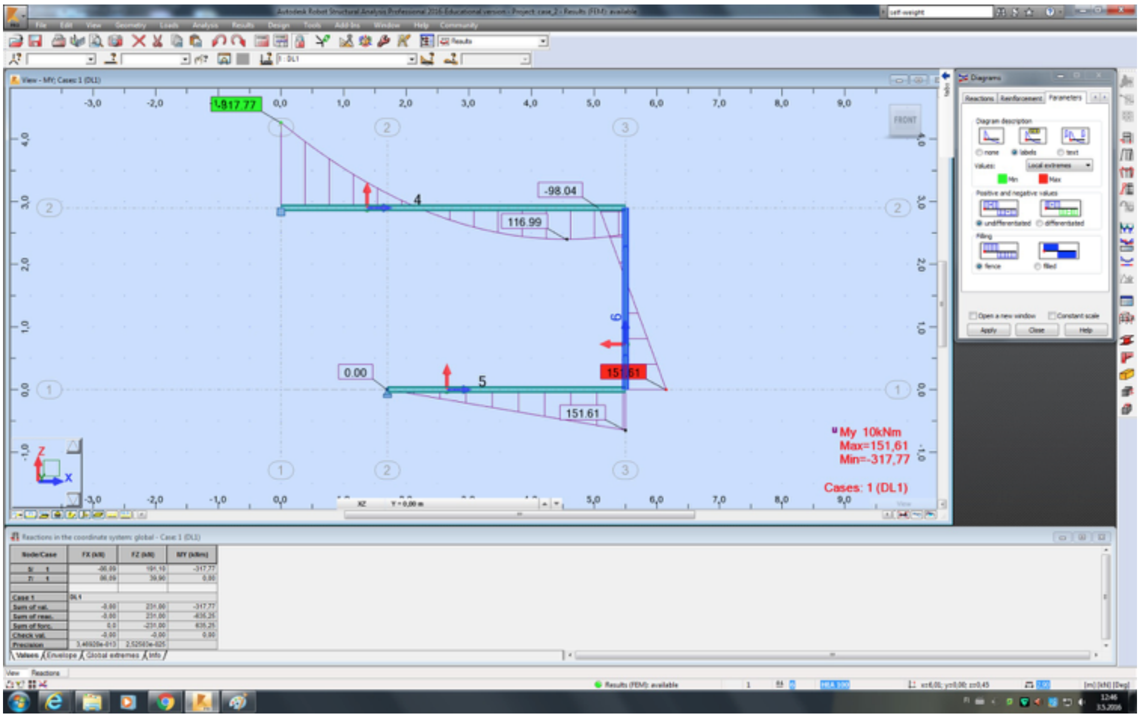


Figure 59. Case 2, Autodesk Robot: moment diagram with table for reactions' magnitudes

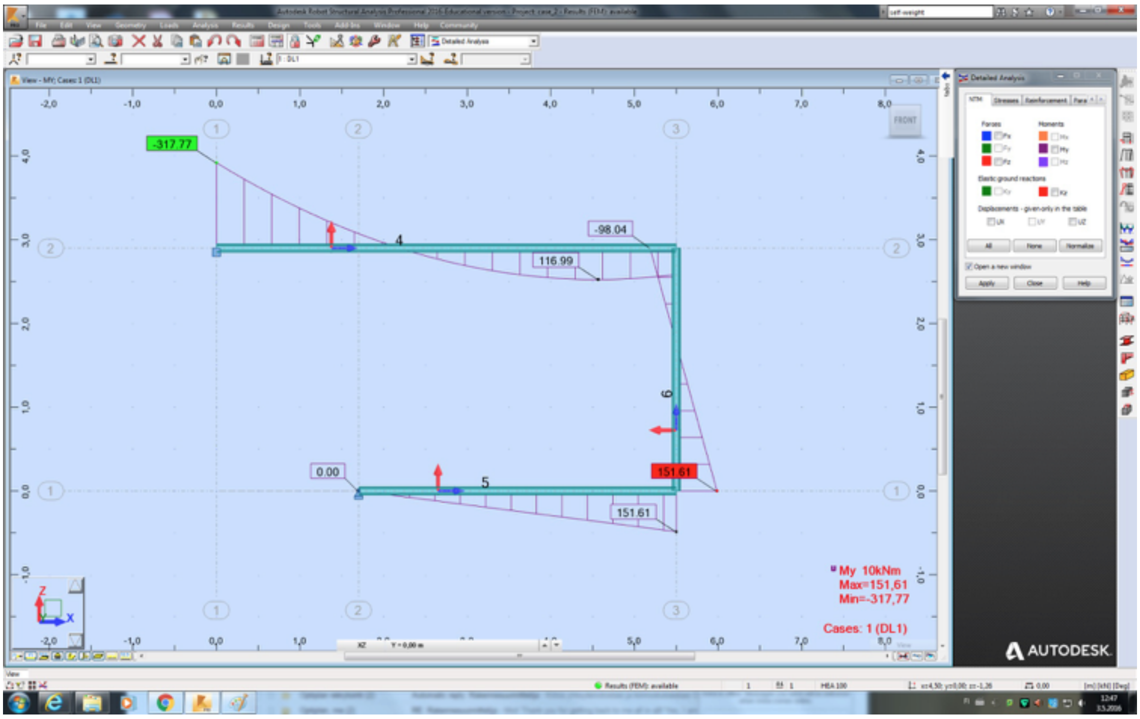


Figure 60. Case 2, Autodesk Robot: final moment diagram

Appendix 6. Case 2: Steel frame design and analysis in Autodesk Robot Structural Analysis

In this Appendix detailed procedure of model integration between Autodesk Robot and Revitf or the 2nd case study is presented.

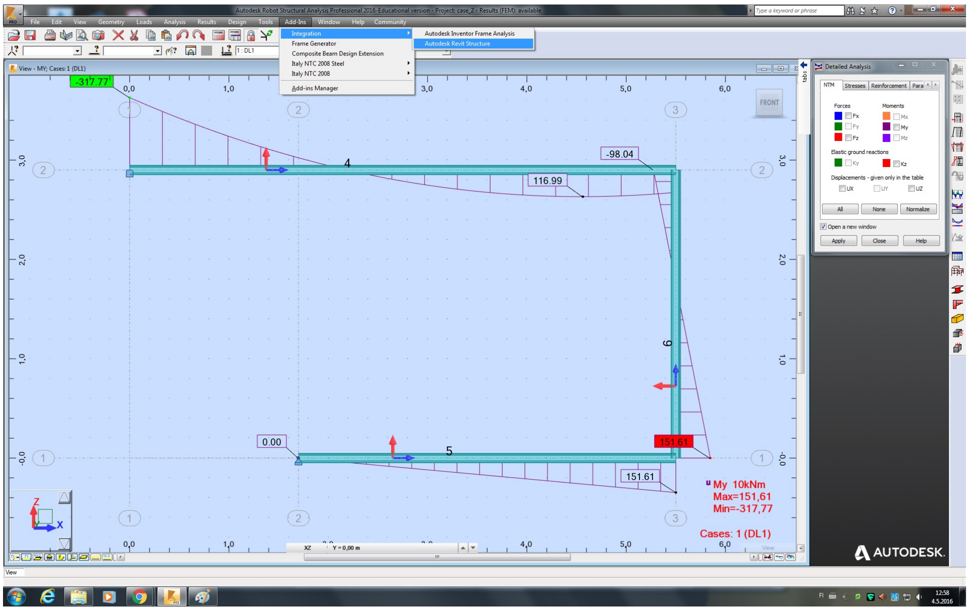


Figure 61. Case 2, Autodesk Robot: establishing the link with Revit 1

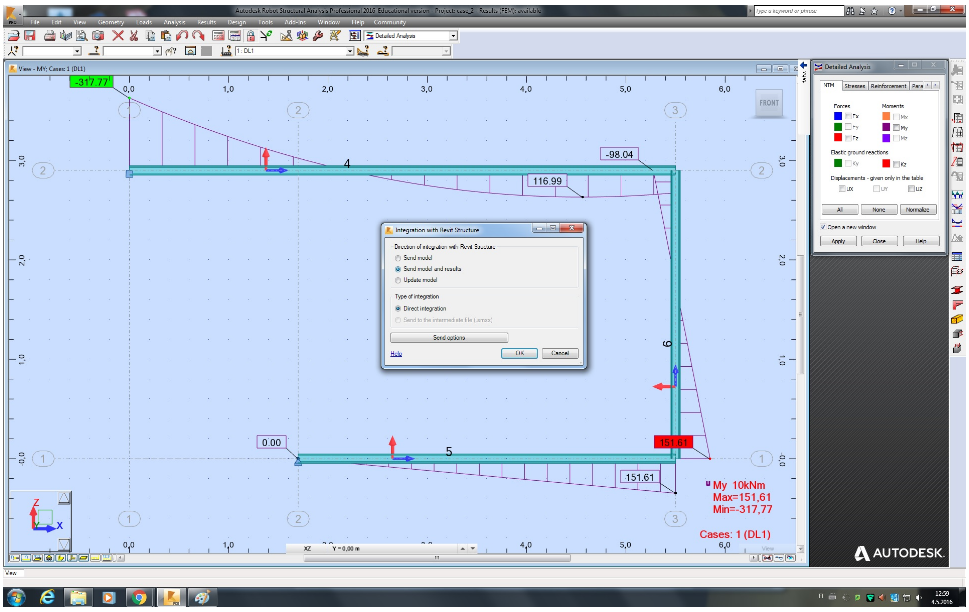


Figure 62. Case 1, Autodesk Robot: establishing the link with Revit 2, properties selection

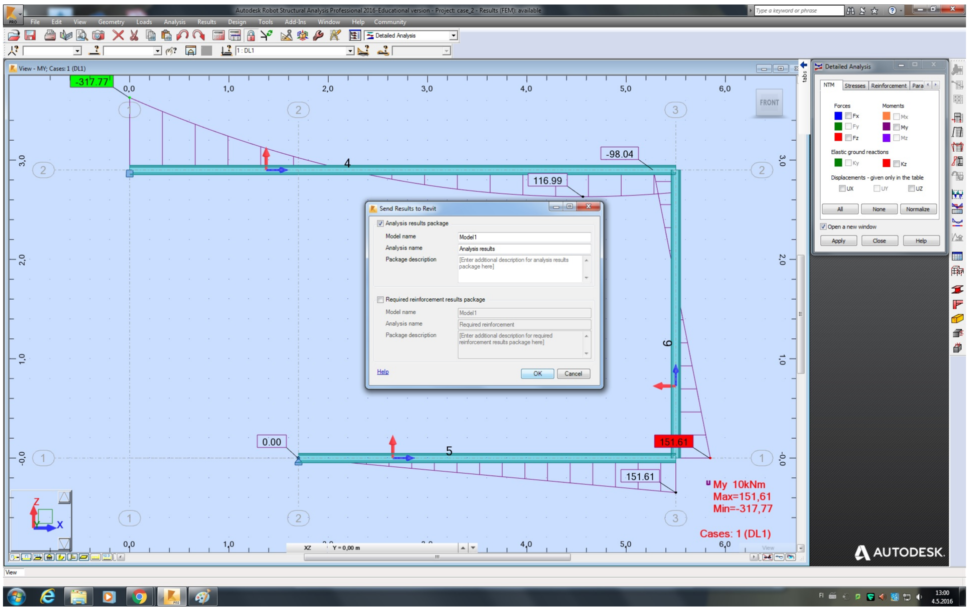


Figure 63. Case 2, Autodesk Robot: establishing the link with Revit 3, properties selection

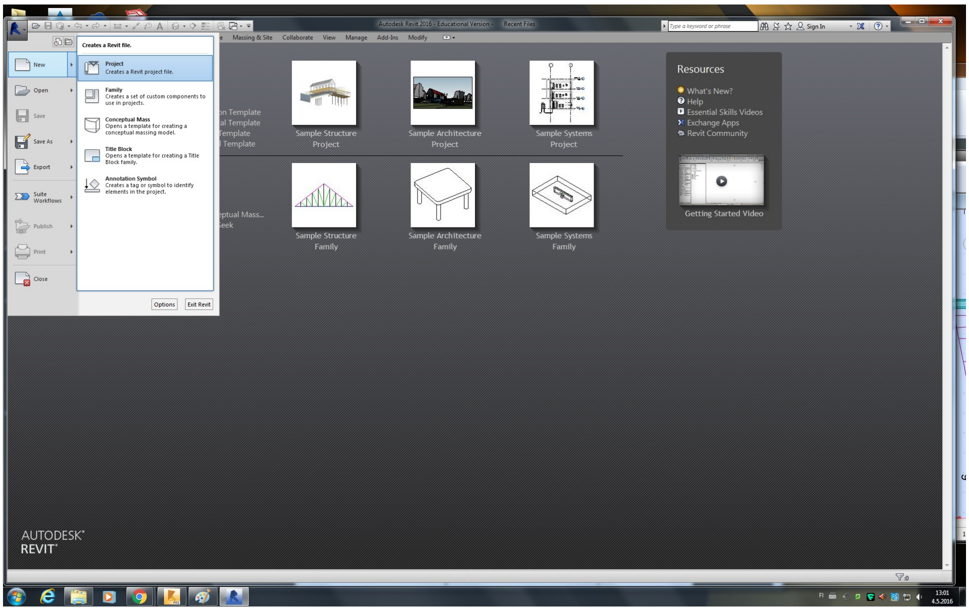


Figure 64. Case 2, Revit: project definition

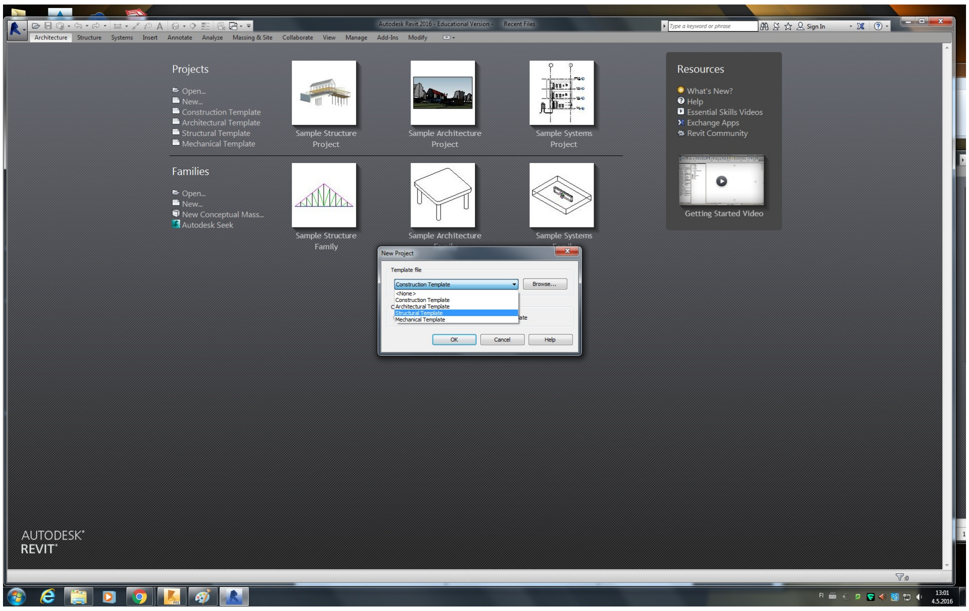


Figure 65. Case 2, Revit: project definition: selection of the environment

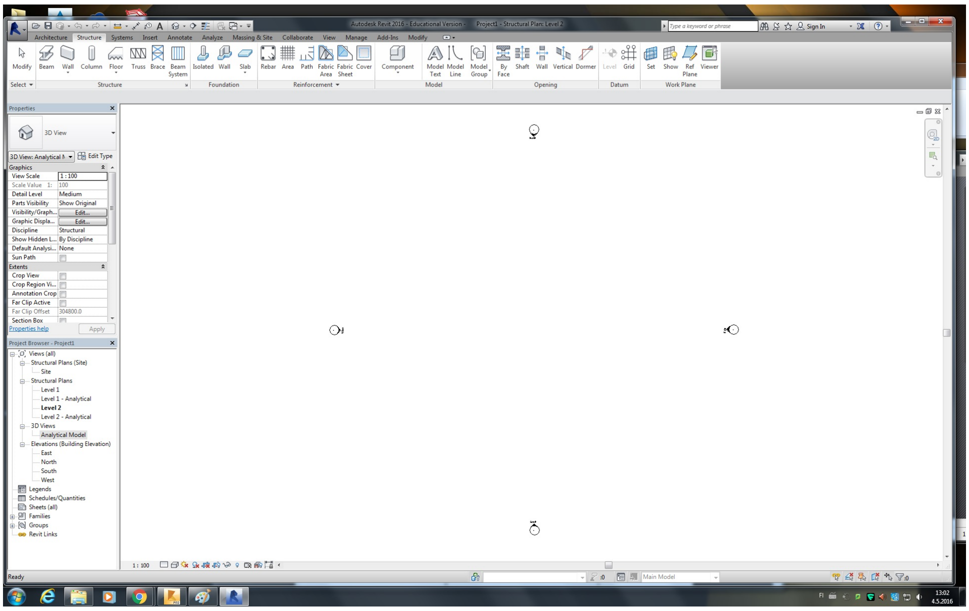


Figure 66. Case 2, Revit: workspace for an imported project

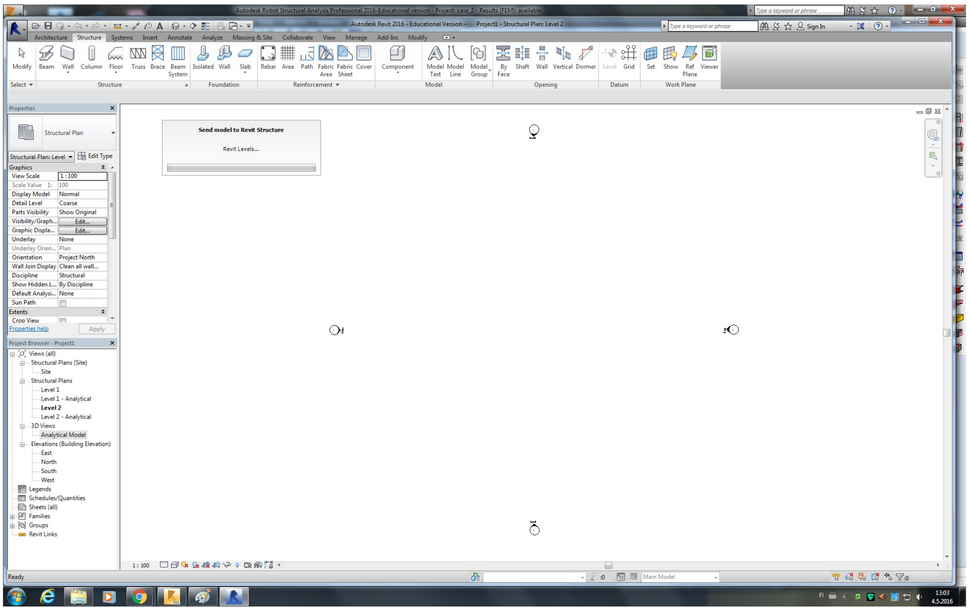


Figure 67. Case 2, Revit: import process of the Robot project

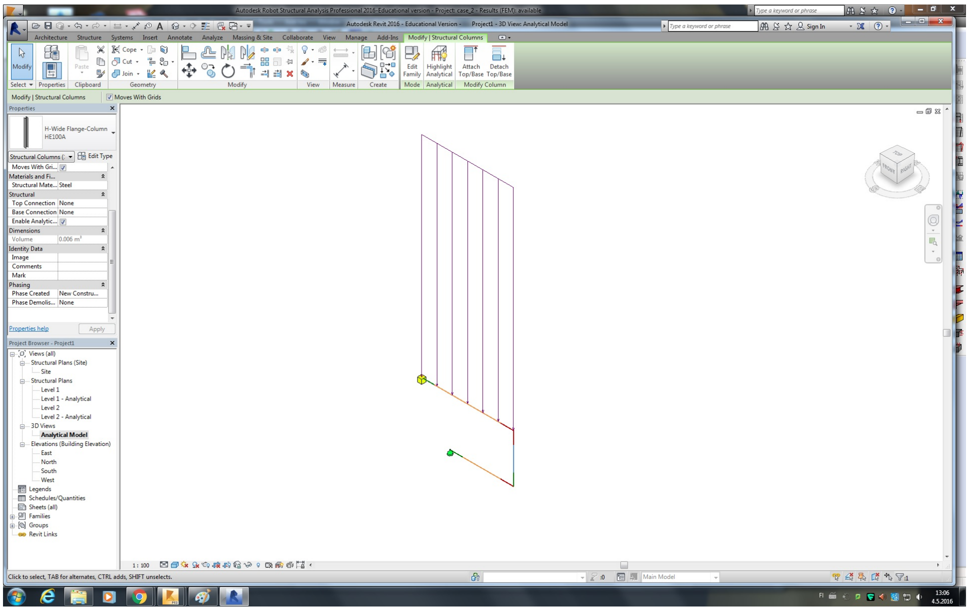


Figure 68. Case 2, Revit: imported Robot model

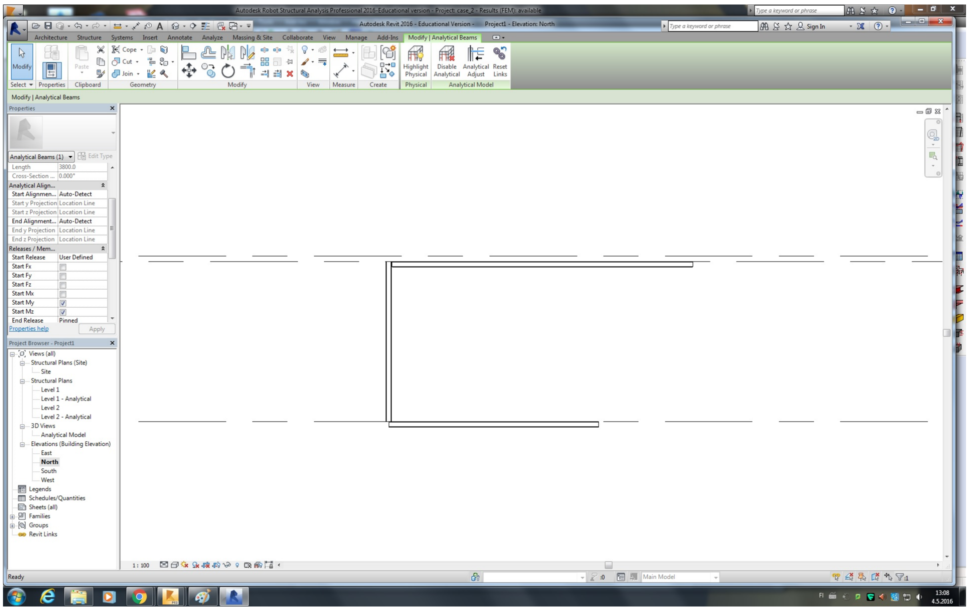


Figure 69. Case 2, Revit: front view of the model

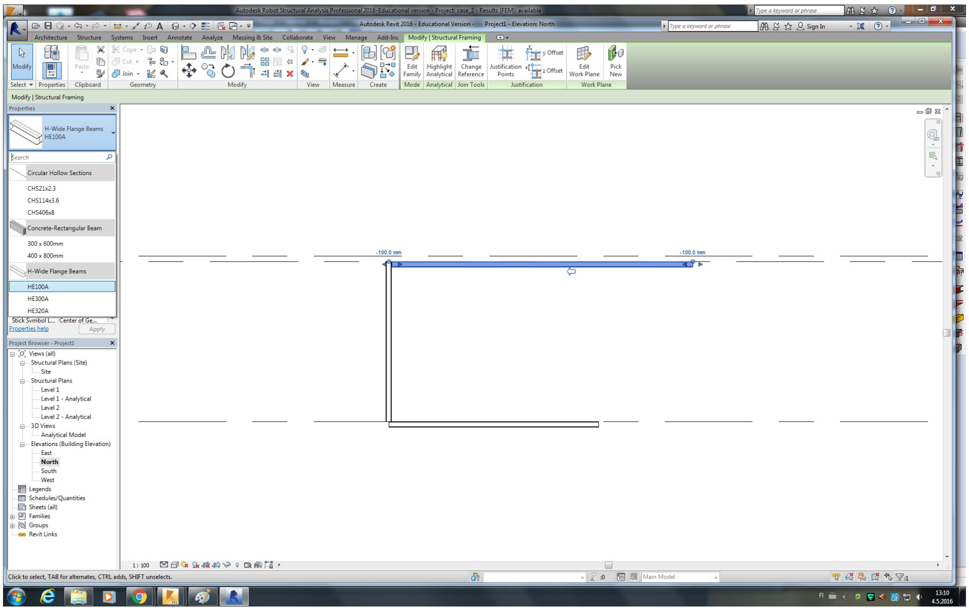


Figure 70. Case 2, Revit: adjustment of a model element 1

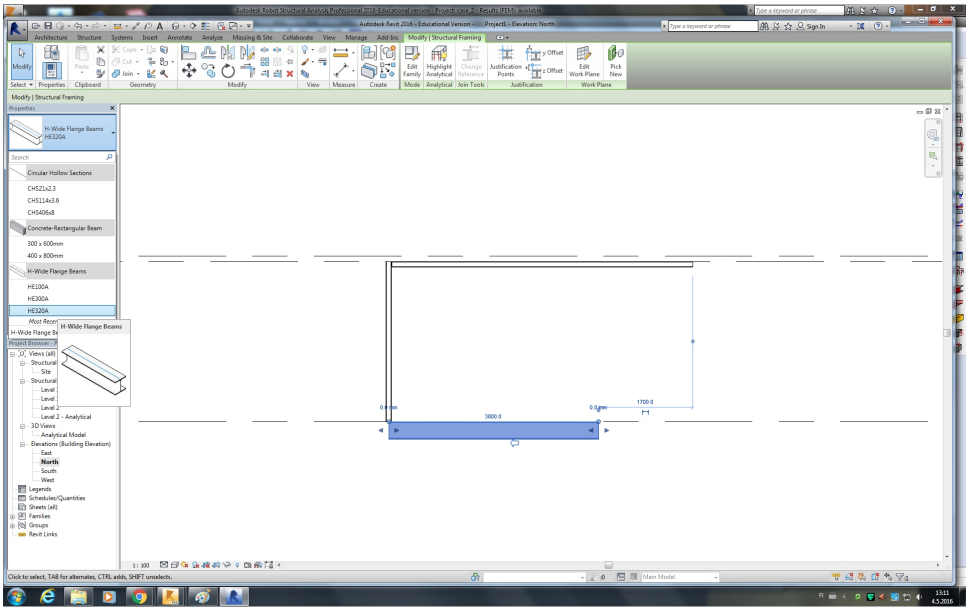


Figure 71. Case 2, Revit: adjustment of a model element 2

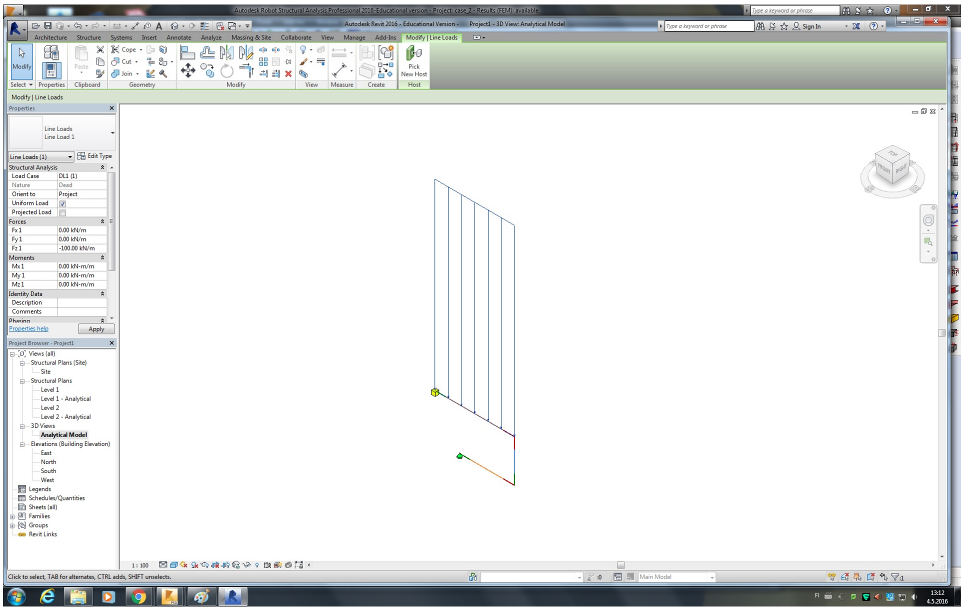


Figure 72. Case 2, Revit: input of new load values

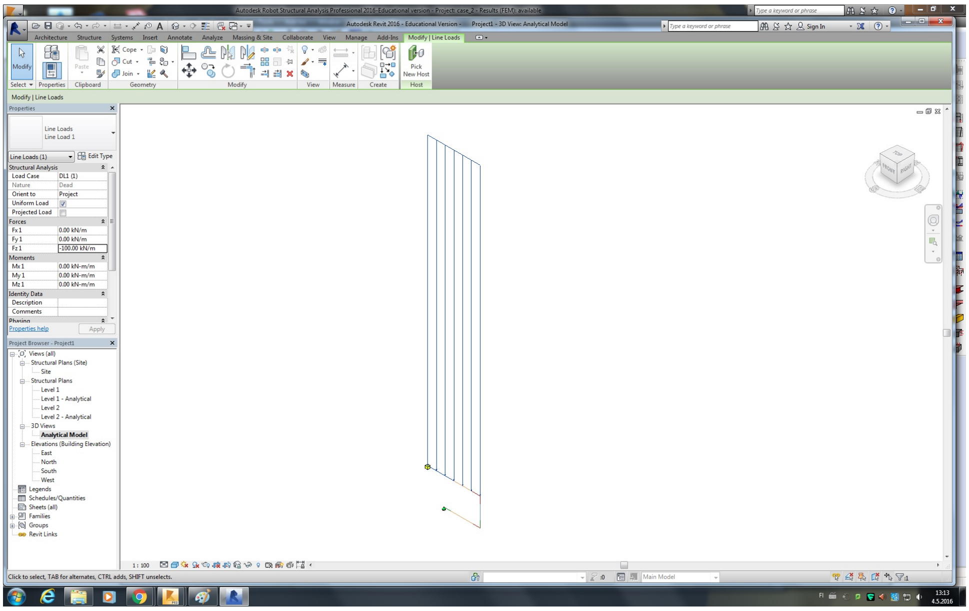


Figure 73. Case 2, Revit: model is updated according to new loads

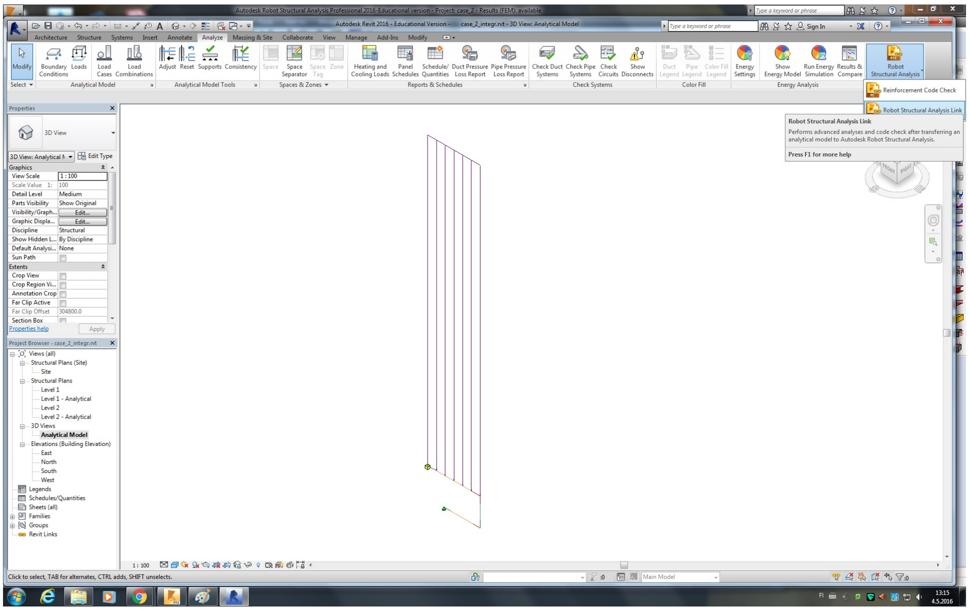


Figure 74. Case 2, Revit: establishing a link with Robot

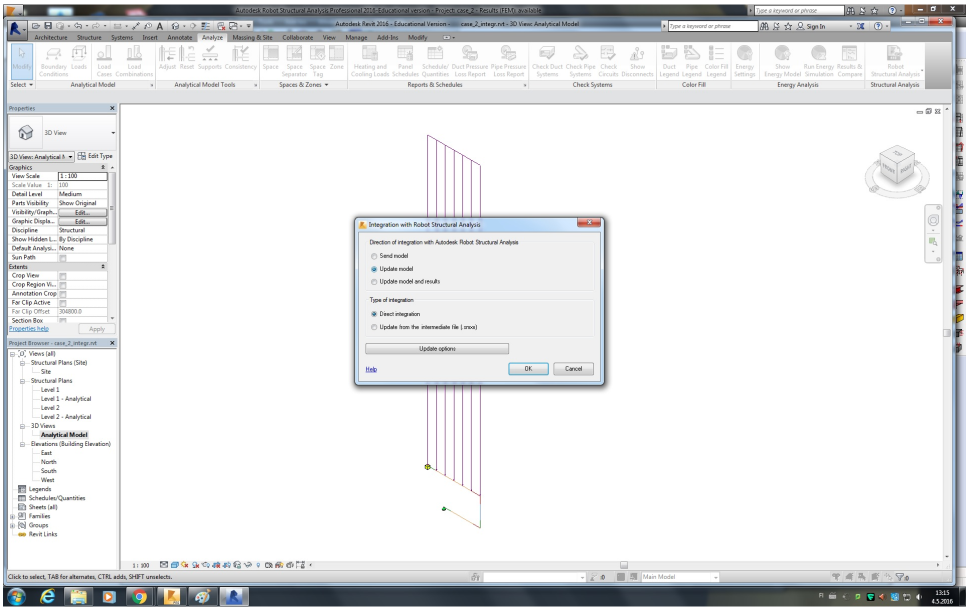


Figure 75. Case 2, Revit: selection of exported properties

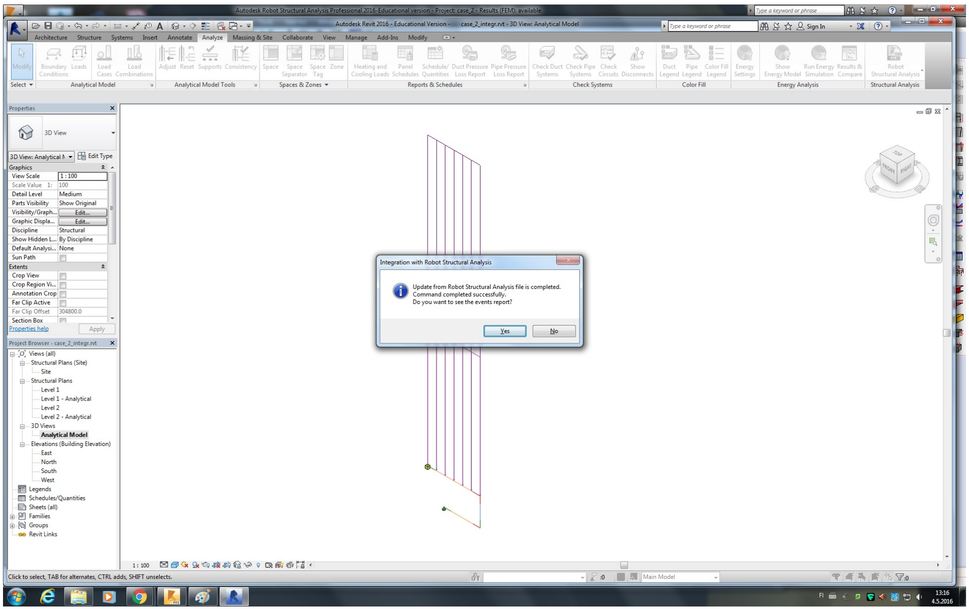


Figure 76. Case 2, Revit: access permission request

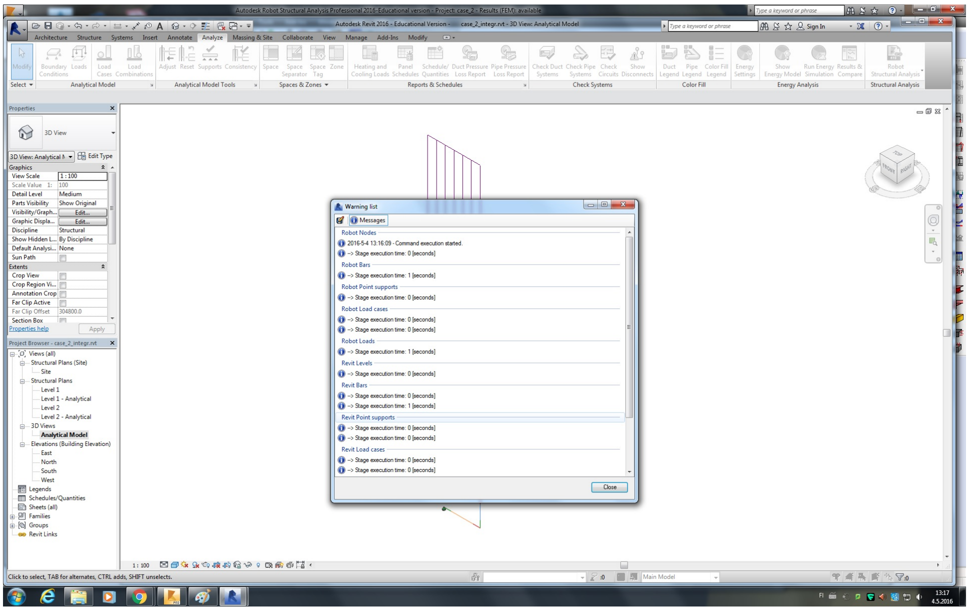


Figure 77. Case 2, Revit: integration procedure

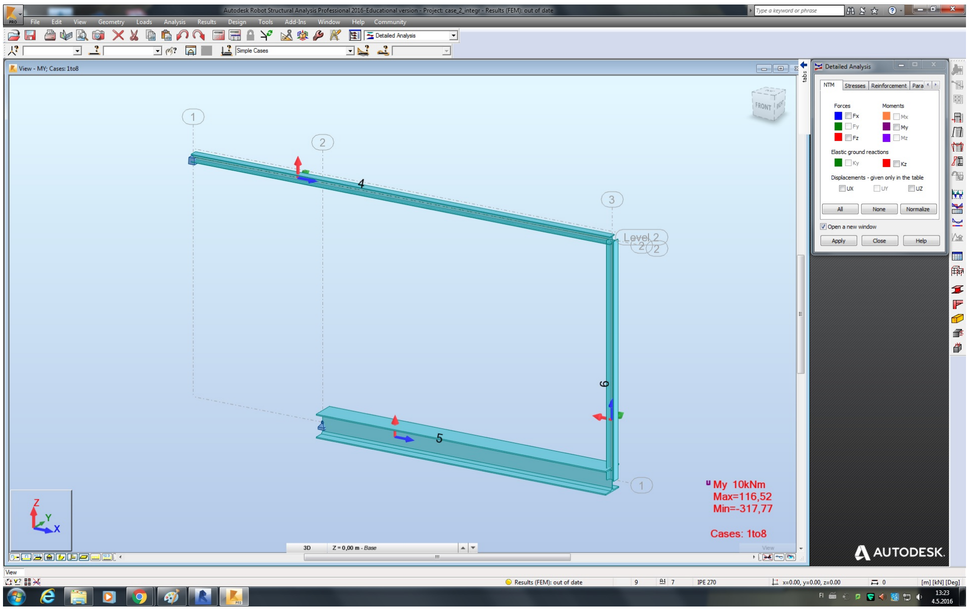


Figure 78. Case 2, Robot: updated model

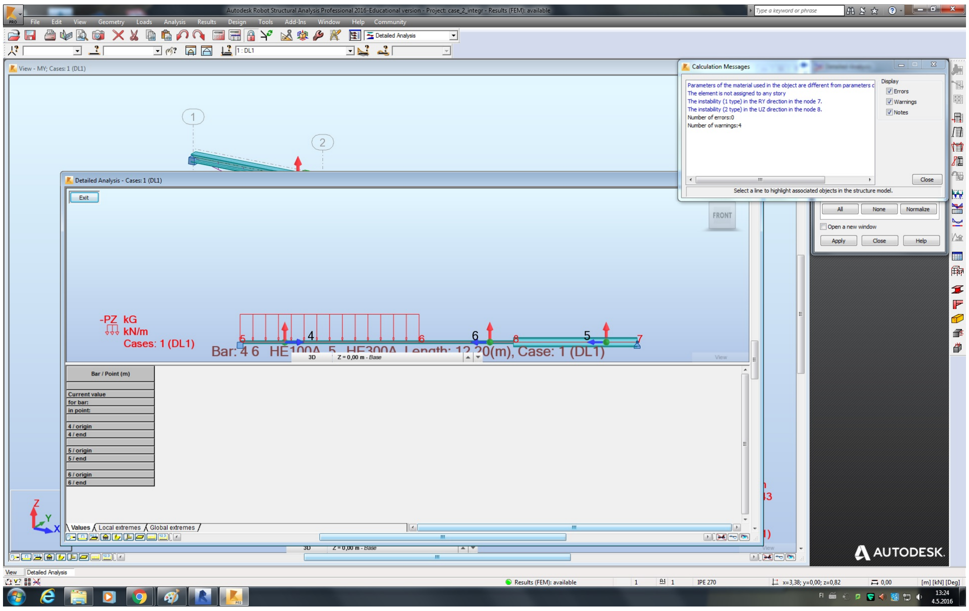


Figure 79. Case 2, Robot: analysis of the updated model

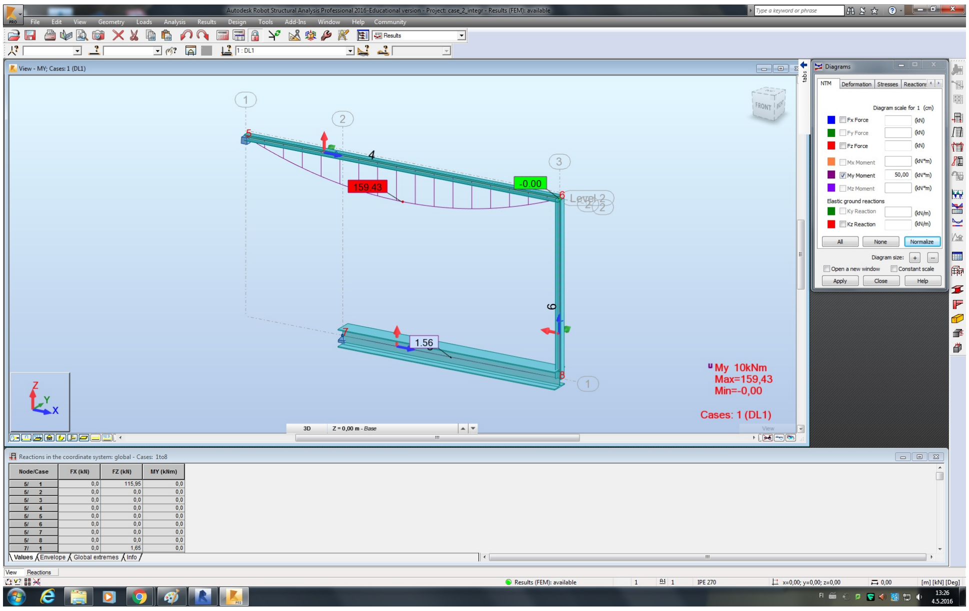


Figure 80. Case 2, analysis results for the updated model