POLITECNICO DI TORINO

Master’s Degree in Civil Engineering

Master’s Degree Thesis

InfraBIM methodology and interoperability for structural analysis

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July 2019

Abstract

The BIM methodology is not too developed in structural analysis sector. The aim of this thesis is trying to define a methodology of work for structural analysis, developing a structural BIM model of an existing infrastructure that will be exported in a structural analysis software.

Interoperability plays a fundamental role in this workflow, two typologies of communication between software will be tested and evaluated, with a particular focus about efficiency in terms of structural analysis.

La metodologia BIM non è troppo sviluppata nel settore dell'analisi strutturale. Lo scopo di questa tesi è provare a definire una metodologia di lavoro per l'analisi strutturale, sviluppando un modello strutturale BIM di un'infrastruttura esistente che sarà esportato in un software per l'analisi strutturale.

L'interoperabilità gioca un ruolo fondamentale in questo flusso di lavoro, du tipologie di comunicazione tra software saranno testate e valutate, con una particolare attenzione volta all'efficienza in termini di analisi strutturale.

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Chapter 1

Introduction

The aim of this thesis is to give an evaluation about possibilities of a structural model, realised according to rules defined by InfraBIM methodology, creating a model with all the useful information related to structural components. Potentialities of interoperability between software for model authoring and structural analysis will be tested.

The InfraBIM methodology is not so evolved, and especially in the structural world could be more developed and exploited. The focus of this work is the modelling of a bridge, realizing a structural model that will be exported in a second moment and evaluated for the next structural analysis. Interoperability represents an opportunity for civil engineers, it is possible to solve problems reducing timings and costs.

The bridge used as case study of the present work is an overpass situated over *Autostrada delle Langhe, A33*, an Italian motorway which should connect Asti to Cuneo. It is a steel composite girders bridge with an overall length of 80 m. It consists of a transversal bracing system and of an inferior bracing plan.

The initial documentation was furnished by *Cordioli & C.* (S.P.A.); these documents are the steel workshop drawings of overall elements that compose the bridge (beams, bracing systems, joints, bolts, plates). Starting from the analysis of this documentation, using the structural BIM software *Tekla Structures 2018*, it has been possible to realize a BIM model based on the constructive drawings containing all the needed information to perform a structural study. Encountered difficulties and possibilities that this software offers will be shown and evaluated, explaining which points can enhance the structural design process.

The main subject of this work is interoperability between software for model authoring and programs for structural analysis. The first point of this passage is the choice of right programs to satisfy the workflow applied to this methodology. There are some aspects that are too important such the exchange of information and the loss of data: a bad transfer of data can bring to vanish the methodology and its workflow.

Two different paths have been tested. The first one is testing interoperability with the open source file format, Industry Foundation Classes (IFC), between *Tekla Structures 2018* and one of the most used software for structural analysis and design, *SAP2000 v20*;

an IFC model contains geometry and data associated to elements inserted in the model, it is the most used file format and its same essence is associated to interoperability.

The second one is a test made with a direct link between *Tekla Structures 2018* and *Midas Civil 2019*. It consists of a plugin furnished by software-houses with the aim of reaching a good exchange of data without involving loss of some information. The study conducted about this theme is focused on some modelling aspects which are necessary to perform a good level of structural analysis. Evaluation of elements geometry, rigid links between parts and possible advices to solve inconveniences are all aspects that will be studied and developed in this thesis.

Before starting the analysis, some adjustments and checks were made to overcome problems linked with the interoperability typology used and avoid errors in the calculation of stresses.

After that this global analysis was concluded, the aim was to bring this work to a more specific level of structural analysis, studying stresses that loads can cause in a bridge union. To realize and study interoperability problems related to this typology of analysis, first, it was necessary to increase the structural model Level Of Detail (LOD) up to 400: once reached this level and studied some criticisms, the exportation was made and the joint stresses calculated with some approximations, which will be shown, in the software for local structural analysis, *Idea StatiCa*.

Finally, advantages and criticisms to this methodology and which solutions could be a starting point for next interoperability studies will be illustrated.

Chapter 2

InfraBIM Methodology for Structural Analysis

2.1 State of Art

Building Information Modelling (BIM) is a methodology based on a digital model containing many information about the different life phases of a building. The model is a digital representation of physical and functional characteristics of the building. [2]

BIM is a methodology based on collaboration between the different professional figures involved in the life cycle of a building. This point is a very important aspect, because the first aim of this system is the creation of a model, which have to contain information: data have to be shared between all the participants to the building process, at different times and for different purposes, to ensure a good quality and efficiency. [S2]

BIM born with the aim of finding a solution to problems of the architecture sector. Its development, that is part of a most complex phenomenon, named digital revolution, has allowed to find solutions more and more advanced that today can already be used in a professional way. If this is valid for the architecture sector, the BIM introduction in civil engineering delays to find its definition.

Nowadays, the BIM methodology interests more sectors and not only the one linked to the architecture world. In these years, new solutions have been proposed about other problems, such as ones related to the structural world.

Today, one of the most important quality of BIM is offering communication possibilities to all the figures which cooperate in the building/infrastructure design phases, making possible to reduce time and save money. It represents an answer to the AEC (Architecture, Engineering and Construction) crisis, giving a possibility of relaunch to the construction world.

BIM methodology coincide, for the construction world, the digital revolution. Its birth is an air of renovation, more than the one has brought CAD to this sector. Before of the BIM introduction, CAD (Computer Aided Drawings) represented a revolution, but, speechless, it has only allowed to transfer all the drawings which once were manually

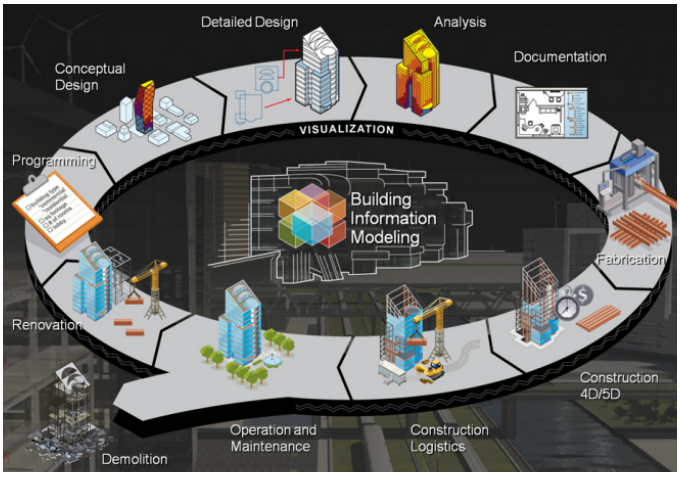


Figure 2.1: Building Information Modelling sectors
Source: http://www.diva-portal.se/smash

made. The problem of CAD is that did not introduce a revolution in the system, it has not affected the traditional methodology of working holding workflows on a same level. Graphical elements introduced in a CAD drawing do not have attached information, a line is just a line and nothing else.

Using BIM methodology, to the simple physical representation of elements many information are added and saved; thanks to these data, users are able to define many typologies of objects, such as beams, columns, plates, footings, walls, doors and many other elements that it is also possible to add to software libraries (user-defined elements). Moreover, it is possible to extract from a BIM model, automatically, just knowing some processes, sections, prospects and drawings, without any necessities of remaking the work another time. Repetitions associated to the traditional way of working have been limited and timings, that once requested a great amount of time, can be avoided. Project data are reused many times thanks to communication possibilities of software, interoperability has increased the entire efficiency of the design process.

This opportunity represents a system to avoid wastes of time, especially when a project involves different professional figures that have to cooperate each other. A lack of communication between people that work on a same project can represent a dangerous for the economy, especially when works interest the infrastructure world, where costs are higher and related to the infrastructures complexity.

Another advantage that BIM models have brought is that they can contain, internally, all the requested data for different design phases; for instance a structural model can contain all the information to extract an analytical one with all the needed data to perform an analysis and studying the resistance of elements to stresses. This possibility of connecting different models allows to execute and manage incongruence that can surge when on a same project many professional figures work, especially when they come from different sectors. All these errors are immediately underlined, avoiding that they can determinate an increase in time and costs of the entire project.

A BIM model is continually and automatically updated, if an important change has been taken, it does not have an excessive impact on costs. Being continuously updated, the methodology gives possibilities to notice errors immediately, avoiding their propagation, synonymous of costs and timings increments. Many mistakes that today can be completely erased by the BIM methodology, once cost money and compromise the work completion.

One of the most important aspects that characterizes BIM is interoperability. Interoperability is an essential feature because the methodology is based on the data sharing between the different professional figures involved in a construction process. Its meaning refers to the ability to communicate between different people, and more technically, between different typologies of software. [S2]

For instance, if this concept is correctly applied, it is possible to extract information from a model and, in a second moment, reuse these information to solve other engineering problems increasing the construction process efficiency.

This data exchange can be realized using different communication methods. The most common type of data exchange is the one realized using the Industry Foundation Classes (IFC) file format.

BuildingSMART, that is the International Alliance for Interoperability (IAI), gives a standard technical description to this file format:

"*In general, IFC, or "Industry Foundation Classes", is a standardized, digital description of the built environment, including buildings and civil infrastructure. It is an open, international standard (ISO 16739-1:2018 [9]), meant to be vendor-neutral, or agnostic, and usable across a wide range of hardware devices, software platforms, and interfaces for many different use cases. The IFC schema specification is the primary technical deliverable of buildingSMART International to fulfill its goal to promote openBIM®.*" [S2]

IFC is a very complete open source digital file, it contains many information that can be reused to solve different aims. This characteristic makes the IFC much more complex and moreover, not always the information contained in it can be used effectively to solve problems related to different sectors involved in the design process.

The aim of BIM interoperability would be, once that the model exported has been update in another software, reintegrating new data in the starting model; this final point presents often issues and troubles, because data is often altered irremediably.

Nowadays, many ways of communication exist but it is not possible to define which one is better, every one will be more accurate to solve some problems than other ones. Software-houses are introducing direct links to connect software used for different aims; they consist of a plugin, that, once installed, allows an internal communication between programs, avoiding that the exportation involves a data loss.

The only way that exists to evaluate this exchange is making interoperability tests, studying criticisms that exist for different typologies of communication and understanding which are programs possibilities to perform a practical resolution of problems related to different engineering sectors.

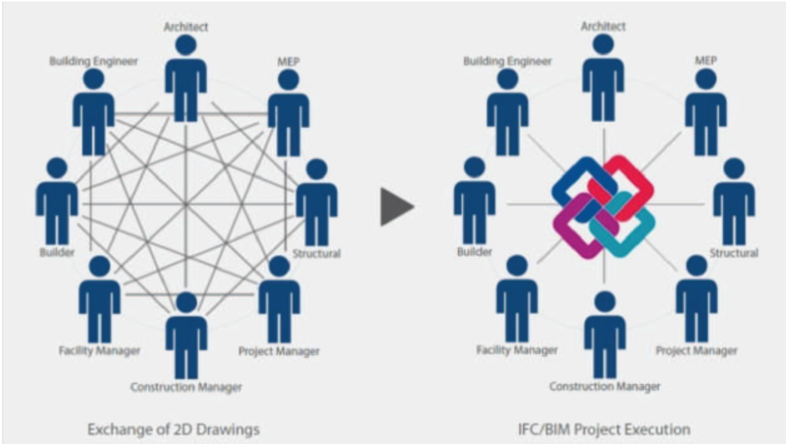


Figure 2.2: Exchange of 2D drawings vs IFC/BIM Project Execution
Source: https://www.wincasa.ch

A good structural mode, if exported in a good way, can become an analytical model, perfect to perform an analysis. Querying a structural model it is possible to obtain a lot of information: schematizing it in linear elements (beams and columns) it is possible to configure a model where continuity between elements is guaranteed by the existence of nodes, points where many beams or columns flow into. [S8]

Today, it is not possible to say which is the best way to follow in civil engineering to solve exigences for structural modelling and structural analysis. It is fundamental to work and test interoperability in order to define standardized processes, needed for the definition of an efficient methodology.

2.2 InfraBIM

Although BIM methodology was born with the aim to find solutions to building engineering problems, today, seen all the advantages that this method brings, it is taking consistence also in the infrastructure construction world. Most BIM users reported very positive feedbacks from their experience of it, and a great part of this percentage has said that they have not assimilated even half of the possibilities that they believe BIM can provide. Nevertheless, this delay in the civil world has determined yet an insufficient usage of the methodology. [S9] [S13]

InfraBIM literally refers to the informative system of digital management for infrastructure constructions. In this sector, the application of a methodology is clearly more complex, there are more aspects that are important to consider in engineering terms and they not always can be easily represented with current software. [S9]

In particular, when an important infrastructure is studied, such as a bridge, it is necessary that all the phases of design will be studied and restudied to obtain a result that is able to resist in safety for years. The structural analysis for infrastructure is not so developed by using the BIM methodology, but in the next years a revolution will change the overall approach to work.

The infraBIM sector is destined to change immediately its approach to work because the first works for which the BIM design process will become obligatory are infrastructures: they have the most important impact on economy. Moreover, when it is necessary to realize important infrastructures, such as bridges, they can affect directly human beings; BIM allows a perfect optimization of the entire work, guaranteeing a better efficiency assisted by the best management of timings.

The possibility of extracting information from a single model will allow to avoid repetitions and errors (linked to the different design phases involved in a construction process) and, at the same time, the definition of a prototype (that in BIM dictionary coincide with the model) can improve the AEC productivity.

Although the structural analysis is still far away to find its position in this process, the possibilities that this new methodology provide are incredible and will allow to facilitate, speed up and make more productive the entire workflow. Software for structural analysis works simply basing their study on analytical models. If users were able to extract perfectly this type of model, they were be able to perform a simple structural analysis with an incredible time/cost efficiency.

Benefits for infrastructures are many, the problem now consists to define efficient workflows adapted to the work typology exigences.

2.3 Legislation & BIM

Italian legislation, with the BIM growing, is starting to control and regulate the digital and informative process, such a way to avoid incongruity and inconsistency which can affect the methodology.

One is about timings and introduction of BIM in the current economy, the other one contains some technical definitions about projects.

2.3.1 BIM decree, Ministerial Decree DM560/2017

The Ministerial Decree 560:2017 (*DM560/2017*) [4] [S3], fulfilment of the article 23, clause 13, of the Legislative Decree 50 on date 18/04/2017 (*DL50*) [3], establishes modalities and timings for a progressive introduction of methods and electronic tools of modelling for buildings and infrastructures. First, this decree fixed the date of BIM implementation: the duty to use methods and electronic tools of modelling from the last past January 1st, 2019 for works with a value equal or more than 100 millions of euro, and then, for minor values becoming effective from years next at 2019 until to works of values minor than 1 millions of euro, for which the term becomes valid from January 1st, 2025.

This represents an important aspect to consider: this new methodology will be introduced first for all these works that have an important impact on economy. Infrastructures world is adopting right now this methodology, because of this reason it is important understanding how this new approach works. InfraBIM methodology has to improve itself, in a way to reach a widespread diffusion of BIM on large-scale.

The timings for BIM introduction in Italy, defined by *DM560/2017* [4] are here summarized, showing how the BIM revolution has to happen in this present:

- complex works related to construction projects with a basic tender price equal or higher than 100 millions of euro, starting from January 1st, 2019;
- complex works related to construction projects with a basic tender price equal or higher than 50 millions of euro, being active from January 1st, 2020;
- complex works related to construction projects with a basic tender price equal or higher than 15 millions of euro, being active from January 1st, 2021;
- construction projects with a basic tender price equal or higher than the threshold belonging to *Art. 35 del Codice dei contratti pubblici*, being active from January 1st, 2022;
- complex works related to construction projects with a basic tender price equal or higher than 1 million of euro, being active from January 1st, 2023;
- complex works related to construction projects with a basic tender price lower than 1 million of euro, being active from January 1st, 2025.

Contracting authorities will have to adopt a training plan for their staffs, an acquisition and maintenance plan of hardware and management software allowing to exploit immediately the possibilities offered by the InfraBIM methodology. Clearly, adoption of this new technology, firstly, will not be easy for a series of reasons that pass through workers inexperience and hostility that come from a traditional run-in approach based on a wasteful workflow source of errors, repetitions and incongruence.

2.3.2 UNI11337:2017

The technical legislation for the project supply chain is the UNI 11337/2017 [14] [S5], its public includes the building/infrastructure world and the redevelopment of environment for the built heritage.

It is articulated in 10 different parts:

- Part 1: models, information and data objects for processes/products. This part is about the definition of general terminology, the differences that exist between models and the digital information objects.

- Part 2: naming and classification of models, products. Although this part could be seem not so important it is the basis for good transmission of data of the entire project.
- Part 3: models for organization and storage of technical information for construction products.
- Part 4: evolution and informative development of design, objects that compose digital models.
- Part 5: this one is about coordination and acceptance workflow to guarantee the digital construction process.
- Part 6: this is a definition of technical digital specifics structured by the part 5.
- Part 7: knowledge requirements, skills and competences of professional figures involved in the digital management of information processes.
- Part 8: it is about the relationship that exists between the Infrastructure/Building Information Modelling and the Project Management.
- Part 9: it is about the quality of works both in their construction phase that during their entire life of use.
- Part 10: it is about the information management of administrative procedures.

2.4 Level of Detail

Resistances to an adoption of the BIM methodology on large scale are not only related to the traditional approach attachment and to the difficulties encountered about the usage of new technologies, but even to a lack of communication languages ans so, of interoperability.

It is important to define different levels of detail/maturity, to give a better idea about the quality of exchanged data. The level of detail of a digital model grows with the project development, it becomes always more accurate in process final phases. Some aspects can be modelled and developed with different speeds, the objects evolution depends on necessity of the construction project.

Model levels of details are generally defined for the key phases of the project, such that the quality of information will be able to satisfy the project exigences.

The Level Of Detail (LOD) it has been defined in this way by the American Institute for Interoperability (AIA) in the Contract Document G202:2013 [1] and it describes LOD in the following way:

"Level of Detail is essentially how much detail is included in the model element. Level of Development is the degree to which the element's geometry and attached information has been thought through - the degree to which project team members may rely on the information when using the model. In essence, Level of Detail can be thought as an input to the element, while Level of Development is a reliable output."[1]

This definition represents the basis on which AIA has articulated the various levels, from a minimum value of 100 to a maximum of 500 (LOD100 - LOD500). The quality and the quantity of attached information increase gradually that the level passes from 100 to 500, with all the intermediate steps.

The choice to use the AIA classification [1] as reference was due by the adoption of Tekla Structures as software for the model authoring. Tekla Structures warehouse classifies in this way the attached data quality: to avoid incomprehensions about this theme, during this work the AIA definition has been adopted, instead of the one defined by the UNI11337:2017[14].

To give a better idea about LOD, it is here reported a table, containing the correlation between LOD ant various phases which compose an infrastructure design process.

LOD	**Project phases**
0	Feasability study
100	Preliminary project
200-300	Definitive project
400	Executive project
500-600	Constuctive workshop

Table 2.1: Relationship between LOD and project phases

Chapter 3

Case study: structural model and modelling

3.1 InfraBIM methodology applied to the case study

The case study of this master's degree thesis is an overpass situated over "Autostrada delle Langhe, A33" near Cuneo. The infrastructure is a composite steel girder bridge with an overall length of 80 m; accurately, it is situated in the sector located between Isola d'Asti and Rocca Schiavino.

The aim of this thesis is interoperability between software for model authoring and programs for structural analysis trying to find and understand which tools can solve practical problems and find a solution to new technologies criticisms. First, it has been necessary to create a BIM model containing information and data individuated in the starting documentation furnished by the company *Cordioli&C.* which has dealt with the bridge design.

This documentation consists of carpentry tables containing all the information related to steel elements: beams and bracing systems, connections with their plates and bolts. Data is necessary for the model realization, but, before starting the modelling of the infrastructure, it was useful studying which are main parts and which are needed for an analytical representation.

After this first infrastructure study from the structural point of view, the first passage of the workflow was the structural elements insertion, exploiting possibilities of *Tekla Structures 2018* about structural modelling.

Once reached a first level of modelling, the study about interoperability was conducted, two different paths were tested. First, a data exchange made with the IFC file format was tested, studying criticisms and possibilities of this data transfer.

Therefore, the study was conducted following another communication language, exploiting an information exchange method made by the usage of a direct link, that is a plug-in provided by software-houses to perform interoperability.

In each case, presented studies have provided some workflow results in this shape:

the best solution to model and realize a structural model ready to be exported and the operations on FEM analysis software, which are requested to reach, at least, a first level of structural analysis.

In both cases, self-weight stresses of the infrastructure were evaluated, but, once that the better path was individuated in data exchange made by the usage of a direct link, the study was addressed on this direction.

Software-houses defined plugin were used to perform more interesting studies about this infrastructure, exploiting possibilities of structural analysis software (ULS combination of loads).

Once developed some modelling skills in Tekla Structures, the model LOD was increased up to LOD400. In this way, it was possible, using another structural analysis software and a new direct link, that allowed interoperability once again, to perform a simple approximate local structural analysis.

Interoperability results will be shown as conclusion of the entire work, giving solutions with a critical eye to the encountered difficulties.

As resume to the workflow, in the flowchart displayed in figure 3.1, main necessary passages to reach all the obtained results have been schematized.

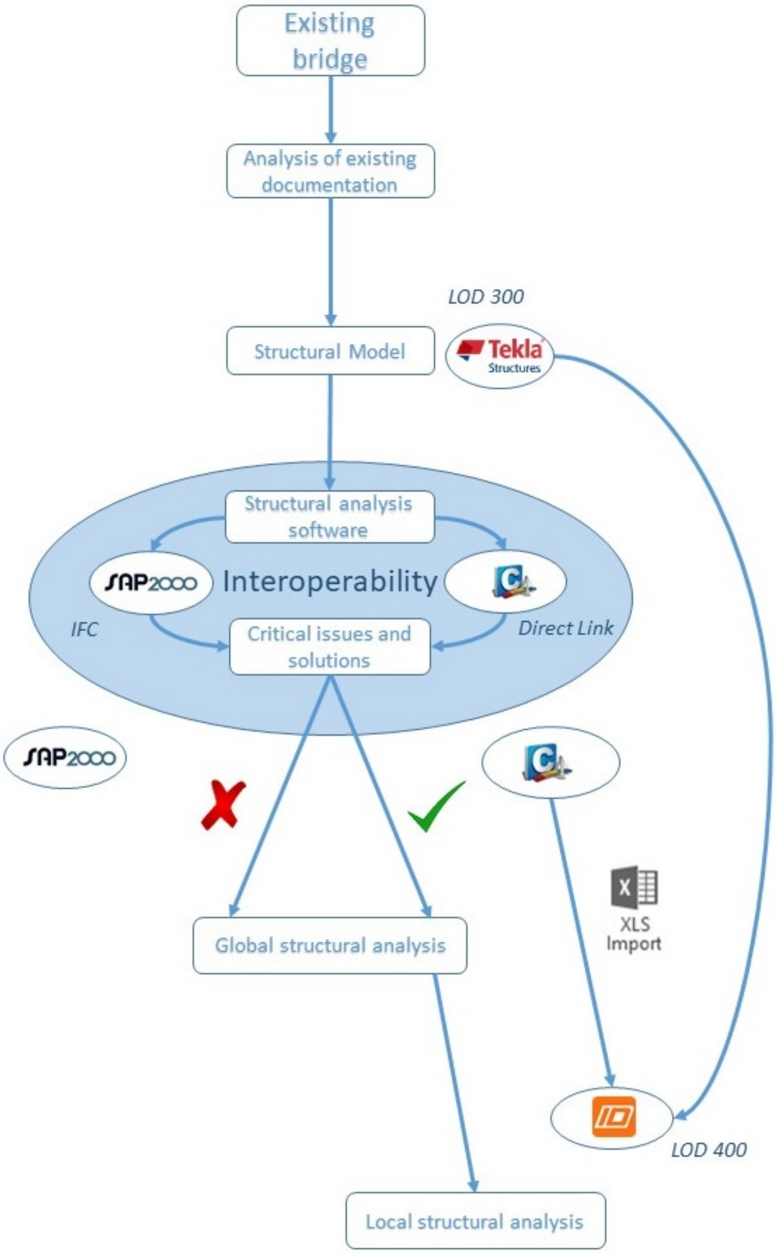


Figure 3.1: InfraBIM methodology for structural analysis

3.2 General overview

The case study of the thesis, as it was anticipated, is an overpass over *Autostrada delle Langhe* (A33) or *Autostrada Asti-Cuneo* (Strada Statale SS231), an highway that should connect Cuneo and Asti.

Figure 3.2: Location of the bridge, territorial view
Source: https://www.google.it/maps

This last one, consists of overpasses, bridges and tunnels for a total length that overcomes 20 km. This arterial road is composed by two regular lanes for every direction, with a total length of 90 km, connected between them by a part of the A6 highway. A33 is part of the European highway E74 and is managed by Autostrada Asti-Cuneo S.p.A. Accurately, this bridge, that is the entire work subject, is situated over the way included between Isola d'Asti and Rocca Schiavino (Lotto 1a).

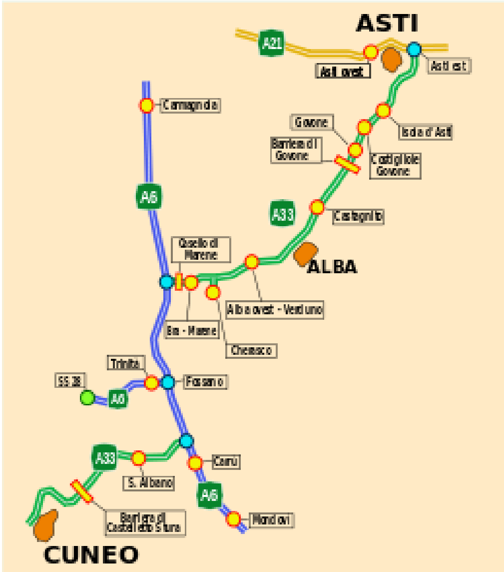


Figure 3.3: Autostrada delle Lange A33 and A6 overview scheme
Source: https://it.wikipedia.org

Under this bridge pass a provincial street, an highway and, moreover, a rail for the passage of a train. An overall of all the infrastructures that interact with the overpass is shown in figure 3.5, a longitudinal section that contain a good level of information about the case study that was investigated. The Google Maps street view (Figure 3.6) from a good perspective allows to reconnect the longitudinal section furnished before to the infrastructure. A starting good comprehension of the work is necessary to avoid errors in the following workflow phases and give lectors a general overview about the infrastructure complex.

Figure 3.4: Bridge framework
Source: https://www.google.it/maps

After a better look to this first simple figure extracted from the documentation and linked with a street view, it is easier to understand the magnitude and dimensions of the bridge. It is supported on three points, two abutments and a pile. This last one divides physically highway and railway from the provincial street. Given an overall about the overpass, in the next section the bridge will be studied from the structural point of view.

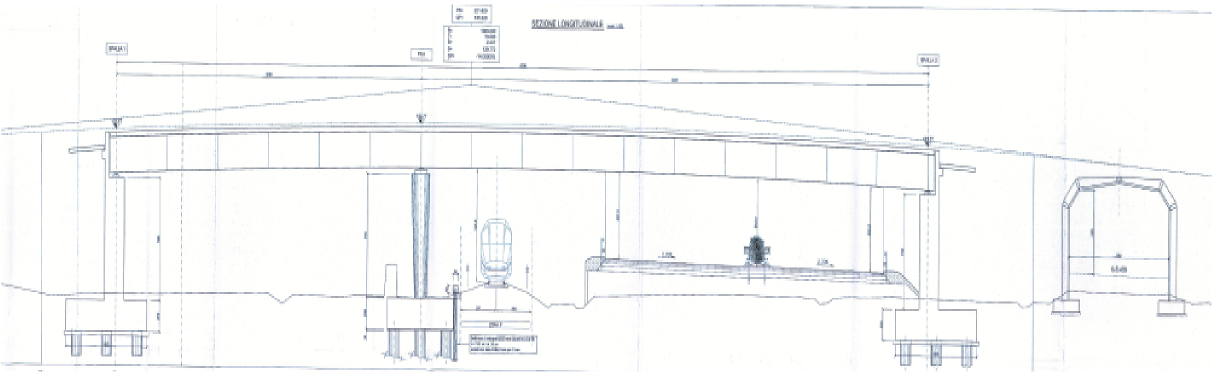


Figure 3.5: Longitudinal section of the bridge
Source: steel workshop tables

Figure 3.6: Google maps street view of the bridge
Source: https://www.google.it/maps

3.3 Starting documentation and structural description

This overpass is a bridge that develops itself above three supports, two side abutments and a pile. Its length is 80 m, the central support is not perfectly in the centre of the bridge but it is 30 m from an abutment and 50 m from another one. Moreover, its elevation is not regular on the z direction, its superelevation changes and for this reason the two side abutments have not the same elevation.

The bridge is a multi steel girder type [S11], a typology with three plate girders placed with an uniform spacing across the entire width of the bridge. These bearing beams are not standardised so that for the bridge construction was necessary to order them to a carpentry that has manufactured them. Indeed, these particular steel beams have a width of 2.3 m and were thought appositely for the realisation of this bridge, there is not a catalogue that furnishes bearing beams with these dimensions. The material used for the realisation of this bridge is steel S355J0; materials used different from this last one are marked in carpentry tables.

The bridge deck is realised with (reinforced) concrete, it spans transversely between the longitudinal beams and cantilevers outside the outer girders. All these beams are braced together every 5 meters in longitudinal direction.

Although that it was said that this overpass is a steel type, the bridge truly works as a composite bridge, there is a composite action between the longitudinal steel beams and the deck slab realised by the use of shear connectors; these last are welded on the top flanges of the steel beams.

Figure 3.7: Bracing systems view
Source: https://www.google.it/maps

The steel beams are I-section plate girders, they have parallel flanges, that means that they have a constant depth. These bearing beams are braced together, for reasons of stability and to act against the transfer of horizontal loads (wind and skidding forces) to the bearings that provide transverse restraint. The real functions of this bracing system are stabilizing the main beams during construction, contribute to the distribution of load effects and to provide restraints to compression flanges or chords where they would otherwise be free to buckle laterally. The choice of designers was choosing two twin beams with a L profile for the realisation of this bracing system. In figure 3.7 it is possible to see transversal bracing systems and the inferior plan bracing system that compose the bridge.

The inferior bracing system is provided in this case to improve the overall torsional system of the bridge at the completed stage of the work. It is possible to say that this kind of solution for the bridge has created a "pseudo-box system". Also in this case the adoption of designers was based on twin L shape beams. The longitudinal section and the inferior bracing plan, referred to it, shown in figure 3.9, allow to have an idea of the overall system: it is clear that this bracing beams repeat their-selves every 5 meters in longitudinal direction.

Figure 3.8: Inferior bracing system
Source: https://www.google.it/maps

The transversal bracing system, although it repeats itself every 5 m in longitudinal direction, presents different dimensions by the position it occupies. Clearly, on abutments and in the central support it has mayor dimensions, due to the magnitude of shear stresses. All these dimensions, are reported in the documents and displayed in figures 3.10, 3.11, 3.12, 3.13. The name assigned to every transversal system has the function of identifying their position in the longitudinal section furnished.

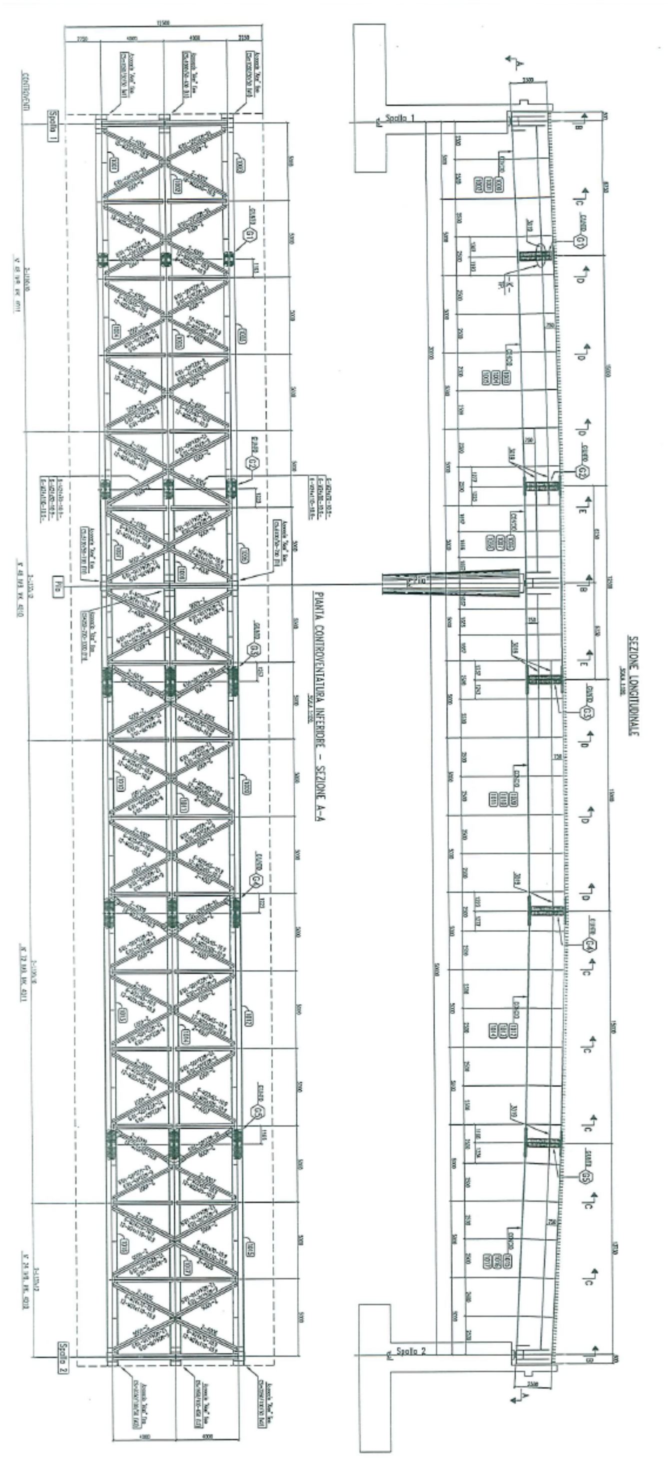


Figure 3.9: Longitudinal profile and inferior bracing system
Source: steel workshop tables

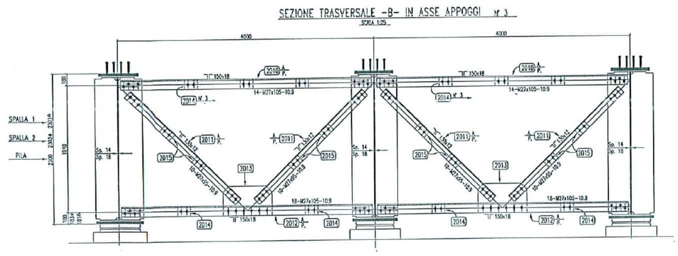


Figure 3.10: Transversal section B
Source: steel workshop tables

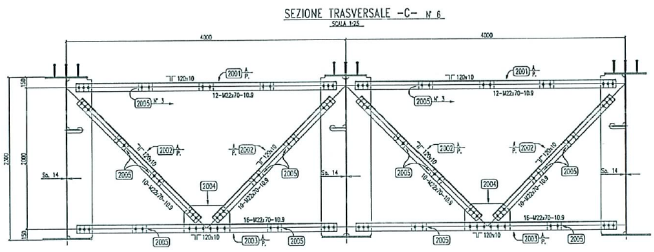


Figure 3.11: Tranversal section C
Source: steel workshop tables

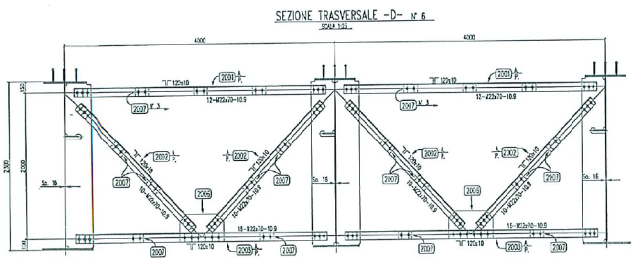


Figure 3.12: Transversal section D
Source: steel workshop tables

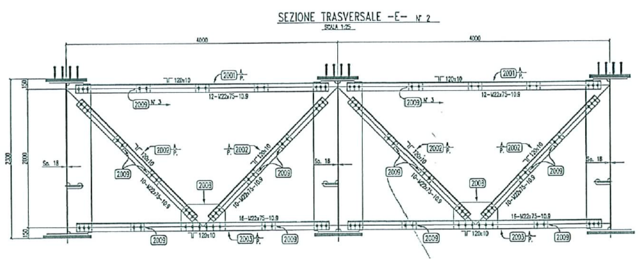


Figure 3.13: Transversal section E
Source: steel workshop tables

Finally, it is important to speak about bridge connections that are used to create unions between the different typologies of steel elements. For main girders union, there are five different joints, characterized by specific dimensions depending on their position and relative stresses they have to resist; clearly, the joints that are in zones most stressed (bigger mid-span) will be the ones with mayor dimensions. They are classified as joints with bolted joint covers. As shown in carpentry documentations, for the main beams connection were used M27 bolts 10.9 and plates with different widths and depths. Instead, speaking about bracing systems, connections between elements were realized using bolts (with minor dimensions, for instance M22) and personalised plates depending on beams involved.

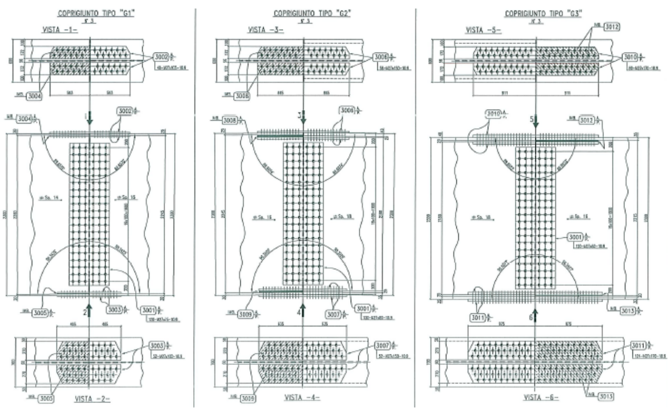


Figure 3.14: Joints 1, 2, 3
Source: steel workshop tables

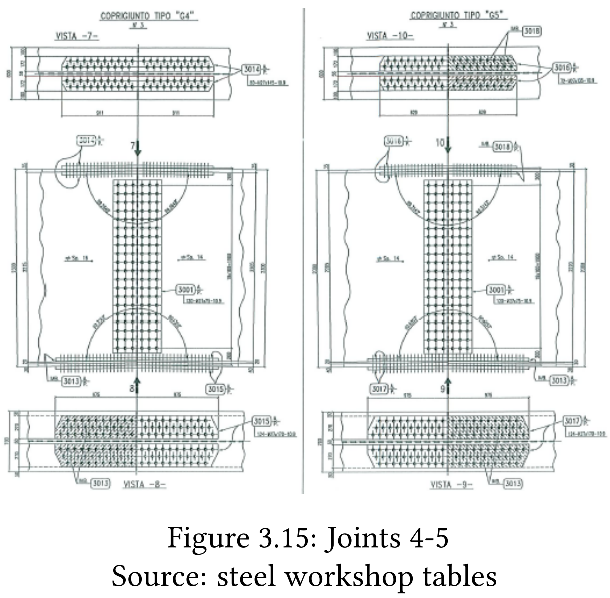


Figure 3.15: Joints 4-5
Source: steel workshop tables

3.4 Modelling and software

The existing bridge digital structural model realisation has been made thanks the steel workshop documentation of carpentry, partially furnished and illustrated in the previous section.

The software that was used for its realisation is *Tekla Structures 2018*, it allows to create constructive structural software for BIM. Using Tekla structures is possible to create accurate information 3D models containing all the structural data. Tekla models are truly constructible because they allow to reach high level of development, up to LOD 500. Moreover is possible to use only one tool for all materials and projects, making modelling easy and adaptable also to complex structures and infrastructures.

Another point in favour of this software is its open collaboration. It allows to collaborate with other project members and reusing all the data of structural models for other level of analysis. It is possible to import, export and link data with other software solutions. Tekla structures interfaces with several analysis and design (A&D) packages through a Tekla Open API (Direct Link), and, at the same time, it allows a free communication supporting the open source file format IFC for import/export. It is important to remark the fact that also this programs provides a free solution for users that do not want to adopt expensive software solutions.

As it will be shown during this work, there are big differences between these two different typologies of data exchange tested, a communication based on IFC with the aim of a structural analysis will result more complex and with a lot of criticisms. On the other hand, the benefits of linking with A&D packages the model authoring programs are many:

- coordination and visualization of models;
- both modellers and engineer can work on the same project model without reduced loss of data;
- efficient change management allows to keep project info up-to-date.

All these aspects of Tekla Structures useful for a structural modelling of a bridge will be remarked during this chapter. To reach the realisation of a the structural model have been necessary some steps, that are here summarized to give a better comprehension to beginners and future users of this works:

- individuation of structural elements to insert starting from structural tables. Only needed elements have to be inserted in the model;
- creation of user-defined profile of structural elements of the bridge;
- insertion of bridge structural elements in the model.

Moreover, with the realisation of a structural model, at the same time, an analytical model will be realized by Tekla, a simple tridimensional model useful to next phases of structural analysis. This analytical model is automatically generated by the software (it is differently generated by the interoperability method used), its quality in terms of structural analysis will be after evaluated.

As said before, the model has been created basing on the knowledge on the carpentry executive tables, which contain all the necessary information and an approximate research of the infrastructure made thanks the aid of Google Maps street view option [7]. Having a general overview of the infrastructure allows a better modelling in a three-dimensional space.

In the software space, it is possible to define different element respect to the material is needed to insert(figure 3.16).

Figure 3.16: Tekla material input

For each element, beam, column, plate will be possible to define every typology of existing section. For each profile will be associated various user defined types, that is all the different dimensions that can have all the structural elements.

Moreover, it is possible to define material of our structural element, every object can be customised following the exigence of engineers and architects.

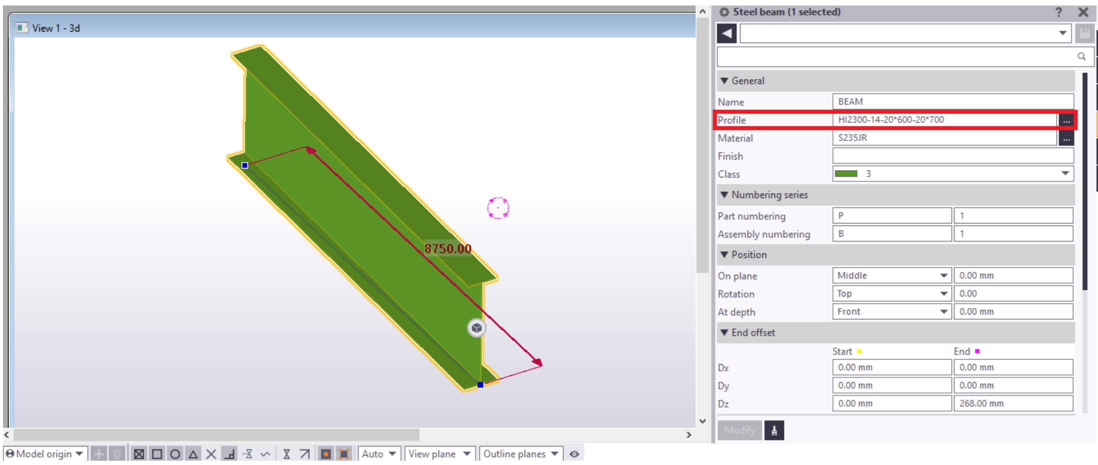


Figure 3.17: Input profile dimensions

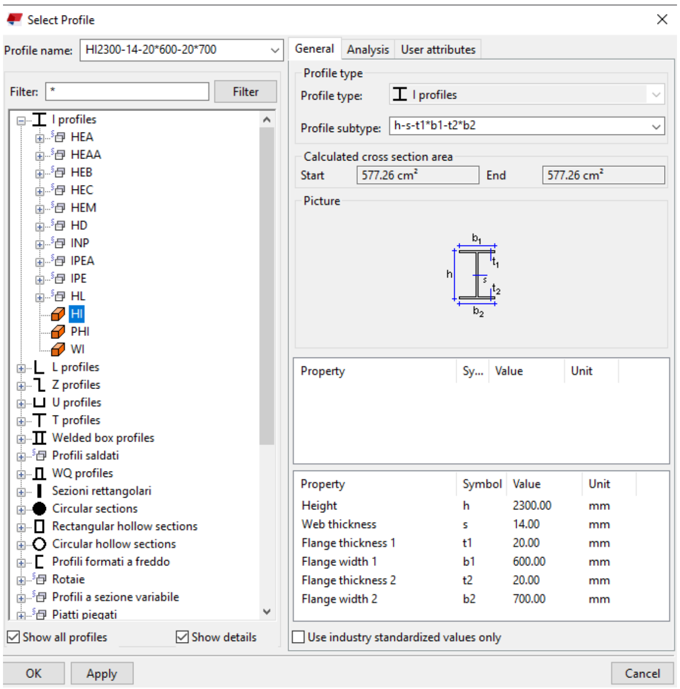


Figure 3.18: Creation of user-defined profiles

One of the best features offered by Tekla Structures 2018 is the user-defined insertion by selecting different subtype. By a graphical and intuitive input system is possible to customize elements which are not present in catalogues. This option allowed me the insertion of main girders spending only a small amount of time.

Same speech is valid about material input 3.19, although for the thesis case study was not necessary to create a new material with new properties, it was simply contained in software libraries.

All the elements created are inserted in the BIM model by the assistance of grids and levels (figure3.20), in this way is possible to model structures. The definition of grids is important to speed up modelling: it represents a way to insert information related to geometry and position from the first phases. Grids make reference to the plane XY, levels to the Z direction.

The advantage points of a model so realized are many. It can be interrogated in every single moment, it is possible to obtain info about many aspects of an element starting from its position in the space until its material and its profile; moreover it is possible to check if the information are up to date or not. Moreover, the model realized, although initially presents a LOD (Level of Detail, this concept will be summarized in the next subsection) not elevated, can be re-used in future to satisfy other exigences and reach other goals.

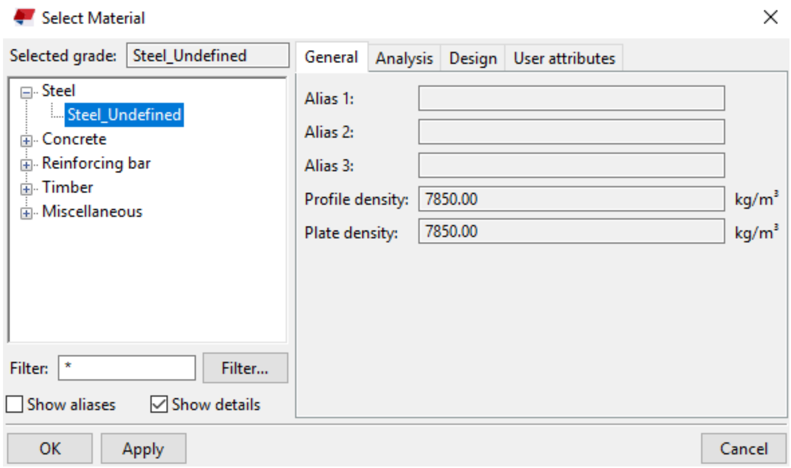


Figure 3.19: Creation of user-defined materials

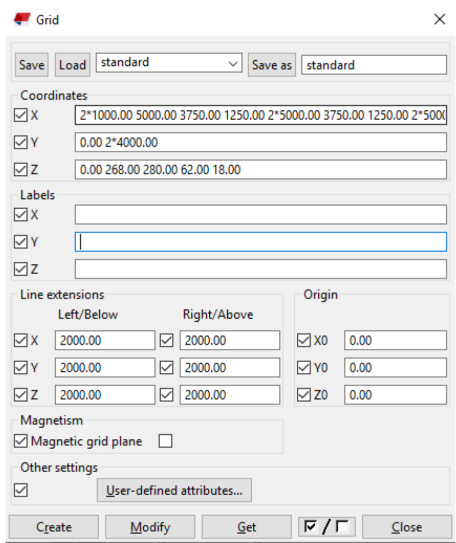


Figure 3.20: Grids and levels input

It will be reported a physical structural representation of the model that was obtained, inserting elements with geometry defined in carpentry documentation. This model will be used for following exportations (3.21).

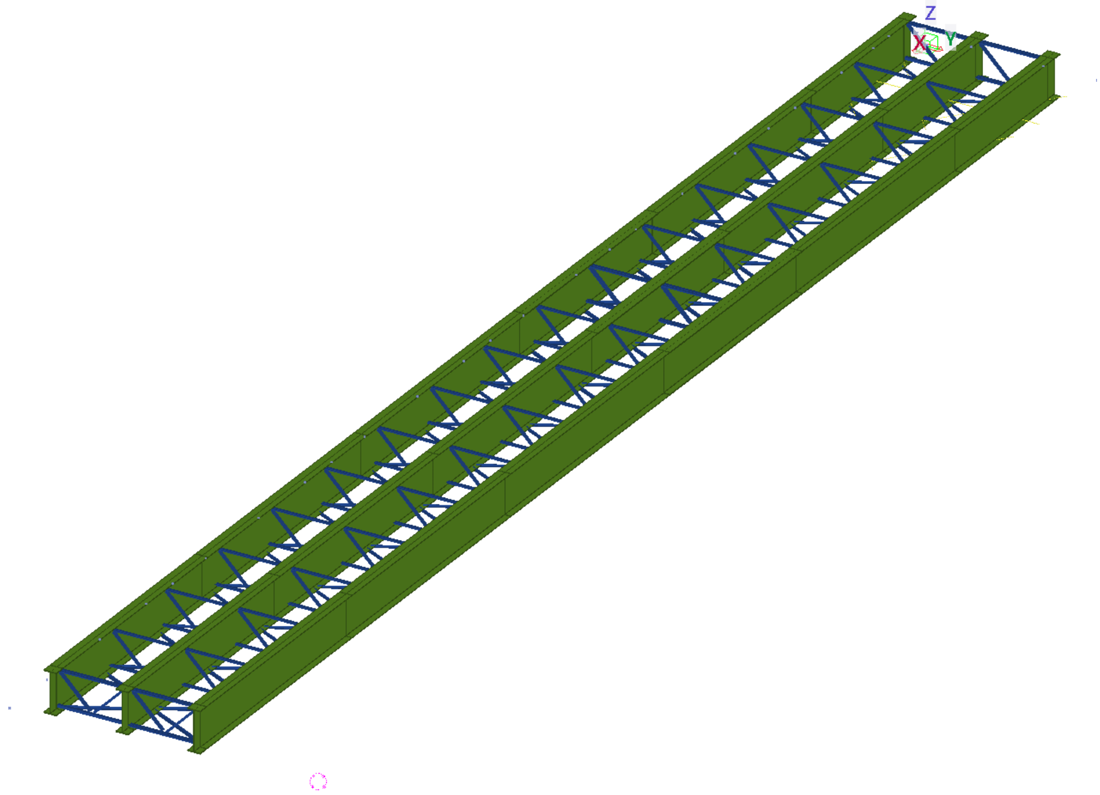


Figure 3.21: Structural Model, Level of Detail 300

3.5 Structural model with elevated LOD

Once acquired confidence with the software environment, possibilities in terms of structural modelling were tested, increasing the Level of Detail of the BIM model.

This exigence born to test two different aspects of the workflow: possibilities of Tekla Structures and even interoperability for local structural analysis, once that the global one was performed.

Tekla Structures provides solution to a series of exigences, it allows to reach up to LOD500 models, defining all the details which compose the structure. Moreover, being this bridge realised mainly with steel, the software has a complete dedicated section performed and thought to steel detailing: thanks to this one is possible to create new and personalised connections.

As said, the main reason that has brought to increase the Level of Detail of the model was the local structural analysis of the most stressed node; the first necessary operation was recreating a model with an incremented LOD. To make the global structural analysis it was simply sufficient a model with a LOD300+. Some results in terms of modelling reached have been here reported.

It was possible to reach a Level of Detail about a LOD400, sufficient for the workflow aim. The complexity of structural detailed modelling in Tekla Structures stays in the existing difficulty in bolts insertion. It is fundamental to select parts that are necessary to bolt accurately without any omissions that can compromise a following exportation.

As it is possible to check in figures 3.23, 3.24, 3.25, as the Level of Detail increases, much more the model is close to reality and can acquit exigencies of the related design phase. A LOD300 expects only beams representation, LOD350 beams and plates, LOD400 beams, plates and bolts (speaking about this case study). Same concepts are valid for joints and all the other bridge parts.

Finally, in the following picture the bridge structural model with LOD400 is represented (6.1).

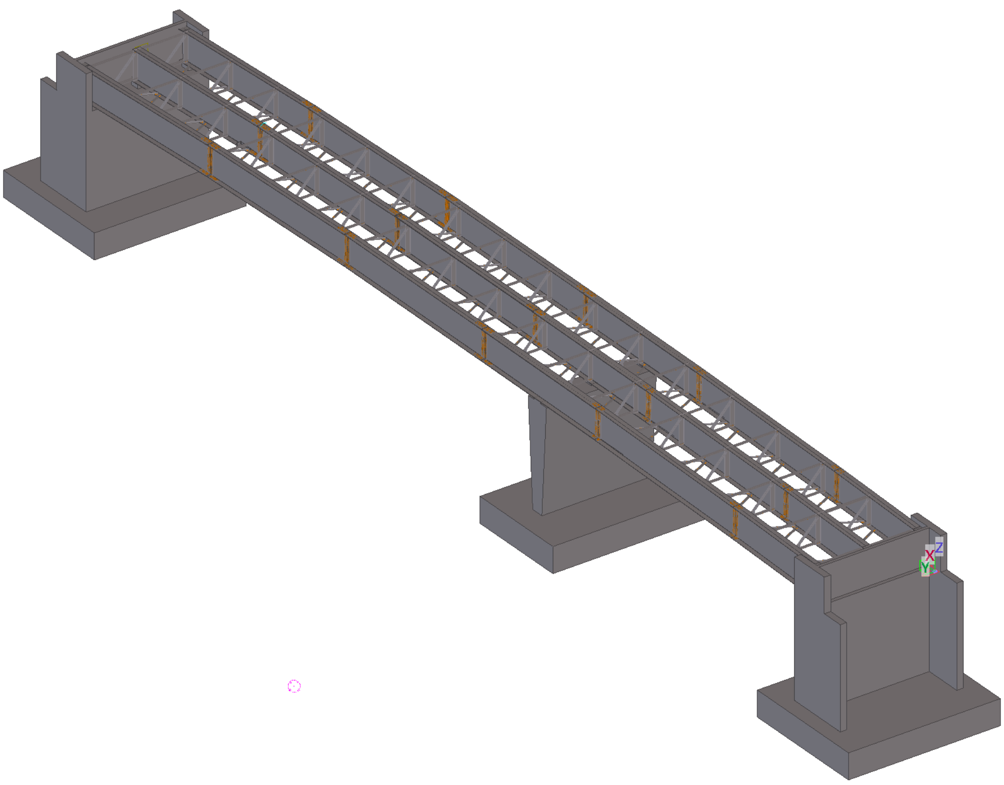


Figure 3.22: Bridge structural model, LOD400

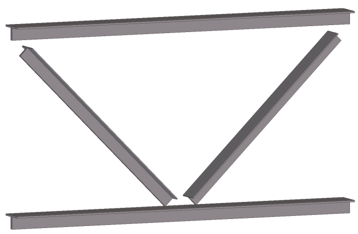


Figure 3.23: Support transversal bracing system, LOD300

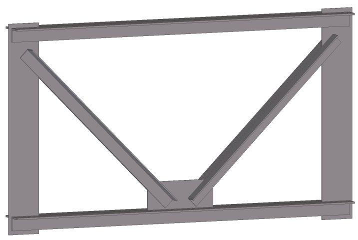


Figure 3.24: Support transversal bracing system, LOD350

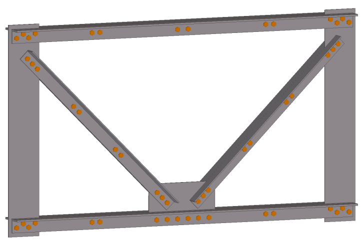


Figure 3.25: Support transversal bracing system, LOD400

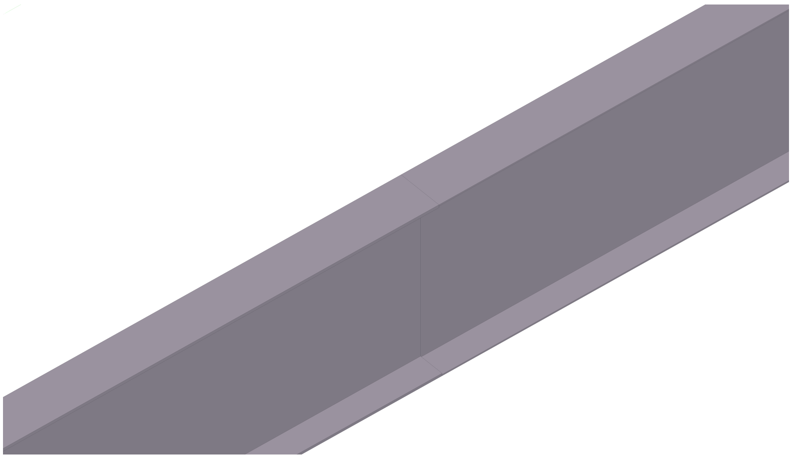


Figure 3.26: Joint 4, LOD300

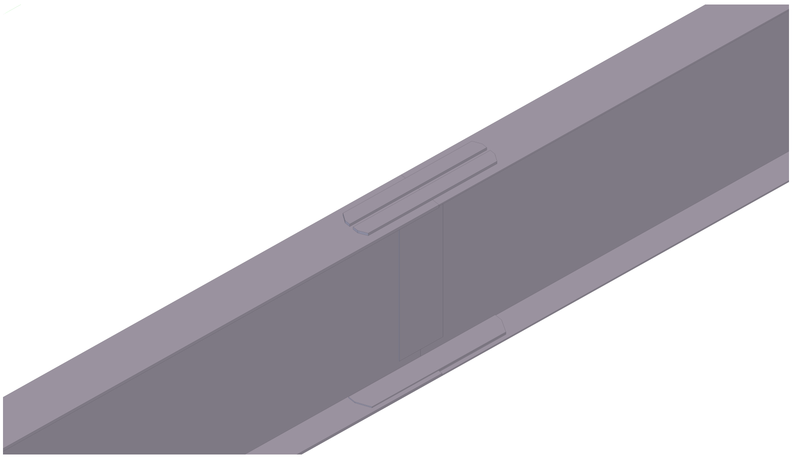


Figure 3.27: Joint 4, LOD350

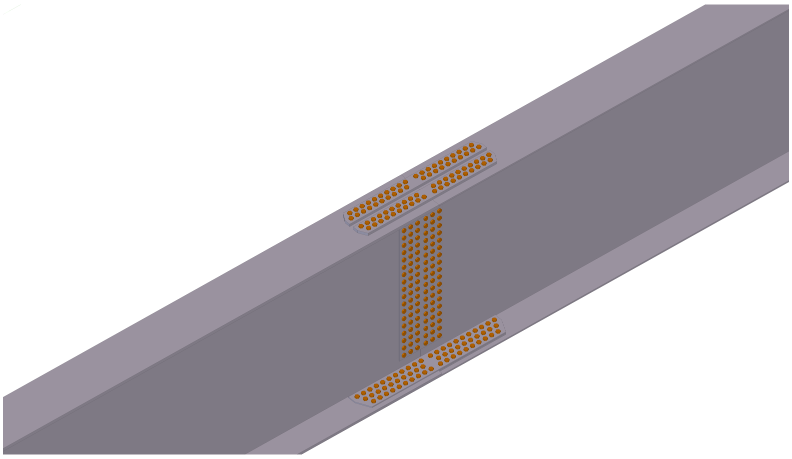


Figure 3.28: Joint 4, LOD400

3.6 A&D model

During the physical model creation, at the same time an analytical one is generated: it is a three-dimensional simplified representation. To each element with importance in terms of structural analysis which will be inserted in the model an analytic representation will correspond. It consists in a line for beams and columns, the two typologies used for the digital representation of this case study.

If IFC file format does not offer possibilities about modifying the analytical model in the model authoring software (as it will be illustrated in the next section), using a Direct Link, in Tekla Structures it is possible to modify it.

It is possible to define an efficient analysis model opening the Analysis and Design dialogue box. It is important to underline and repeat (avoiding the creation of confusion) that the Analysis and Design box can be used only in the case that the sudden exportation will be effectuated with a direct link; it does not affect in any way the export effectuated with other file format.

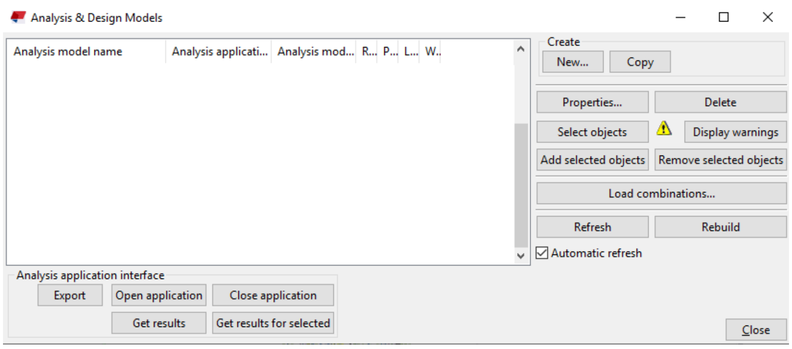


Figure 3.29: Analysis and Design dialogue box

Clicking on new it will display another window which contains all the properties of the future analysis model. This part of the modelling is the most important, it is the one that will allow to save time in second phases of analysis when the model will be exported in a FEM analysis software. All the problems related to criticisms about interoperability will be shown in the following chapter, it will be explained how a structural model should be created in a way to obtain a good exchange of information, giving solutions to criticisms and interesting points.

To understand how the Analysis and Design Dialogue Box works, it is possible to make reference to this picture that displays the physical model and the analysis model hidden in it (figure 3.30). Beams are schematized and shown as in a structural analysis software: they flow into nodes and their representation is made in terms of structural analysis. It means that the model contained is ready for a structural study. The process to obtain an analytical model as this one will be explained in the interoperability dedicated chapter.

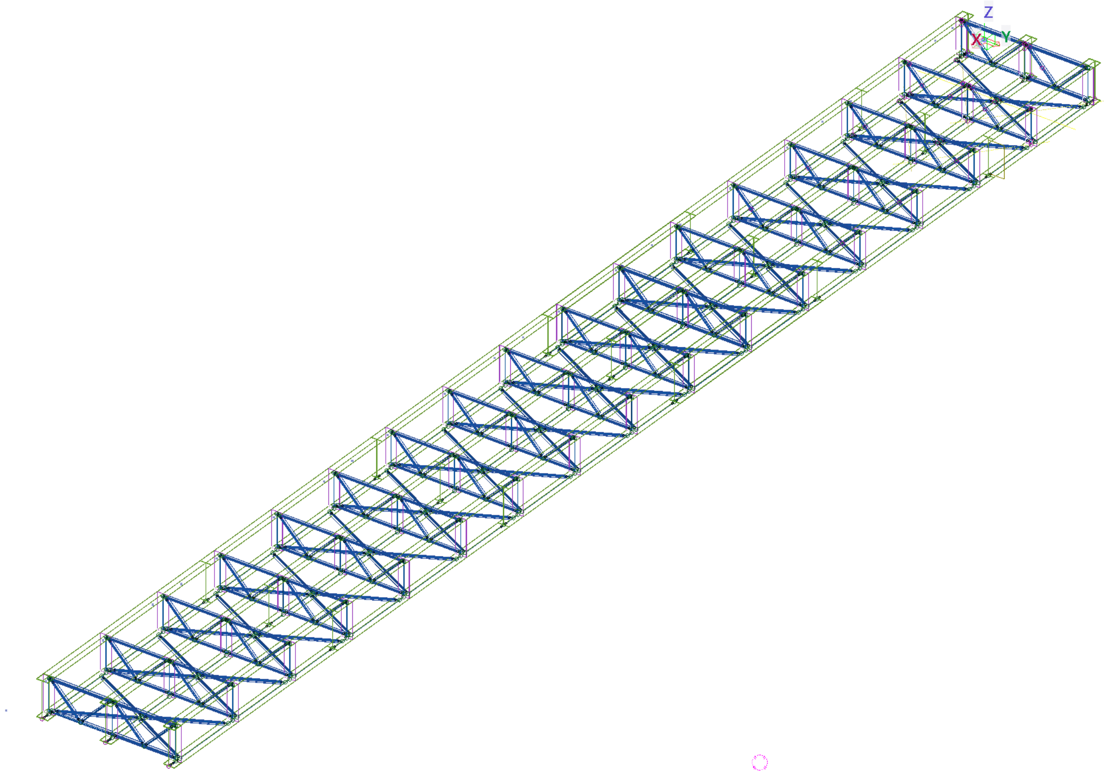


Figure 3.30: Analysis & Design model

3.7 Considerations about structural model for Midas Civil

The structural BIM model created and performed to be exported in *Midas Civil 2019* present some implementation respect the one used for *SAP2000 v20*. It contains some information about the concrete deck, although the starting documentation did not contain information about this part of the structure. For this reason, it was decided to insert this subsection making some considerations about the structural analysis of the slab. Interoperability test made using *SAP2000 v20* concerns only steel beams and this subsection can be ignored.

The concrete slab of the studied bridge results completely collaborating with the main steel girders. Defined this concept two different solutions are possible:

- considering the concrete deck as a plate (bidirectional calculation), but in that case it will be necessary to calculate stresses for every element of the mash;
- leading back the concrete deck calculation to the steel longitudinal beams, in this case the deck will result completely collaborating.

For this case study, the idea was using the second one approach and following the actual legislation, NTC2018 [5] subsection 4.3.2.3 about efficient width. As reported in it, normal stresses distribution in composed elements have to be determined by a model that considers the stresses distribution in wings beams and in the concrete deck.

Theoretically, it would be correct to consider an efficient depth defined by this relationship:

$$b_{eff} = b_0 + b_{e1} + b_{e2}$$

where b_0 is the connectors axes distance and $b_{ei} = min(L_e/8, b_i)$ is the value of the collaborating distance from each side of the composite section (figure 3.31):

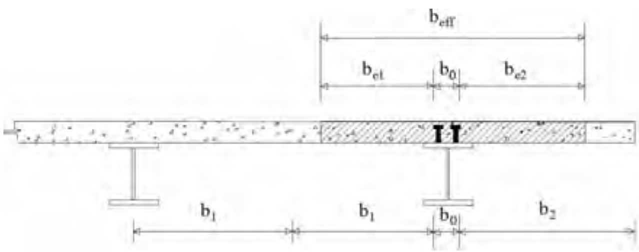


Figure 3.31: Effective width and rate definitions
Source: NTC2018 [5]

L_e indicates approximatively the distance between two bending moment diagram null values points. In the case of continuous beams with beam bending determined predominantly by distributed uniformed loads, indications of figure 3.32 can be used. For end supports it will be applied some corrective coefficients that are not here reported.

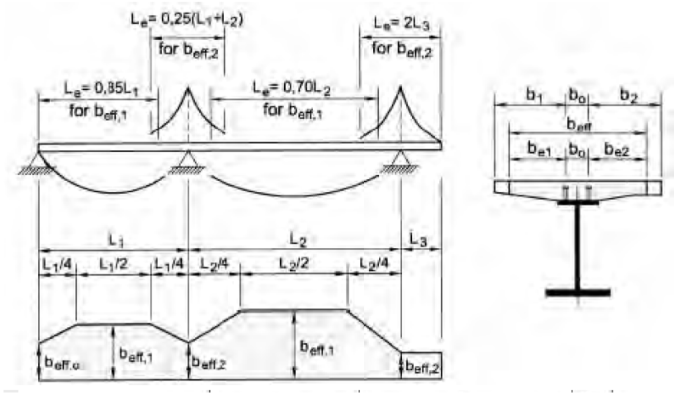


Figure 3.32: Efficient width and equivalent span
Source: NTC2018 [5]

In this case, being spans sufficiently long, the deck will result equal to the deck semi-width. Having not accurate dimensions about this deck (only a table realised in the pre-design phase, with dimensions not surely correct and corresponding to reality) it was supposed a semi-width of 2 m and so, inserted the deck as three concrete beams with section dimensions of 4000x300 mm.

The structural stiffness has been furnished to beams inserting some fictitious elements orthogonal to beams longitudinal direction in the structural analysis software.

Finally, this is a graphical output of what was modelled:

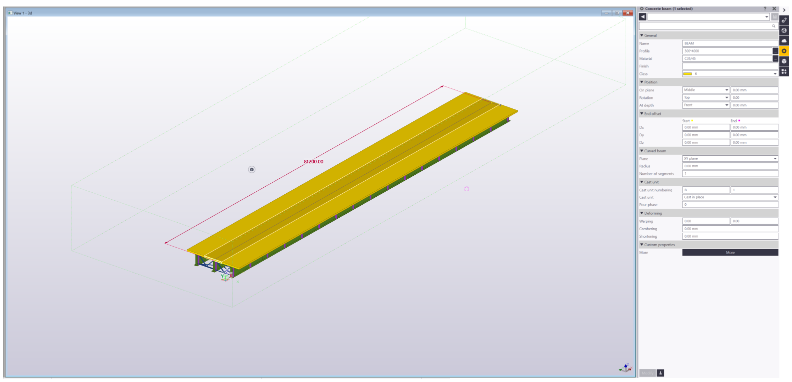


Figure 3.33: Structural model for Midas Civil and properties

Chapter 4

Interoperability

In this chapter has been analysed the main topic of this thesis: interoperability for structural analysis.

Interoperability is the fundamental aspect that characterizes the InfraBIM methodology, the main aim of BIM is the information sharing between different professional figures involved in the design process. Literally, this word refers to the ability of software to exchange data or information. [8] [S2]

During the development of a project, it will be surely necessary to share data between different software. Nowadays, it is not possible to think that a same program would be able to solve all the problems that a design process brings with itself. Interoperability born trying to provide solutions and furnishing supports to engineers and architects.

This data transfer can happen between software that belong to a same software-house, or between software that were not conceived to work together. There are many typologies of data exchange, the most common and about I want to spend some words now is the IFC file format. This last one is open source and free; it has been developed by buildingSMART (ex International Alliance for Interoperability) to satisfy the interoperability demand that BIM and InfraBIM methodology request. The best characteristic of this data exchange typology is that it allows to transfer information in a free way, being completely independent from proprietary file format (that is not open and free). There are many versions developed of this file format, dedicated to the data exchange between different disciplines (structural, architectural and MEP). The main versions now developed are the IFC 2x3, Export Type Coordination View 2.0 (it implied data losses or changes) and IFC 4; the first one is probably the most common and used today, the version 4 presents some innovations about entities (someone has been erased, someone has been modified). Currently, buildingSMART has released the version IFC 5 with even additional information. More details will be given in this chapter.

The starting point of interoperability workflow is the software for structural modelling used, *Tekla Structures 2018*. Created the structural model, the aim was testing two paths to understand which is the best option of communication, and which are limits and problems in these two different typologies of data exchange.

4.1 Software for structural analysis research

Software for structural analysis and design are always more developed. They provide solutions more and more specific to structural engineering problems, allowing to study structures and understand how they work.

There are many software dedicated to this aim, every one presents some advantages but also problems; two different solutions were chosen, studying some aspects that are important in the first phase of decision that will influence the entire workflow. These points touch many aspects, from interoperability to possibilities of software:

- the existence of a plug-in in Tekla Structures warehouse that allows the communication between software;
- the data exchange possibility with the open source file format IFC (Industry Foundation Classes), a format created to make easier the communication between programs;
- possibilities of structural analysis software of using legislation packages, it is important to find a software that is able to save time and possible mistakes;
- possibilities of structural analysis furnished by the software; the complexity of structures could be or not elevated, the aim is finding a workflow that can work with all the existing structures.

Many software allow an exchange of data with *Tekla Structures 2018*, two different software solutions were chosen, as anticipated.

The first is *SAP2000 v20*, one of the most famous software for structural analysis, and the second one is *Midas Civil 2019*, a software for FEM analysis specialised in infrastructures, especially bridges.

4.2 Sap2000 v20 - IFC

SAP2000 v20 is a product of Computers and Structures Inc. (CSI), it is one of the most known structural programs for analysis and design, thought for civil engineering; its catchment area permits to this software exploiting of important checks and feedbacks by its same users.

It allows to solve all the problems for every typology of structures/infrastructures, even complex ones with particular characteristics. Modelling phases, analysis and design are integrated in a graphical environment that make easier the use of this software and easy to assimilate. Dedicate commands allow a simple input of data, starting from the application of loads (static or dynamic) and the design in accord to the legislation chosen. Its versatility allows to exploit this software from small problems to big projects that require more attention. For this reason it is probably one of the best software for structural analysis and with the great productivity.

This software is one of the most suggested for the companies that want/have to work with BIM methodology, it permits interoperability and data exchange with software for architectonic design. It offers the possibility of importing and exporting data by the main standards of modelling: IFC, dxf, Steel Detailing Neutral File. Moreover, it allows a direct interface with some BIM modelling software such as Tekla Structures and Revit, using plugin provided from the same software-houses.

In this case, the choice was to not follow immediately the most simplified path, dictated by the use of a direct link, but using a different type of communication, in a way to understand the level of interoperability that can be reached with a free exchange. It was decided to test the most known format of information exchange, the IFC file format; as introduced, it is an open source transfer of data with a file that is imported from Tekla Structures and then reimported in SAP2000 to actuate the structural analysis.

Before explaining the criticisms and advantages of this interoperability path, it is important to define this file format and its possibilities, illustrated in a dedicated subsection.

Figure 4.1: IFC workflow

4.2.1 IFC

The Industry Foundation Classes (IFC) information model born with the aim of describing building, architectural and construction industry data. This platform is an open file format that (and it is important to remark this point) is not sold from some software-houses but is completely free and accessible to each user. It is an object based model that contains information, studied and developed by buildingSMART [2], that is the IAI. This idea born with the aim of improving interoperability in the world of AEC industry (Architecture, Engineering and Construction) where the digital revolution has delayed to reach. It is one of the most common way of data exchange in Building Information Modelling sector, so for all those professional figures that have adopted this new methodology to improve the quality of their work. In some countries of the north-Europe this technology IFC BIM based is yet integrated in the AEC economy.

Therefore, IFC is a standardised digital representation of a building or infrastructure, providing a good description of the built environment; it is defined by ISO 16739-1:2018 [9], that is an open international standard: it is neutral from vendors (probably its main advantage) and has been recognized by many software-houses that have developed software for many different work sectors. Clearly, this typology of data exchange, based on an open source file format, represents the base of the entire openBIM world.

OpenBIM is an universal approach to collaboration during design phases, to the realisation and management of infrastructures or building. This idea was created and now supported from many software-houses, and, as previously illustrated, it is an open source file format for interoperability. This idea born because of the lack of a real coordination workflow, the various parts do not coordinate their work but they use to share only the initial documentation of the project. [8] [S2]

Particularly, the IFC schema is a way of standardizing information in a model, with the aim of codifying all the data with a logical approach (identity, attributes, relationship,objects, abstract concepts, profession figures, work processes). This typology of schema can contain a lot of data and describing many specifics about a building or an infrastructure: IFC allows to describe physical and not physical characteristics of a product, its structural analysis model, its mechanical and electrical systems, its costs and many other points. Nowadays, this exchange of data is used to communicate between professional figures that cooperate in the entire design process. Moreover, its possibilities allow to use the IFC with the aim of saving and archiving information that will be reused in future, avoiding future errors and problems. Therefore, this open communication present advantages on the immediate and on the long-term future.

Tekla Structures recognizes automatically objects as IFC entities when a model is exported into an IFC file; it is possible also to make this operation manually in user-defined attributes of information objects, it means assigning to Tekla model elements the corresponding IFC element wanted.

Tekla Structures guide for IFC exportation furnishes a table that contains Tekla

Structures object and its relative entity in the IFC file format. This table is here summarized:

Tekla Structures object	IFC element
Beam	IfcBeam/IfcMember
Column	IfcColumn/IfcMember
Curved Beam	IfcBeam/IfcMember
Polybeam	IfcBeam/IfcMember
Pad Footing	IfcFooting
Strip Footing	IfcFooting
Slab	IfcSlab
Panel	IfcWall
Plate	IfcPlate
Bolts	IfcMechanicalFastener
Reinforcements	IfcReinforcingBar
Assembly	IfcElementAssembly

Table 4.1: Tekla Structures object vs IFC elements

4.2.2 Export from Tekla Structures to SAP2000 v20

This is a simple summarized guide for the export with the IFC file format, with all the fundamental steps that it is necessary to follow. It has been reported divided in main steps.

- Clicking on export with the IFC file format;
- it will appear a window to input the setting for an exportation. In this case Coordination View 2.0 has been chosen, the only one that is almost partially dedicated to solve structural interoperability problems;
- finalizing the exportation selecting the elements that are necessary to export and then clicking on the export button.

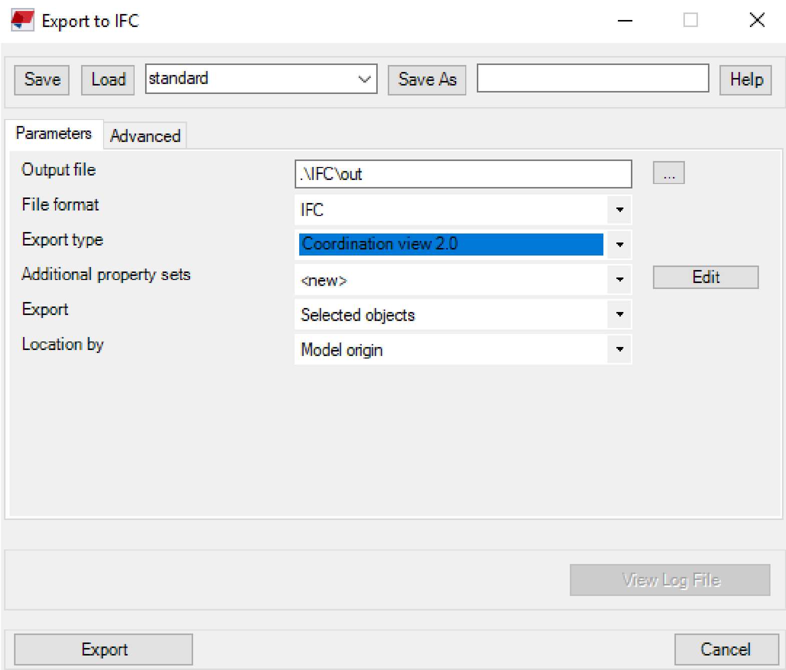


Figure 4.2: Export to IFC

4.2.3 Interoperability issues

Once the method of communication has been chosen and the general points to perform an exportation shown, the study about problems of data exchange that exist using this file format was started.

Many tests were necessary to understand all the errors and problems related to this kind of communication; this typology of data transfer, as it will be illustrated, need to make some important steps ahead if it wants to become the first and only file format of information exchange.

Position of analytical elements

If a simple export is performed using the IFC file format from Tekla Structures, the model in SAP2000 will be imported in this way (image 4.3) .
Checking this model there are some evident problems which can compromise the entire analysis. First point that leaps to eye is that all the beams present an axis, but these axes are all separated between each other; it is obvious that using an analytical model of this type is not possible to perform a structural analysis, it would not even start. Elements have to be connected between them in a correct way to perform a good analysis, frames should flow into nodes, only in this way the model could be defined correct.

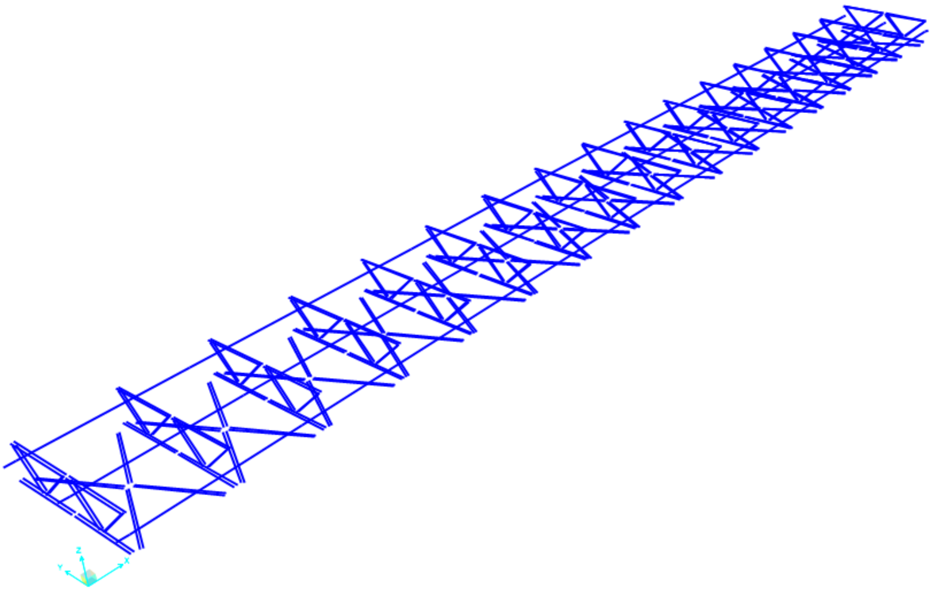


Figure 4.3: Analytical model obtained with IFC export method

Making some other check on this model, another problem bumps to eye; if the display settings are changed in SAP2000, clicking on the set of extruded elements, another issue can be identified.

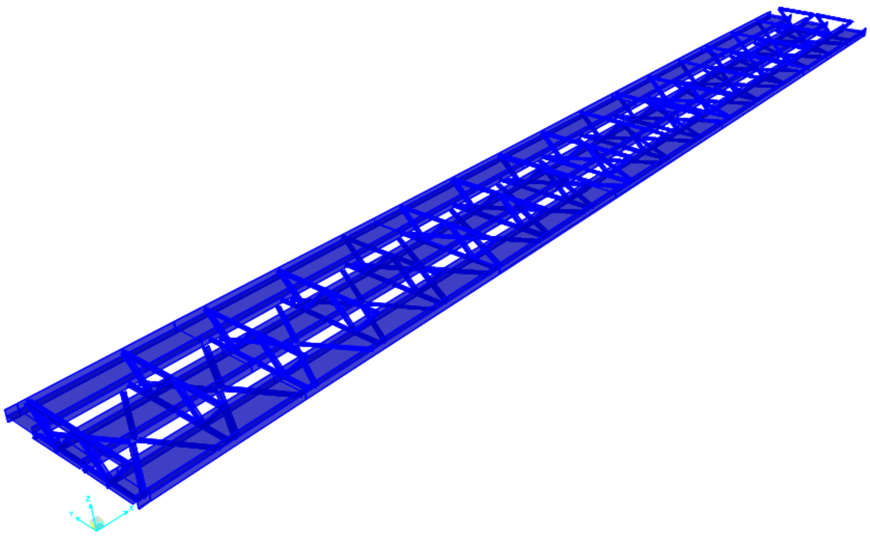


Figure 4.4: Beam elements with 90 degrees of local rotation

All the beam elements, inserted with the importation by IFC file format, are rotated of 90 degrees respect their same local axis. Checking settings of a general beam element, it is possible to ascertain that this error is true and consistent.

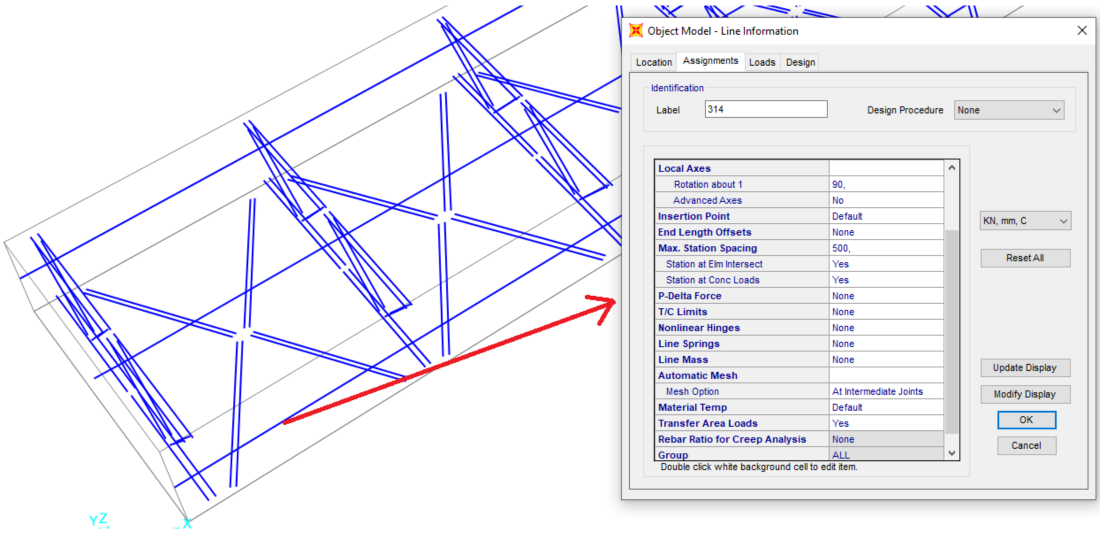


Figure 4.5: Local axis rotated of 90 degrees

These errors, linked to the different way of interpreting informative languages, are a limit of this data exchange typology; nowadays, there is no solution and interoperability experts know that these problems exist and that have to be solved if BIM wants to become the most used methodology of work for all the design phases.

This type of error, although is partially resolvable, is not so easily detectable. It costs a certain amount of time to the entire workflow, due to the fact that, in structural analysis software environments, users are wrongly accustomed to work with analytical elements and not with the corresponding extruded ones.

Materials

Another error, that has cost time and efforts to be solved, was related to the typology of material exported by the IFC file format. It did not correspond to the one inserted in Tekla Structures and the magnitude of stresses was wrong.

The first idea was that this error was connected to a wrong representation of the analytical model, but, after checked all the criticisms related to a bad geometry representation, it came to eye that it could not be connected to this reason, but due to another error. Checking the material data it easy to check that the imported one was different, containing a wrong weight for volume unit (and so not a steel S355J0): because of this problem stresses were not correct.

4.2.4 Solutions and settings for a correct export

In this section, it will be shown how all the criticisms encountered during this phase of interoperability have been (partially) solved.

First of all, when it is important to set a right input for a correct export: it is necessary to select the export type on coordination view 2.0 (this point was anticipated at beginning of the chapter). This is the most used type of data exchange of Building Information Models, especially when the model is thought to be used for a different aim respect the one that was created for (structural model and structural analysis in this case study). Its target is the coordination, as the name says, between different sector related to a same project: architectural, structural engineering and MEP. The Model View Definition contains parametric representation for a certain number of standardised elements and a non parametric representation for all the other ones. Properties, materials and some alphanumerical data can be exported after a preview assignation to the digital elements. It was not possible to use the structural analysis view of the IFC2x3 file format schema because this version is even under study and represents a research field in interoperability sectors.

Consulting the buildingSMART archive, the file format quality was checked with an export type of Coordination View 2.0. [S2]. Results were summarized in tables with the aim of understanding the level of interoperability that can be reached and causes behind these errors in the structural analysis model. It will be reported only results about data that interest the structural analysis.

These tables are developed on two columns; in the first there is the typology of IfcEntity and in the second one it will be reported if the exchange is allowed, that is if the information are contained or not in the BIM object.

Constraints	**Structural exchange requirement**
IfcConstraint	No
IfcConstraintRelationship	No
IfcPropertyConstraintRelationship	No

Table 4.2: Constraints

Material Property	**Structural exchange requirement**
IfcExtendedMaterialProperties	No
IfcGeneralMaterialProperties	No
IfcMechanicalConcreteMaterialProperties	No
IfcMechanicalMaterialProperties	No
IfcMechanicalSteelMaterialProperties	No

Table 4.3: Material Property

Material	Structural Exchange Requirements
IfcMaterial	Ok
IfcMaterialClassificationRelationship	Ok
IfcMaterialList	Ok

Table 4.4: Material

Measure	Structural Exchange Requirements
IfcContextDependentUnit	Ok
IfcConversionBasedUnit	Ok
IfcDerivedUnit	Ok
IfcDerivedUnitElement	Ok
IfcSIUnit	Ok
IfcUnitAssignment	Ok

Table 4.5: Measure

Profile Property	Structural Exchange Requirement
IfcGeneralProfileProperties	No
IfcReinforcementBarProperties	No
IfcRibPlateProfileProperties	No
IfcSectionProperties	No
IfcSectionReinforcementProperties	No
IfcStructuralProfileProperties	No
IfcStructuralSteelProfileProperties	No

Table 4.6: Profile Property

Profile	Structural Exchange Requirements
IfcClosedProfileDef	Ok
IfcOpenProfileDef	Ok
IfcIShapeProfileDef	Ok
IfcLShapeProfileDef	Ok
IfcParametrizedProfileDef	Ok
IfcRectangleProfileDef	Ok
IfcRoundedRectangleProfileDef	Ok
IfcTShapeProfileDef	Ok
IfcTrapeziumProfileDef	No
IfcUShapeProfileDef	Ok
IfcZShapeProfileDef	Ok

Table 4.7: Profile

Property	Structural Exchange Requirements
IfcComplexProperty	Ok
IfcPropertyEnumeration	No
IfcPropertyListValue	No
IfcPropertyReferenceValue	No
IfcPropertySingleValue	Ok
IfcPropertyTableValue	No
IfcSimpleProperty	Ok

Table 4.8: Property

Representation	Structural Exchange Requirements
IfcGeometricRepresentationContext	Ok
IfcGeometricRepresentationSubContext	Ok
IfcMaterialDefinitionRepresentation	Ok
IfcShapeAspect	No
IfcShapeRepresentation	Ok
IfcShapeModel	Ok
IfcStyleModel	Ok

Table 4.9: Representation

Structural Load	Exchange Requirements
IfcBoundaryCondition	No
IfcBoundaryEdgeCondition	No
IfcBoundaryFaceCondition	No
IfcBoundaryNodeCondition	No
IfcStructuralConnectionCondition	No
IfcStructuralLoad	No
IfcStructuralLoadLinearForce	No
IfcStructuralLoadPlanarForce	No
IfcStructuralLoadSingleDisplacement	No
IfcStructuralLoadSingleDisplacementDistortion	No
IfcStructuralLoadSingleForce	No
IfcStructuralLoadSingleForceWarping	No
IfcStructuralLoadStatic	No
IfcStructuralLoadTemperature	No

Table 4.10: Structural Load

Giving a careful look to these results table, furnished by buildingSMART, it is clear that it is not possible to reach a good level of interoperability using the IFC file format for structural analysis; moreover, this problem is not about the knowledge of software users but it is an interoperability limitation.

Indeed, structural exchange requirements completely not satisfied for constraints, material property, profile property and, especially, structural load. This table represent an important step in this research about interoperability: IFC file format is not able to guarantee a cleaned and linear workflow with structural analysis software because of its same informative definition.

Problems related to analytical models, their materials and profiles can be only partially solved, for the only thing to do it is waiting for new export types of IFC files to reach a perfect level of communication. Possible adjustments and improvements can be taken only in the structural analysis software.

Although the problems in this case are many and appear unsolvable, it was decided to persist on this way and try to find an approximate solution to perform an analysis. This decision was taken because this interoperability path represents an important chance in the spread of BIM in the international view: allowing a total free exchange of data is the starting point to persuade all companies, even the most settled in the traditional methodology of working, to approach this new workflow for all the design aspects. Moreover, engineers have to understand that they can do without any licenses, only following this way they can avoid becoming software-house *slaves*.

Summarized problems and limitations of this workflow, it was found a solution making some adjustments on model elements in the software for structural analysis. It will be illustrated the main points in this chapter dedicated to interoperability, then they will be accurately described in the next chapter where structural analysis will be performed.

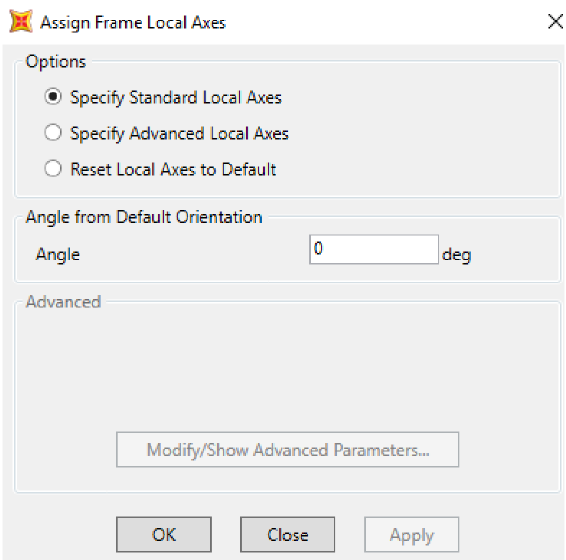


Figure 4.6: Assign frame local axes rotation

The first point to solve was the rotation about their local axes of beam elements; as seen in the previous section, these elements result rotated of 90 degrees. To obtain a model with all the elements rotated it was necessary to assign beam frames an angle of rotation, respect their same axes, of 0 degrees (image 4.6). It is necessary opening the window to assign frame local axes and then selecting beam elements to give a new local rotation; it was necessary to apply this operation many times: once for horizontal beams parallel to X global axis, once for horizontal beams parallel to Y global axis, twice for oblique beams that compose the transversal bracing systems, twice for oblique beams that compose the inferior bracing system.

Then, the second critical point analysed, before starting the structural analysis, is that steel beams of the imported model result not connected between them as amply said before. To obtain a analytical model with all the elements correctly connected between them, it was decided to define a new frame section.

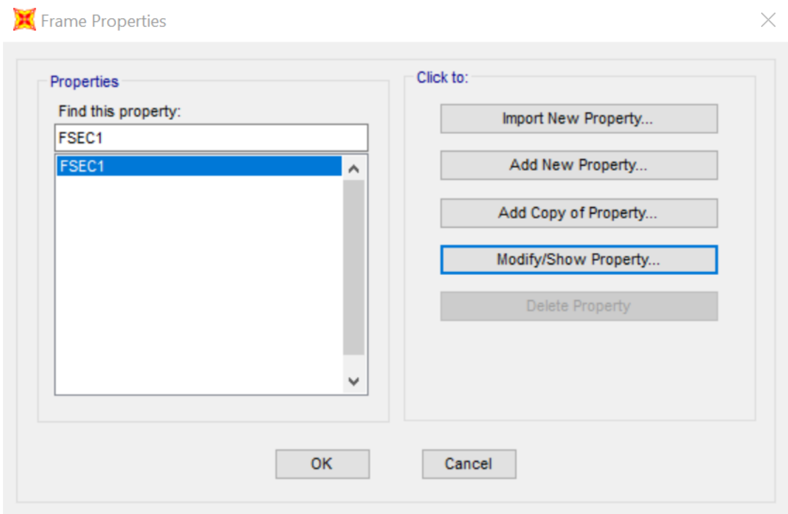


Figure 4.7: Properties creation for frames

A new fictitious rectangular section was defined with dimension of 10 mm for depth/height (image 4.9) and a new material with a null value of weight per unit volume (in this way future values of stresses will not be altered) and an elevated value of the modulus of elasticity, E and consequently of the shear modulus, G (image 4.9); in this way a “connection” was created using frame elements, which could be called rigid link between beams.

It does not affect the structural analysis, but rather it allows this last one. This solution was adopted after noticed that the function contained in sap2000 for rigid links comported problems to the structural model, once that the analysis was performed (trend of stresses did not correspond to the right trend expected).

This is a simple summarized explication of what was made in the structural analysis

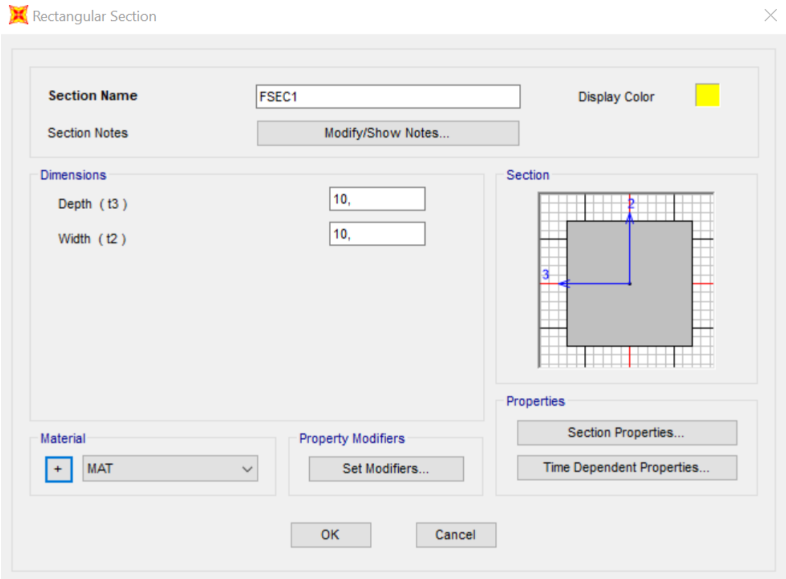


Figure 4.8: Input data for rigid frames section

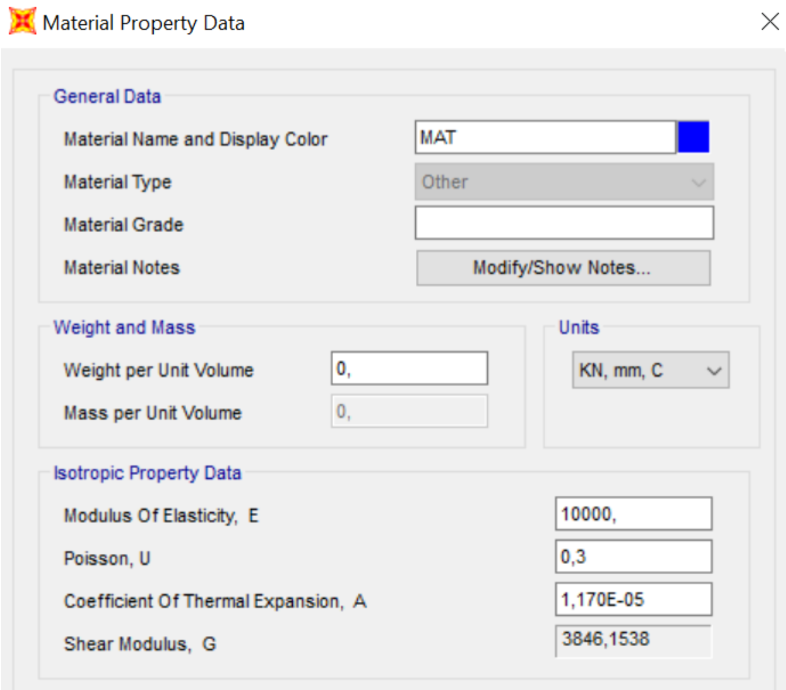


Figure 4.9: Material properties of rigid links

software to obtain a model ready to run structural analysis. More information will be given in the section dedicated to SAP2000 of the next chapter, making some considerations about solutions given. As said before, an important fact, that also after this little research comes to eye, is that it was not possible to make operations and modifies in Tekla Structures: it is not possible to make important and efficient adjustments in the BIM model authoring software, an important interoperability limitation for the workflow.

Final results will be shown only to give an overall idea of what the author have tried to describe with words and that will be elaborated on in the next chapter.

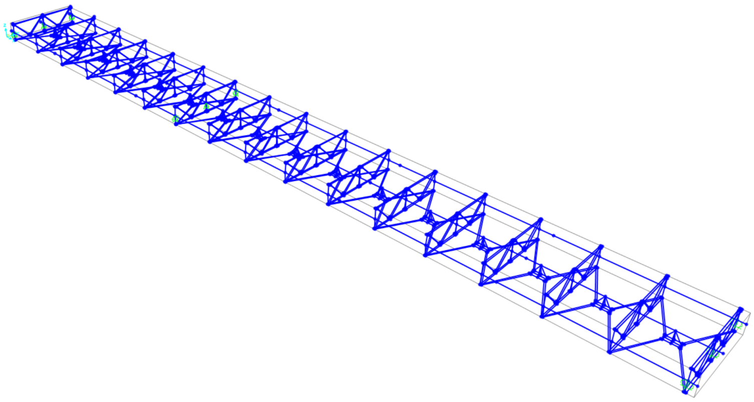


Figure 4.10: Analytical model with adjustments

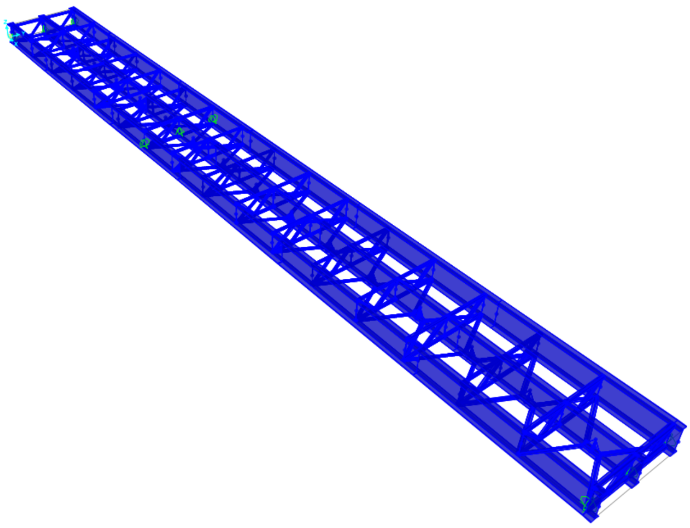


Figure 4.11: Analytical model with correct local axes

4.3 Midas Civil 2019 - Direct Link

Midas Civil is a software for structural FEM analysis belonging to the software-house *MIDAS*. Midas software for design and FEM analysis are oriented to solve problems of civil, mechanical and industrial engineering.

Midas civil is an optimal solution for design and analysis in the civil field of infrastructures. The system is based on the FEM (Finite Elements Method) and it has enormous possibilities developed appositely for analysis and design in the civil infrastructure sector, first of all bridges.

All these possibilities presented are integrated in a very simple and powerful interface to manage every typologies of structure, even complex structures with important dimensions.

This software allows to manage in a very simple way structural modelling, as we were drawing; moreover it is provided of some automatic functions like the auto mash generation.

The post processor is furnished of an automatic generator of load combinations conform to the design standards requested by various legislations; it interfaces itself with Excel, allowing to users to manage results in the way they believe more opportune.

Midas Civil allows elaboration and management of models with a great number of finite elements. It consists of beam, wall, plate, solid, truss, each one with a big database of profiles that include all the main legislation used in the world, and it is possible to add them manually too.

The program allows to insert every typology of loads, static, dynamic or mobile. Infinite condition of loads are possible, managing all the combination of loads inserting coefficient defined by the legislation adopted (AASHO, Eurocode).

Finally, Midas Civil is a BIM compatible software, it supports data exchange with other software solutions, among them Tekla Structures. This information transfer is permitted by a apposite plugin, that is a direct link, that allow a good quality in terms of interoperability efficiency.

Figure 4.12: Workflow Direct Link flowchart

4.3.1 Direct Link: Tekla Structures 2018 - Midas Civil 2019

Midas Civil is a BIM oriented software furnished of a direct link that allows a good communication with some important software for model authoring, such as Tekla Structures and Revit.

As amply said before, in this case study interoperability with Tekla Structures will be evaluated. An important point that the author wants to remark is that this typology of interoperability, that is direct link, it works only with some specific versions of these two software, and, moreover they have to be installed on the same machine to allow the data exchange. A focus on these limitation is necessary because using this typology of interoperability is not free but a license has to be bought. This fact represents an important limit: the choice of this method by companies implies a dependence on software-house decisions.

Returning on main characteristics of this communication between software, first some features of this plugin will be described. The following tables contain some information about the data exchange recognized in the two different directions. All these information have been extrapolated from the user manual of the link furnished by Midas software-house. [1] [S1] [S12]

Element type	TS to Midas Civil	Midas Civil to TS
Beam	Ok	Ok
Curved Beam	Ok	No
Column	Ok (Beam)	Ok (Column)
Inclined Column	Ok (Beam)	Ok (Beam)
Slab	Ok	No
Panel	Ok	No

Table 4.11: Element type import/export table

Material	TS to Midas Civil	Midas Civil to TS
Concrete	Ok	Ok
Steel	Ok	Ok
Wood	User-defined	User-defined
User-defined	User defined	User-defined

Table 4.12: Material import/export table

Boundary conditions	TS to Midas Civil	Midas Civil to TS
Support	Ok	Ok
Rigid Link	Ok (Only between beams!)	No
Elastic link	Ok (Only between beams!)	No
Beam end offset	No	No
Beam end release	Ok	No
Section offset	Ok	Ok

Table 4.13: Boundary conditions import/export table

Confronting them with the ones developed by buildingSMART for the IFC file format, the results seem more efficient. Really, a true and valid confront is not possible, two different typologies have been considered: this one is performed exclusively for structural analysis, IFC to solve a vast range of data exchange and for this reason is defined by more parameters.

However, following information contained in TS - Midas Civil plugin guide, element types, materials and boundary conditions present an efficient data exchange in both directions speaking about the analytical model. A good starting point for this new interoperability study.

4.3.2 Export from Tekla Structures to Midas Civil

It will be reported a simplified guide of the resume path to execute an exportation from the model authoring software, Tekla Structures, to the program dedicated to structural analysis, Midas Civil.

- Click on Analysis and Design models in the Analysis and Design window;
- creating a new model;
- setting the right Analysis application plugin, in this case Midas 2018 - Rel. B (4.13);
- selecting elements that will compose the analytical model and checking it (how to create a correct model it will be shown in the subsection dedicated to interoperability problems);
- click on the export button (image 4.14).

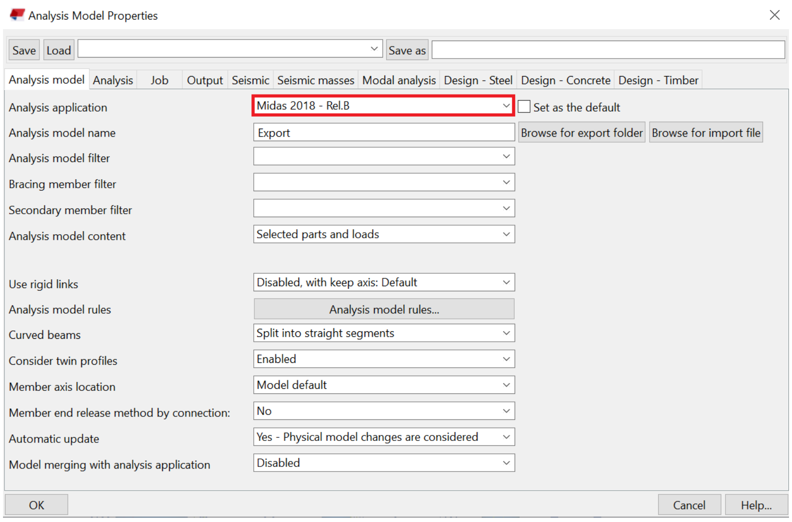


Figure 4.13: Setting for exportation to Midas Civil

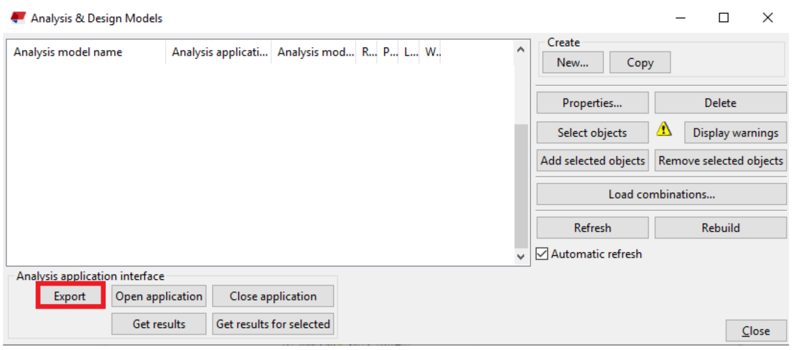


Figure 4.14: Export finalized

4.3.3 Interoperability issues

In this section issues related to interoperability between software and which are best solutions to take in a way to optimize the workflow have been studied.

The best result in terms of interoperability would be obtain a model in the software for structural analysis ready to be performed.

To obtain this goal it is necessary to understand how to model this infrastructure in the A&D model dialogue box of *Tekla Structures 2018*.

Two main problems have to be avoided or partially solved to create a correct analytical model:

- the *rigid links* creation between parts of the model for the presence of *eccentricities*, that is beams which do not flow into nodes perfectly;

- problems related to Tekla Structures *user-defined elements*.

Position of analytical elements

When an analytical model is created in the Analysis & Design box it is important to set some parameters in a way to optimize the workflow. If the right setting is not inserted in Tekla Structures, timings to perform and apply the methodology for a structural analysis raise.

To understand this problem it will be shown which is the result if the output setting is not studied, such to give an explanation of because settings in this phase are fundamental.

These are the analysis model properties of the test which was performed:

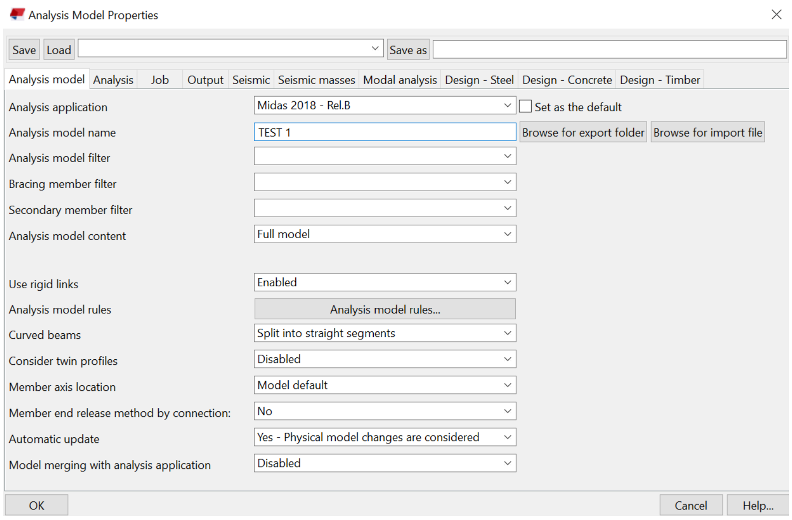


Figure 4.15: Analysis Model properties, test 1

As it is possible to check in figure 4.15 rigid links are enabled. If some modifies are not produce to this model and to the elements that compose an analytical model as the one that is shown in figure 4.16 will be obtained.

These new violet elements created automatically by Tekla are named rigid links. They are elements generated by the software, it tries to create an analytical model by itself that should be able to perform an analysis. But as it will be shown, this automatic analytical representation does not work, probably it will work only with very simple structures.

The creation of these rigid links involve an important loss of information; they are not recognized in Midas Civil, and for this important reason, their existence modifies the model obtaining a structure that does not correspond to reality and that will be never usable for a structural analysis.

To understand what this means an exportation was performed in the structural analysis software, showing common errors of interoperability. Results are displayed in image 4.17.

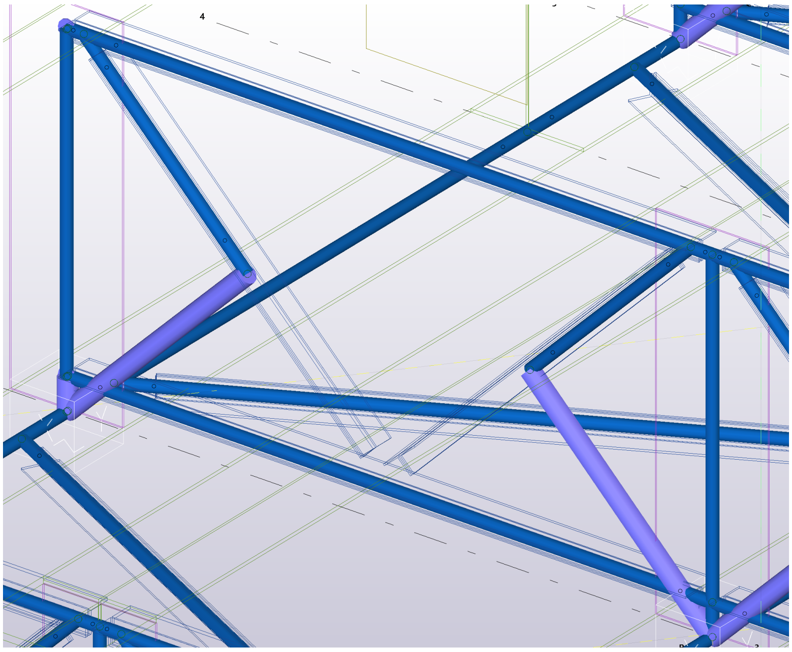


Figure 4.16: Rigid links between element

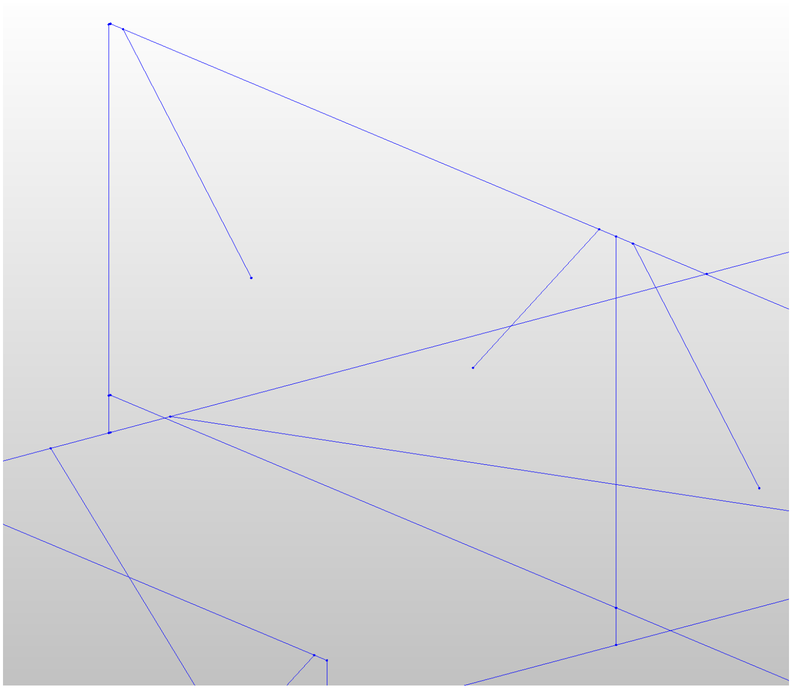


Figure 4.17: Imported model in Midas Civil, test 1

It is easy to ascertain that the model obtained in Midas Civil present some important issues. First, rigid links are not exported and elements of the bracing system clearly result cut. The software is not able to recognize rigid links and creates an analytical model with some errors.

Zooming on the upper-left corner of the bracing system, it is possible to scrutinize another error:

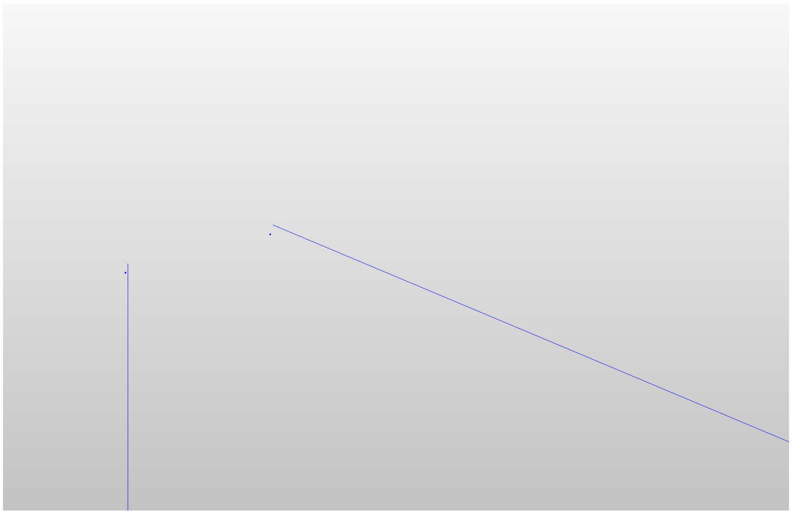


Figure 4.18: Errors in test 1

This error, in structural terms of evaluation is important because it is not possible to run an analysis with beams that are not connected between them. Moreover, it does not represent a solution connecting these beams with rigid links, software is not able to recognize all as errors: it will be cost more time that creating a new model by using only the software for structural analysis, so the entire aim of the work would be lost.

These problems related to the analytical model creation have been the most complex part of the work, it was hard to find the right set of properties to insert in a way to obtain an analytical model ready to its structural analysis.

To reach a good result of interoperability it is necessary to change the properties inserted in the analysis model creation. The right settings to perform a perfect exchange of data between software using the direct link provided in the next subsection will be illustrated.

User-defined beams

Another important issue that has cost a great loss of time to the workflow was the user-defined beams exportation. As said in the chapter dedicated to the case study of the work, this bridge is composed by main girders that present not standardised dimensions.

These steel beams were designed by engineers and committed to a carpentry for their manufacture.

Speaking in terms of modelling, these not standard dimensions are not a problem: the model authoring software allows to insert user-defined elements with a very simple graphical input way. The problem surges when it is necessary to export this typology of elements in the software for structural analysis.

If an exportation is ran, inserting the correct dimensions of these steel beams, the exportation crashes. There is no way to exchange the information contained in these elements by using the plugin provided; this is a limitation of the direct link, a review of this one should be required to software-houses.

It was hard to discover this problem, because this crash could be due to many unknown reasons, that are not reported in any guides. It was necessary to test and query the file that was exported by the plugin to discover the error.

Opening the mct file (that is the file format that is possible to export from Tekla Structures when using the Analysis and Design dialogue box) by the Midas text editor is possible to check the code written by the plugin; this last one represent the way between the two software communicate.

A test was made for a beam with the following dimensions:

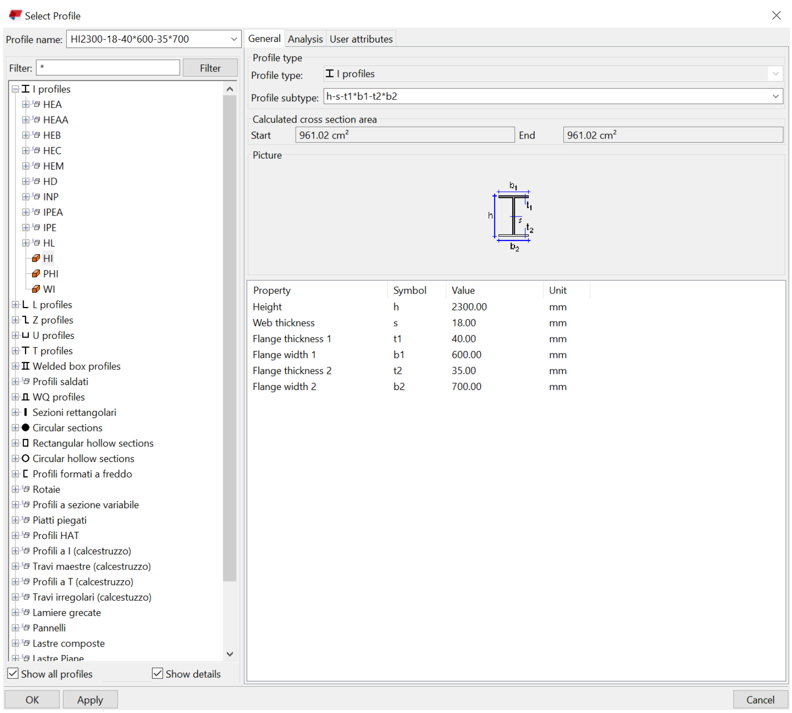


Figure 4.19: User-defined beams with accurate dimensions

Then the software was interrogated using the text editor:

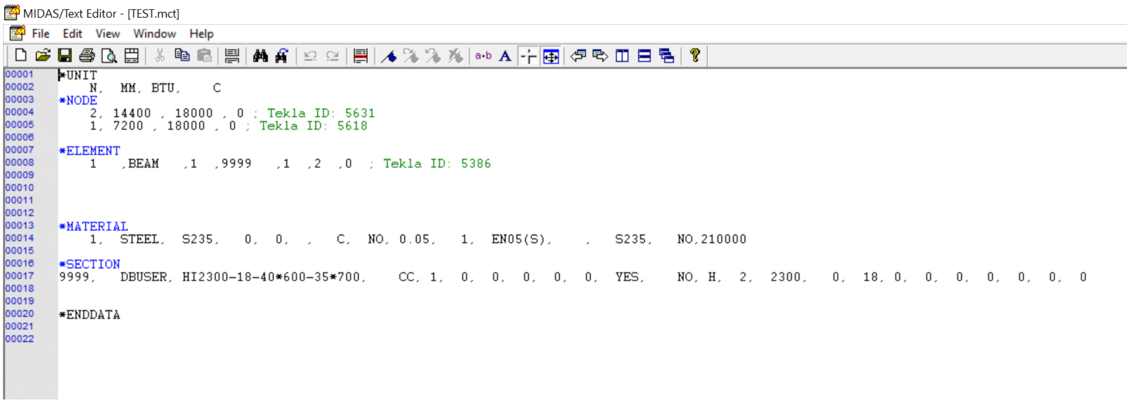


Figure 4.20: Midas text editor, code error

Line 17 is the one used to define the dimensions of this particular beam: the plugin, when this specific profile-subtype is inserted, it is not able to compile this part of the text, and so an interoperability error occurs.

Good results have been obtained to understand the error about this topic, trying to export a user-defined beam, but this time with the following subtype dimensions:

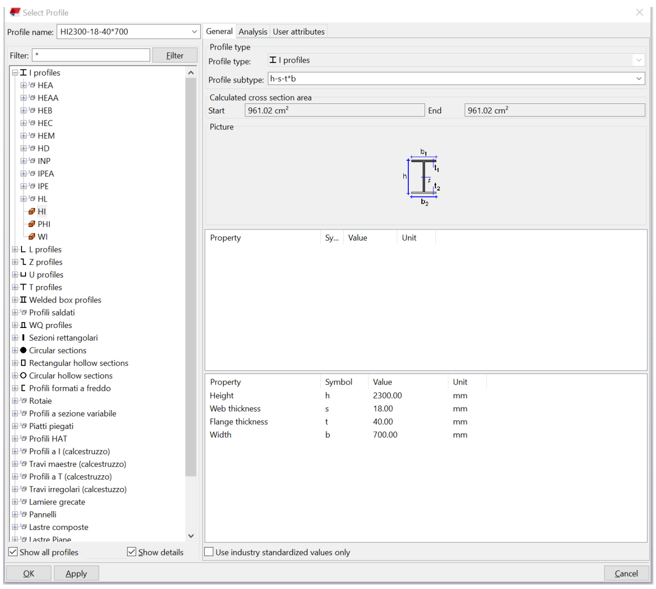


Figure 4.21: Beam exported correctly

This time the exportation finalized, and, moreover, interrogating the Midas text editor the zeros of line 17 have been substituted by the correct dimensions used:

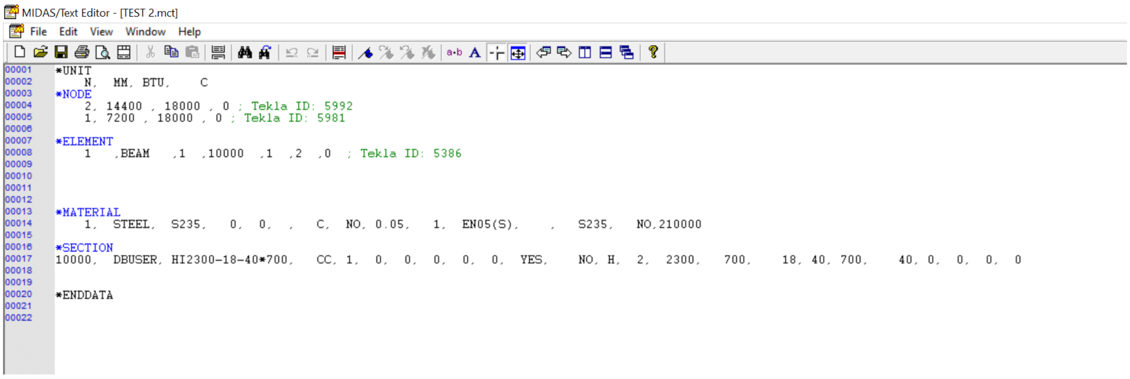


Figure 4.22: Midas text editor, user-defined beam subtype correctly exported

This problem, because is due to the software, is unsolvable; many attempts were necessary with other dimensions and with other profile subtypes. The catalogue of beams contained in Midas Civil was also implemented, inserting and defining a new profile with the dimensions contained in the Tekla model, but this has not represented a solution because the error is surely contained inside the plugin definition. This error was also reported in the software-house forum, but an answer does not exist.

4.3.4 Solutions and settings for a correct export

This section is dedicated to solutions that are necessary to solve important errors which have compromised a perfect exportation.

First, to create a good analytical model it is necessary to insert an output setting as the one is reported in image (4.23)

It is useful to set rigid links with this default option, in this way rigid links are not (always) generated. Another reason that can produce rigid links is the existence of eccentricities between beam elements, the software automatically create them to obtain a model with all the nodes linked. The critical point is that it is not able to understand the good way to unify these nodes.

However, there is a way to solve this error, just playing with the position of elements axes. Clicking on steel beam part analysis properties, it is possible to put some data about the element that will be exported in the structural software. Among these output settings there is a window about the axis position of beam elements. By this box it is possible to choose the position of axes and avoiding the creation of eccentricity.

Alternatively, it is possible to change the beam elements position with a right click on the axis that we want to select and the clicking on move. This last solution is not recommended by the direct link guide, some important modifies can change the global structural behaviour. If a modify of this type is taken, users have to be aware of consequences on the structural analysis.

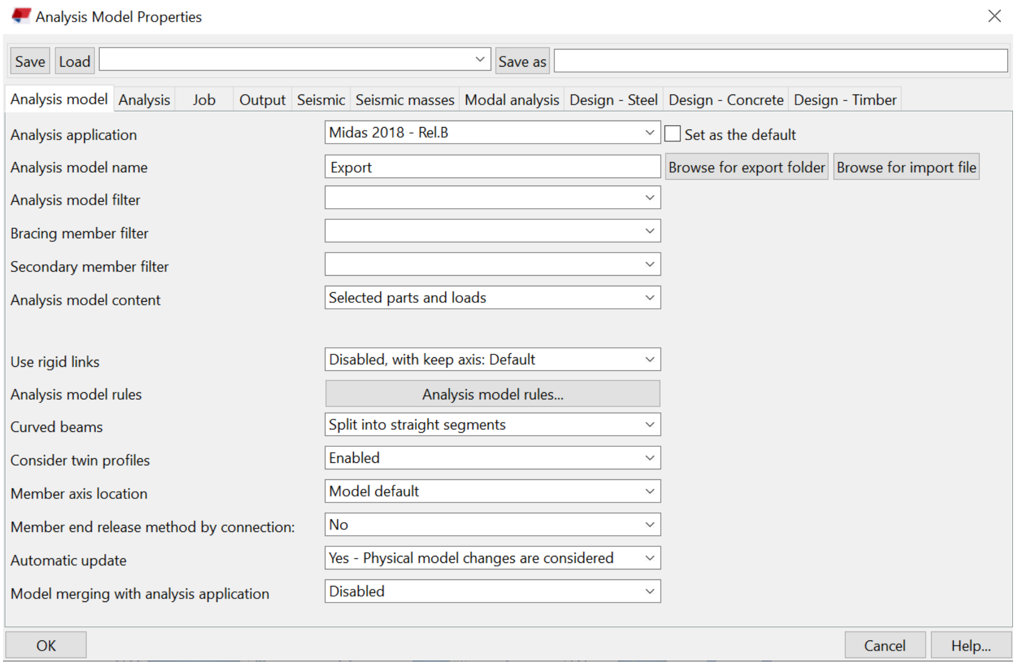


Figure 4.23: Correct analysis model properties

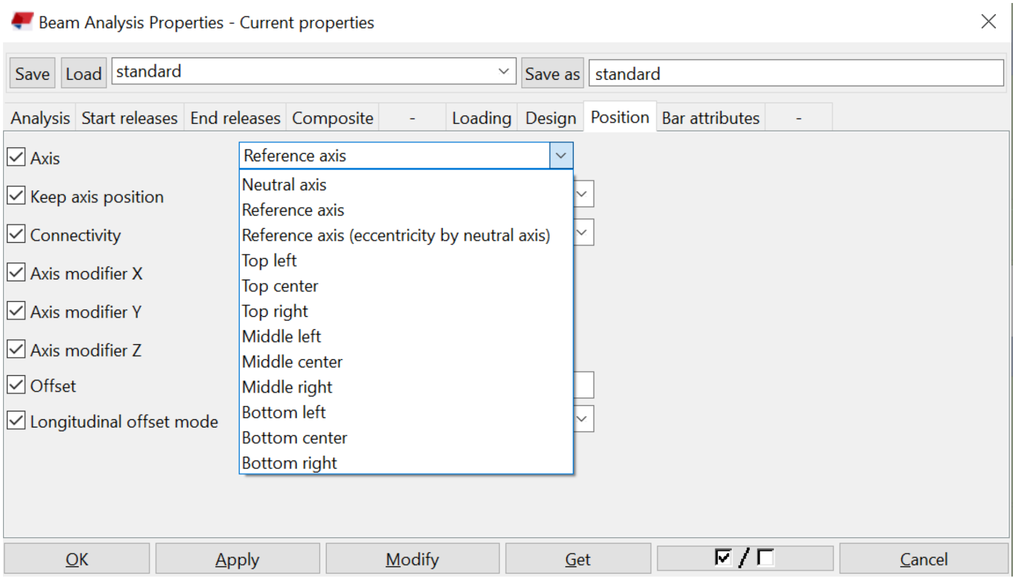


Figure 4.24: Beam analysis properties, axis position

Following these possibilities in terms of analytical modelling, it was possible to obtain a model ready for the analysis, without any rigid links or eccentricities. The final solution has allowed me to obtain a model read almost ready for a structural study.

By the author opinion, this part is the most important one of the workflow, creating a good analysis model it is possible to reduce the entire work time. Although this part has been expensive in terms of time, all the work spent it will be saved in a second moment, because after the exportation we will see that, although some adjustments are necessary, the model is concretely ready to be analysed by the FEM software.

The graphical result of the exportation is shown in figure 4.25. A complete description about applications and adjustments taken on structural analysis software will be illustrated in the chapter dedicated to modelling on structural analysis software.

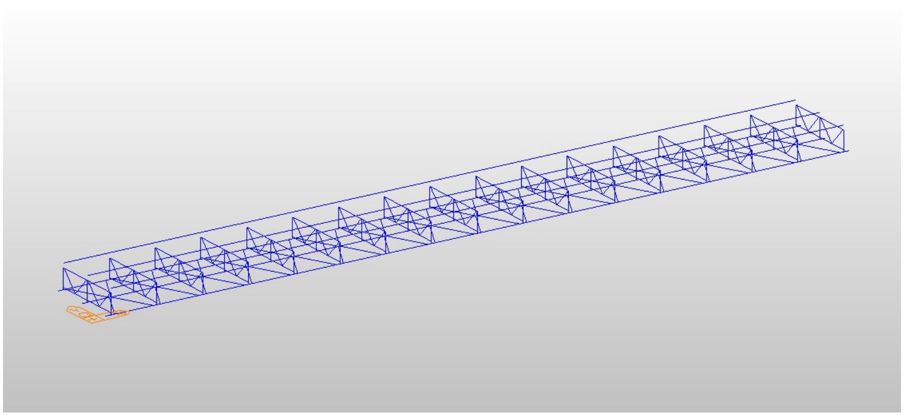


Figure 4.25: Imported analytical model in Midas Civil

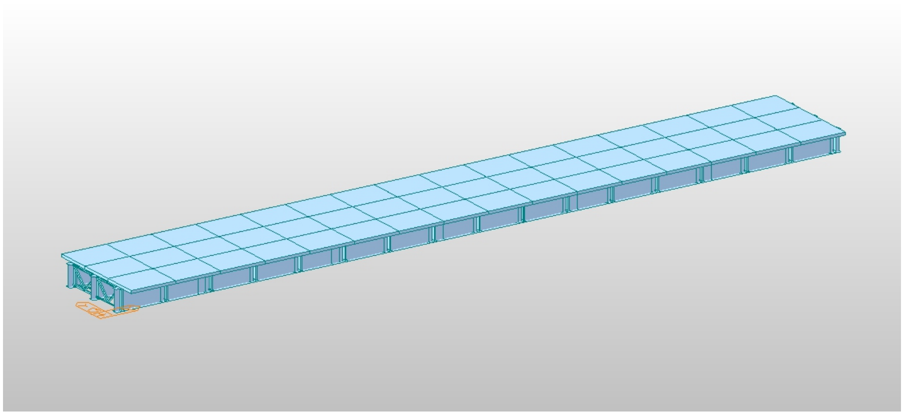


Figure 4.26: Imported model in Midas Civil

4.4 Idea StatiCa

Idea StatiCa is a software for structural design of unions, connections, sections, beams, bolts, and other structural elements. This software allows to design steel unions of each shape, connection and plate without any limitations in geometry (although some rules have to be respected) and in the definition of loads. Its precision allows to understand and avoid errors, minimizing risks and cost related to construction defects. Another important aspect that we have not to underestimate is that, using this software, we can reduce the material quantity used for the realisation of structural connections. If we run a correct analysis we can reduce cost on material up to 30 percent of the total price they required. Even this software it is based on an analysis method named CBFEM that works with the Finite Element Method Analysis, running perfect calculation for every component that will compose the connection. [6] [S6]

With all the parameters inserted it is possible to verify all the objects that are present, understanding if the number of elements used is correct. All these aspects are unified with a good and simple graphical output that allows to understand imprecision in the definition of elements which are disposed in a very small space. It automatically provides a report of the results obtained, with a level of detail that varies from a simplified version to a detailed one.

Moreover, this software is a BIM based one, that allows the data exchange with other software for global structural analysis and with ones for the model authoring like Revit and Tekla Structures.

It allows engineers to obtain results about connections previously created in another software, for instance CAD programs, and result of loads combination from other ones. The combinations of software used to solve different aims allows to obtain a better results in terms of efficiency and completeness of the work.

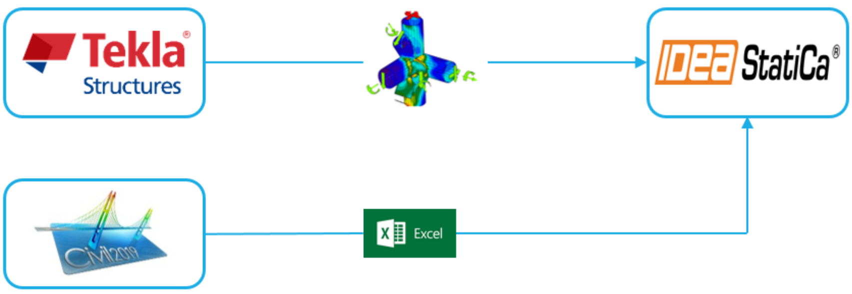


Figure 4.27: Local structural analysis workflow

4.4.1 Export from Tekla Structures to IdeaStatiCa

It was decided to test this typology of interoperability and the infraBIM methodology for local structural analysis too.

The joint studied is the number four, the one with biggest dimensions and surely the most stressed because it is positioned early near the mid-span. Its structural analysis it will be performed with the effect of load calculated in the ULS combination of loads: this analysis is also known as joint at partial restoration.

First of all, to perform a local structural analysis in Idea StatiCa, it is necessary to increase the connection Level of Detail (LOD) in the structural model. Once that the joint LOD has been increased to 400, a custom component connection has to be defined in Tekla Structures.

To create and define a custom component is important to follow some accurate steps; if a custom component is not created the exportation is not able to finalize.

It is necessary, in application and component dialogue box, clicking on define a new custom component and then:

- selecting all the elements that will compose the custom component, that is the steel connection (in this case it was necessary to select bolts and plates);

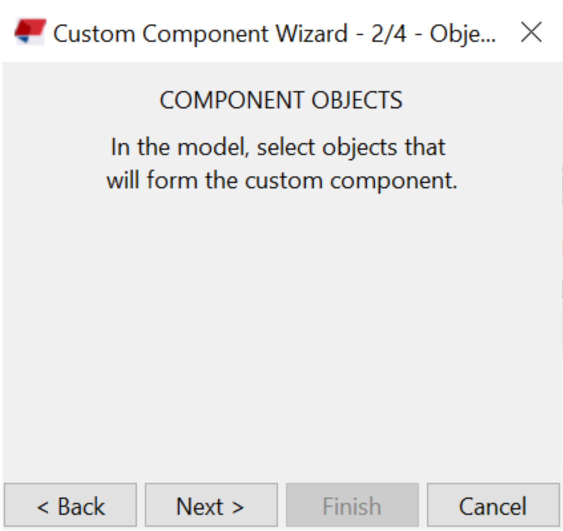


Figure 4.28: Selecting component objects

- selecting the main part (main beam, resistant element);
- selecting the secondary elements (other beams).

The new custom component defined is shown in the image 4.29. The modelling of this joint to perform a structural analysis has brought the author to face many problems, they were shown in the next section of this thesis.

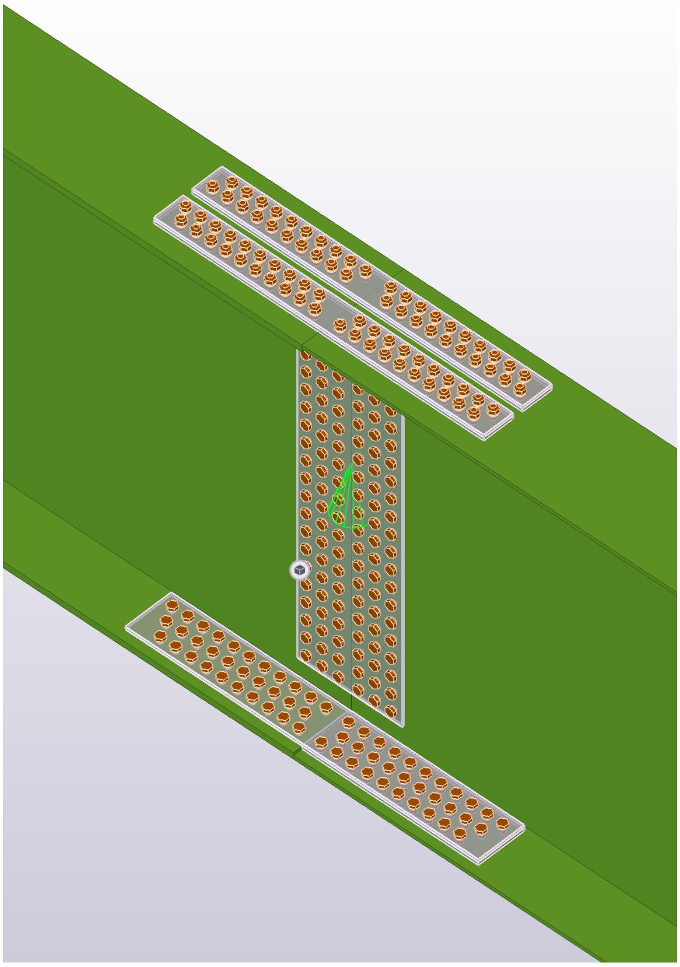


Figure 4.29: Defined custom component ready to exportation

Once that the custom component is created, it is possible to run the direct link and performing the exportation. If this plugin is installed correctly, a new dialogue box will appear named IDEA Connection. Clicking the orange button an exportation will begin. First of all, it is necessary to click on new project and decide the national design code that is requested for the case. It is important to choose the correct one, because Idea StatiCa is able to make automatically some checks about the connection using coefficient defined by different legislations.

Figure 4.30: Idea connection, creation of a new model and chose of the design legislation

Then, it is necessary to select in Tekla the insertion point of our connection, the beams involved in our joints (it is not necessary to define the resistant element, this information is attached to the custom component definition) and finally the other object, that is plates and bolts. After that this little process is terminated, it is possible to export the connection in Idea StatiCa (figure 4.31)

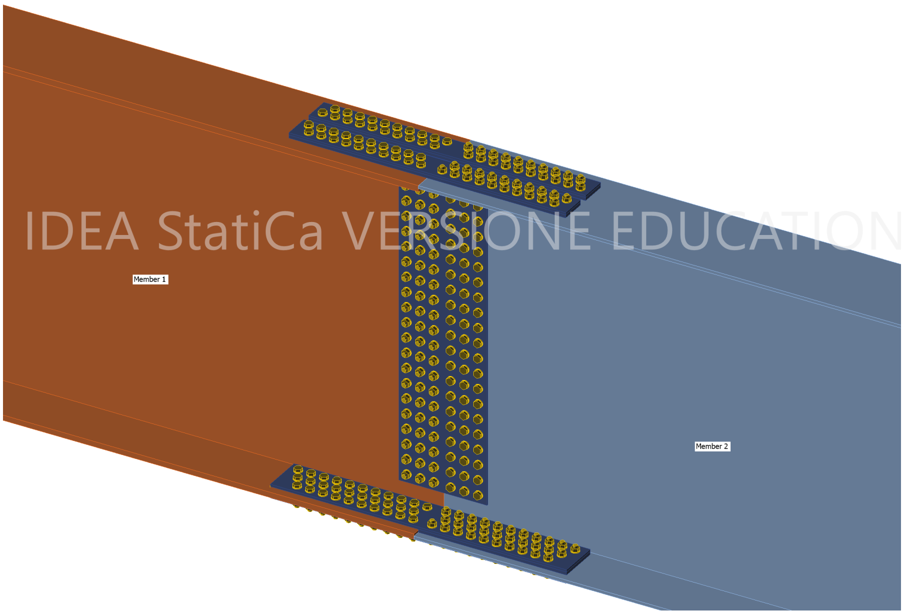


Figure 4.31: Exported connection in Idea StatiCa

4.4.2 Interoperability issues

Definition of a valid custom component

One of the most important problems that the author want to remark is one regarded the definition of a custom component that has to be valid and recognized by the software for structural analysis. It is not possible to export a connection if we do not define a correct custom component in Tekla Structures.

To realize this point it was necessary to model another time the joint, realized before, because some changes were needed by the structural analysis software. A splice plate component, as the one which was modelled, can be defined in Tekla only modelling in a certain way. If some modifies are not made correctly, the analysis will go wrong. It was necessary to define some other plates to obtain a good model ready to be analysed. For instance, to reach this goal, it was essential to divide some plates (particularly wings bolted plates) with a depth of 35 mm in two plates, one of 20 mm and another one of 15 mm. This exigence related to the structural analysis was solved only making some attempts that had cost the author a great amount of time.

It is note easy trying to explicate this type of criticism without having the structural analysis software in front of us: it was possible to discover it only once that the first local structural analysis was ran.

Moreover, Idea StatiCa, inserted all the effects of loads calculated, does not allow to run the analysis if elements positions are not correct, that is they are not positioned accurately, with an accurate of mm. For instance, if a bolt is near to the plate edge, FEM analysis does not start (figure 4.32).

Substantially, the program does not permit the analysis if it is not able to recognize the connection as something that is contained in its library.

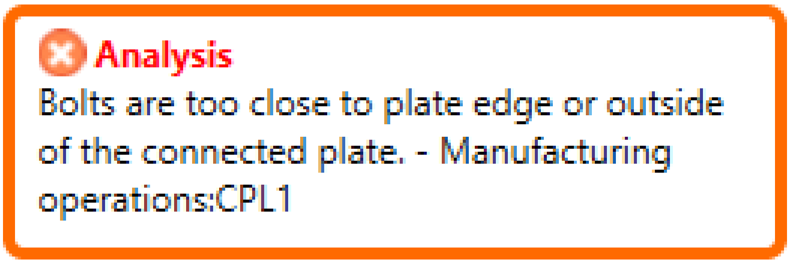


Figure 4.32: Bolts are too close to plate edge or outside of the connected plate

This identification issue, actually, represents also an advantage: if an engineer does not have any experiences of modelling, it can understand immediately if its connection respect some geometrical parameters and has not committed some rough errors related to his inexperience about modelling in a BIM software environment. On the other hand, often, this excessive precision in positioning and about recognizing could compromise the workflow making it more slow and intricate.

Plates 5, 19, 20, 21

This problem was underlined in the previous subsection, but the author has decided to speak more about it because its definition represents something that comes to eyes easily. Moreover it is contained and shown another time in the report and in the material itemized list (extracted directly from the software). Plates 5, 19, 20, and 21 are not correctly defined and exported, but they are necessary to obtain stresses of the node. It was impossible for the author to solve this type of error, it represents probably the big limitation of this direct link between Tekla Structures and Idea StatiCa.

Rounding plates

Another important point that the work wants to focus is about plates and their geometry. It was impossible to realize a model exactly corresponding to reality, rounded parts of plates were not recognized by the structural analysis software. Probably, this error occurs because to generate a cut in Tekla Structures, the software creates automatically a cut plane that cannot be exported. This is a limitation of the plugin but, it does not affect the entire structural analysis, the author has decided to omit their presence and continue the work.

Chapter 5

Modelling and structural analysis on calculation software

In this chapter all the topics linked to the structural analysis will be discussed, showing which adjustments were necessary to reach a first level of bridge analysis.

The analytical model will be exported from Tekla Structures and imported in SAP2000 and Midas Civil, some checks will be made (about the analytical model and about the effect of loads, understanding if the results of loads have or not a correct magnitude.

After that the overall LOD has been increased, stresses in the biggest node (joint 4) have been calculated with a Idea StatiCa using a FEM software.

5.1 SAP2000 v20

The final analytical model obtained, with all the adjustments described in the previous chapter has been controlled, making some checks on the structural elements weight. Particularly, to obtain a goods analytical model it is opportune that all the elements result merged in only point; it means that beams have to flow into single points and all the model have to be correctly connected in terms of structural engineering.

To verify if that the analysis model is correct, it is opportune to check if elements deformed shape is qualitative correct or not. Once that this simple visible check is verified, it will be opportune a control about the magnitude of stress effects, understanding if the model imported is correct or not and if the analysis has sense in terms of structural meaning.

5.1.1 Operations on structural analysis software

Some operations were needed before performing the structural analysis. All this important points will be reported in this section, solving criticisms that will not allow to run the analysis. Nowadays, it is not possible to reach a model that, once its exportation is finished, is completely ready to perform an analysis. Some adjustments it will be necessary, but they have not to affect the entire workflow.

Rigid-zones

The first check made, as partially said in the chapter dedicated to interoperability, was about the lack of connection between axes of modelled beams.

To solve this point, rigid frames were created to merge all the elements in a way to perform a first simple structural analysis.

Specifically, speaking about the inferior bracing system and the transversal bracing system, a rigid-zone was created, allowing the connection between unconnected beams. This point was necessary because, running the analysis, this elements present an important deformed shape, surely symptom of a bad analytical model (figure 5.1). Rigid-zones were not applied immediately, some attempts performed have defined the right path to find a solution avoiding an excessive deformed shape of these kinds of elements. The final solution applied is the one represented in figure 5.2, it is the rigid-zones deformed shape after loads application.

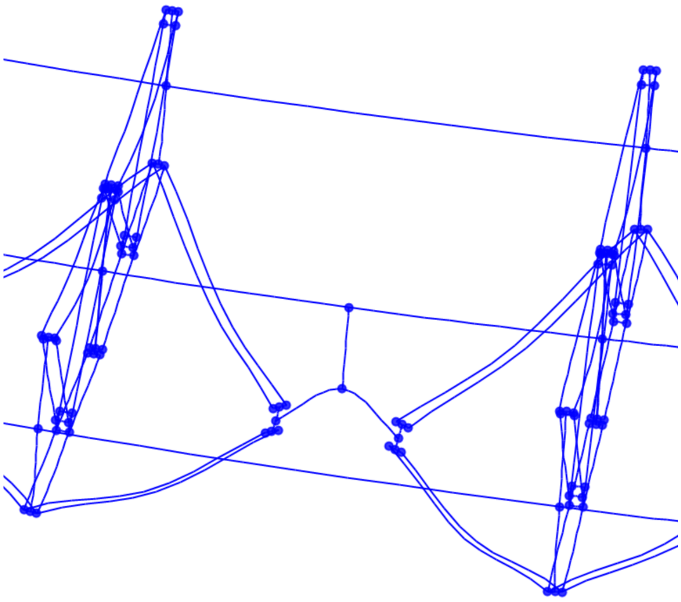


Figure 5.1: Bad rigid-zones definition and application - SW Deformed Shape

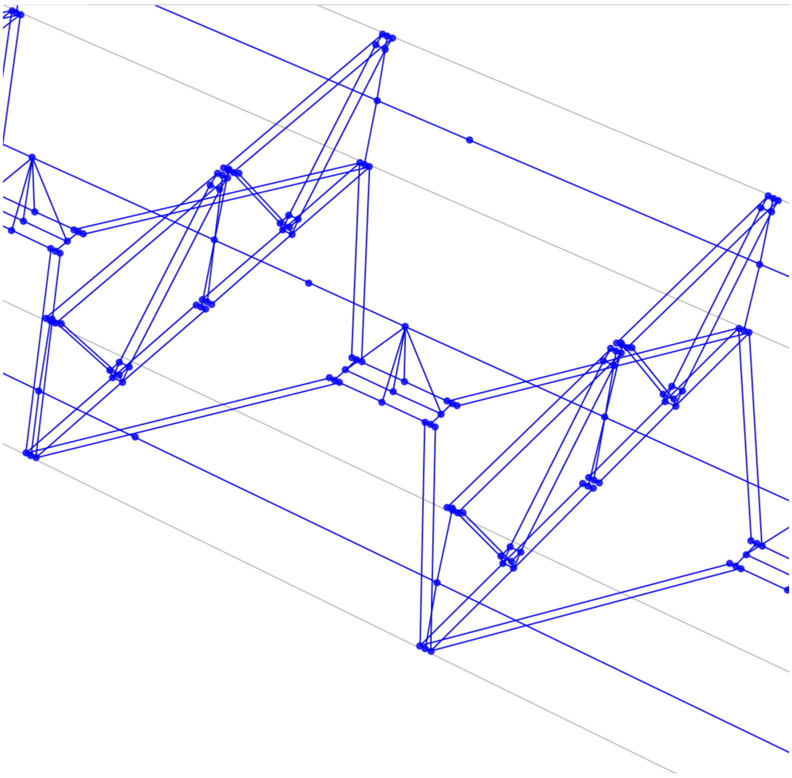


Figure 5.2: Good rigid-zones definition and application - SW Deformed Shape

Boundary conditions definition

It was necessary to introduce information about boundary conditions. The decision of inserting them in the structural software was the result of two different reasons; the first one is that the IFC file format does not allow to transfer this kind of data, so it is not possible for information technology reasons. The second one is not related to software possibilities but taken to speed up the entire workflow. One of the aim of BIM methodology is to solve problems related to efficiency of the design process, so the author decided to exploit the structural software to speed up this part of the workflow. An input of this information typology has not a great contribute about timings.

Boundary conditions were inserted in SAP2000, setting the displacements fixed considering the position of supports insertion (abutments and pile present different necessities).

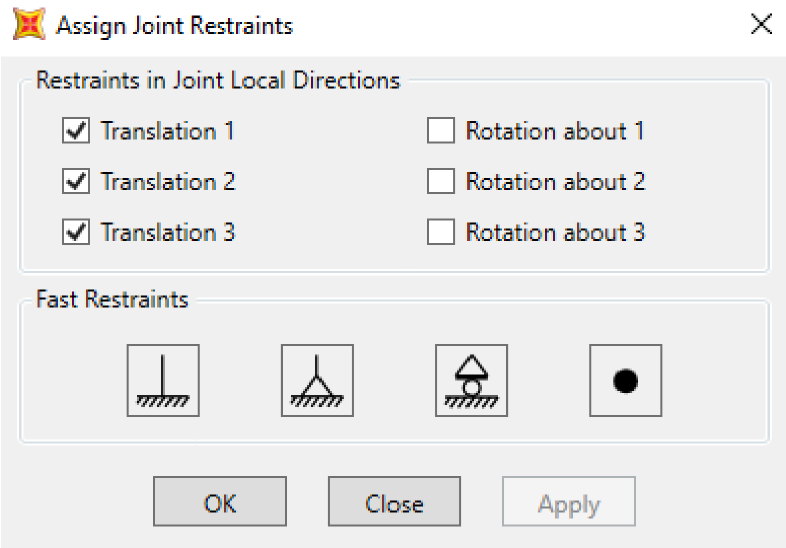


Figure 5.3: Assign joints restraints

How the image 5.3 clarifies, this assignation it is obviously made to joints and not to frames.

5.1.2 Structural analysis

The analytical model obtained, once that all the modifies were taken, is shown in figure 5.4.

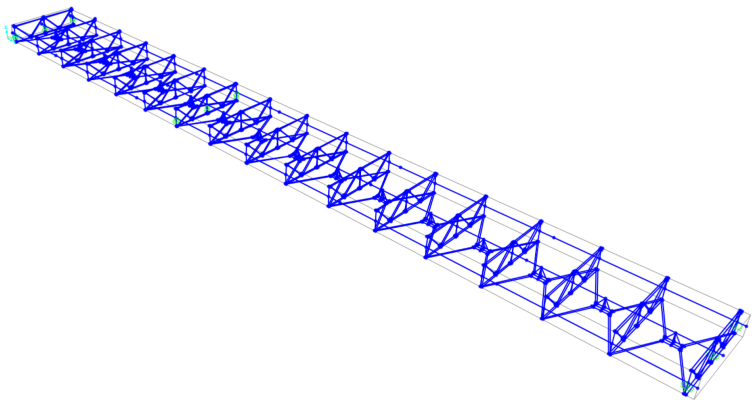


Figure 5.4: Final analytical model

After that all the criticisms were solved and interoperability problems fixed (or partially fixed) a first structural analysis was ran, using only the self-weight of elements.

To set this it is necessary to click on the run button that allows to run the analysis. Then it will appear a dialogue box where it is possible to set load cases that users want to run, considering the work necessities.

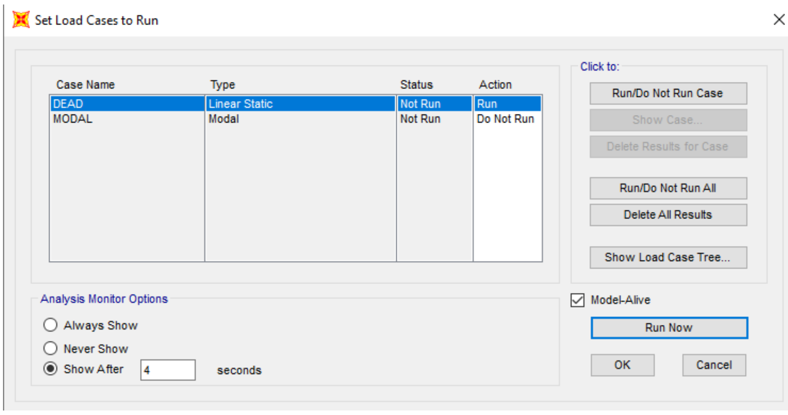


Figure 5.5: Set load cases to run

Once that this setting are completed, finally, it is possible to run the analysis and check the structural results.

Effect of loads - Self-Weight

The first structural analysis was made considering only structural dead loads effects, substantially the self-weight of steel beam elements.

A first check that it is possible to make is a qualitative one, about the deformed shape of the bridge. In the studied case, it seems qualitatively correct, confronting it with the one obtained in Midas Civil (displayed in the next session dedicated to this software), and using the author personal background about structures developed during the structural civil engineering studies.

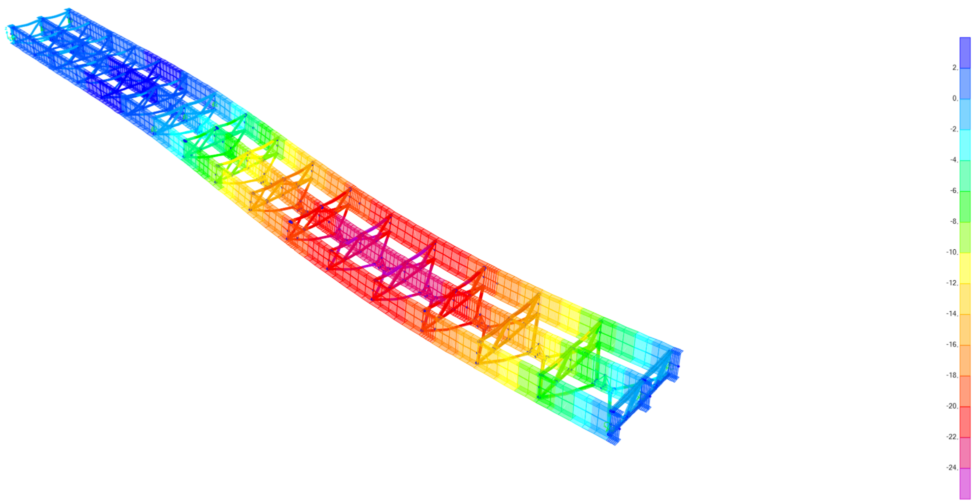


Figure 5.6: Bridge deformed shape

Therefore, it will be displayed the self-weight loads effect on the main girders of the bridge; it will be displayed the bending moment (M3) and the shear (V2) diagrams of main girders (figures 5.7 and 5.8).

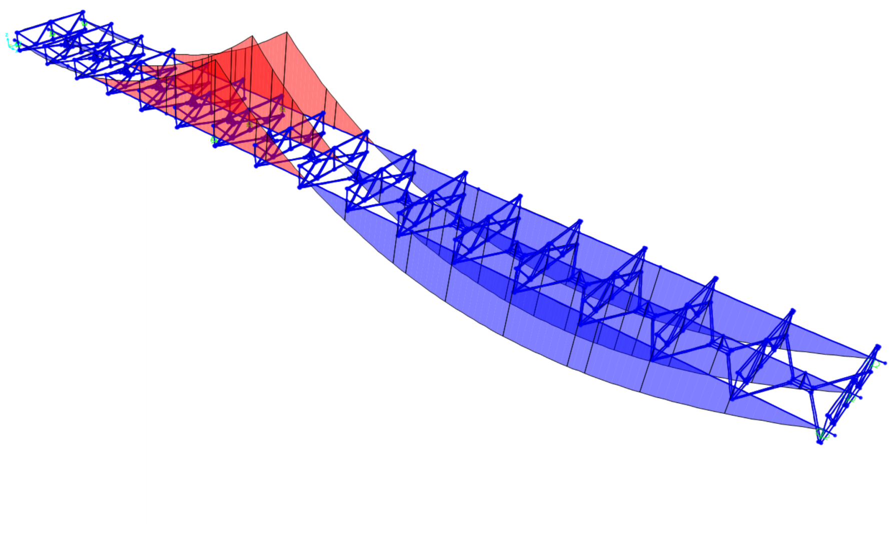


Figure 5.7: Bending moment on main girders, M3

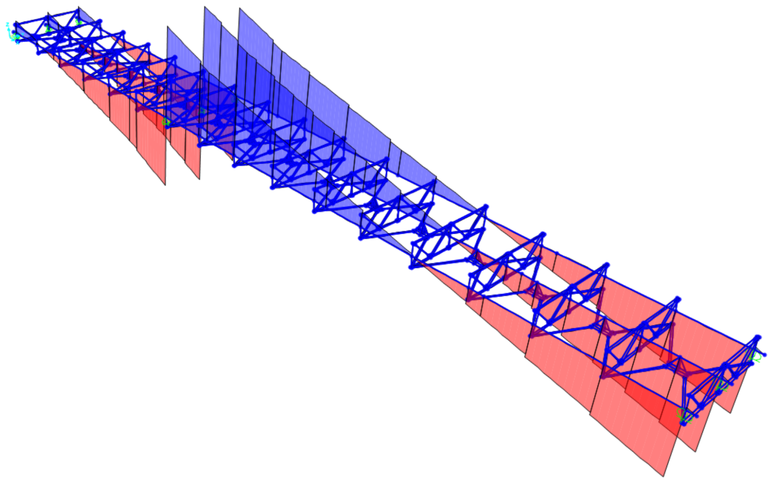


Figure 5.8: Shear on main girders diagrams, V2

In figures there are some values for bending moments and shear to understand the magnitude of values obtained. It is possible to interrogate frames and evaluate the shear and moment value in a points. Two screens will be reported, one for the maximum negative moment (on central support) and one for the maximum positive moment at the second midspan centre.

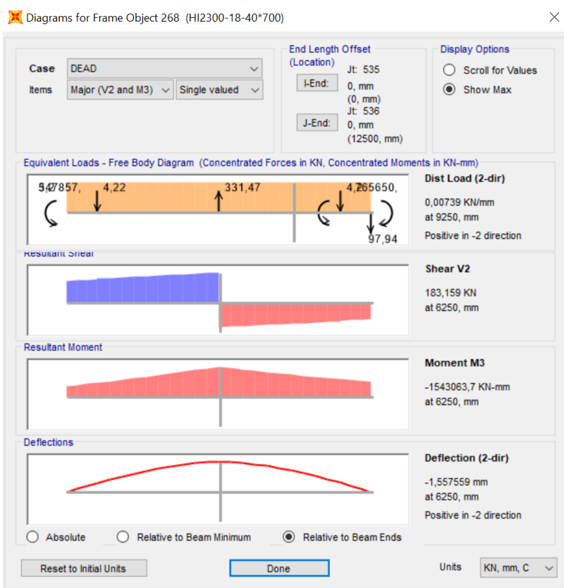


Figure 5.9: Diagram for frame 268

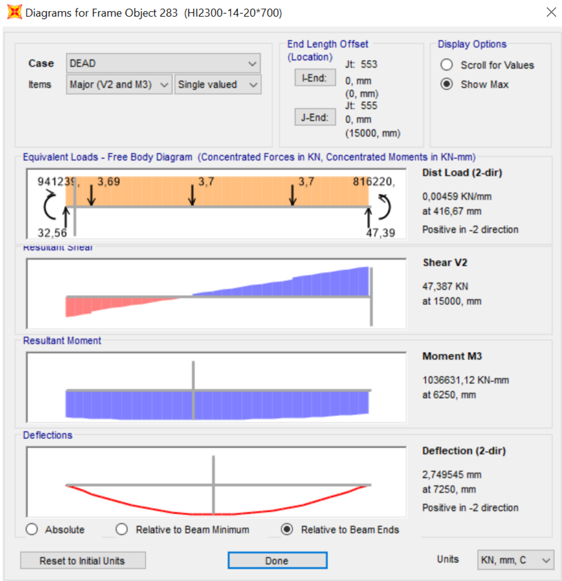


Figure 5.10: Diagram for frame 283

To understand in a better way the development of bending moment and shear, it is possible to extract and export from SAP2000 values of forces in a excel file format. It is opportune to set only the results that we want to export, because the information contained in our model are many and not all indispensable. This is the output selected to obtain the following report on excel.

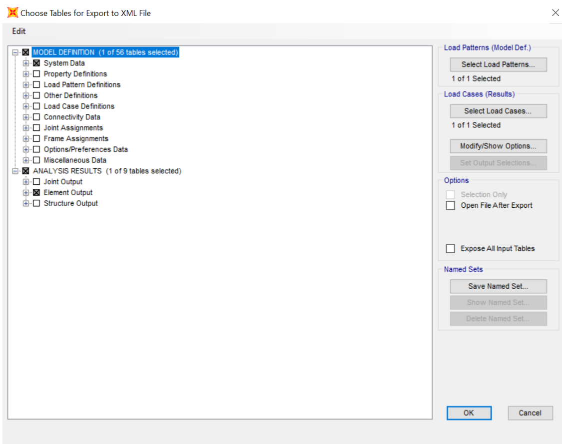


Figure 5.11: Choose tables for export to XML file

After selected these option many results are obtained in a excel file format. How it is easy to understand in the print of image 5.12, too information are contained and not all of them are useful to a structural analysis.

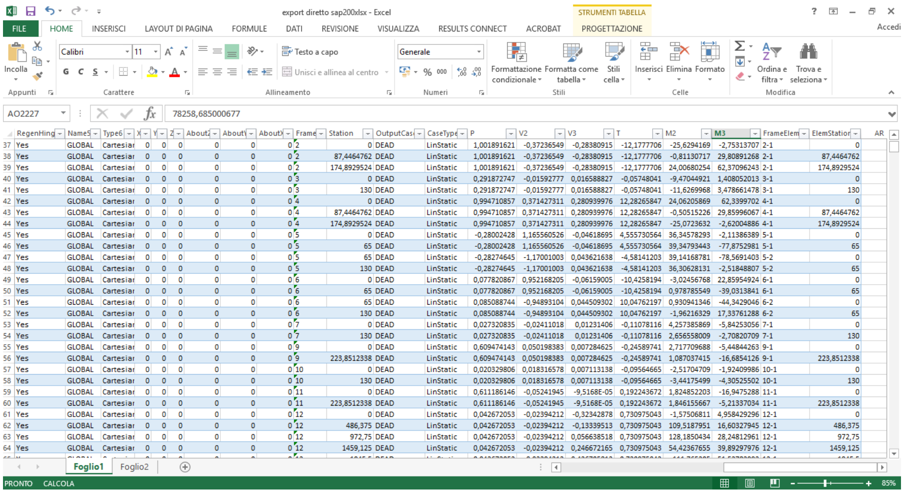


Figure 5.12: Export from sap2000, XML file

To obtain graphics of loads effect, it is opportune to find in the XML file, the information needed; the author has decided to select one of the side-beams, checking frames that compose its analytical model and then exporting information to obtain graphs for shear and bending moment.

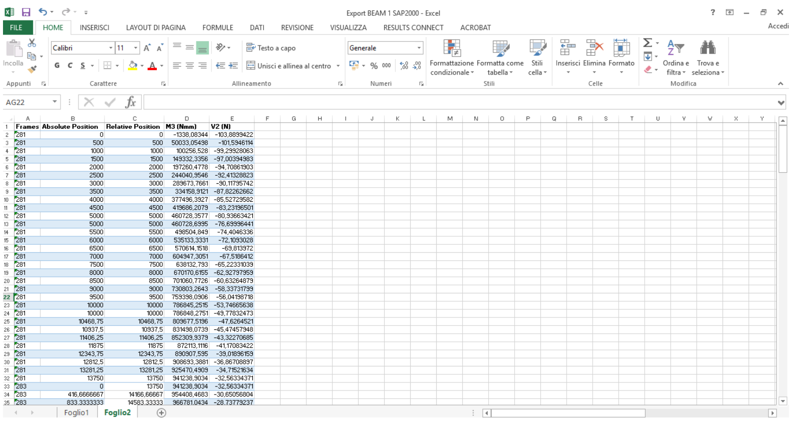


Figure 5.13: Ordered values of frames: element, position, moment and shear

Finally, two graphs will be shown, for bending moment and shear obtained in excel. An excel output represents a good opportune that software for structural analysis offer in case an civil engineers want to personalize their results. Obtained graphs will be here displayed.

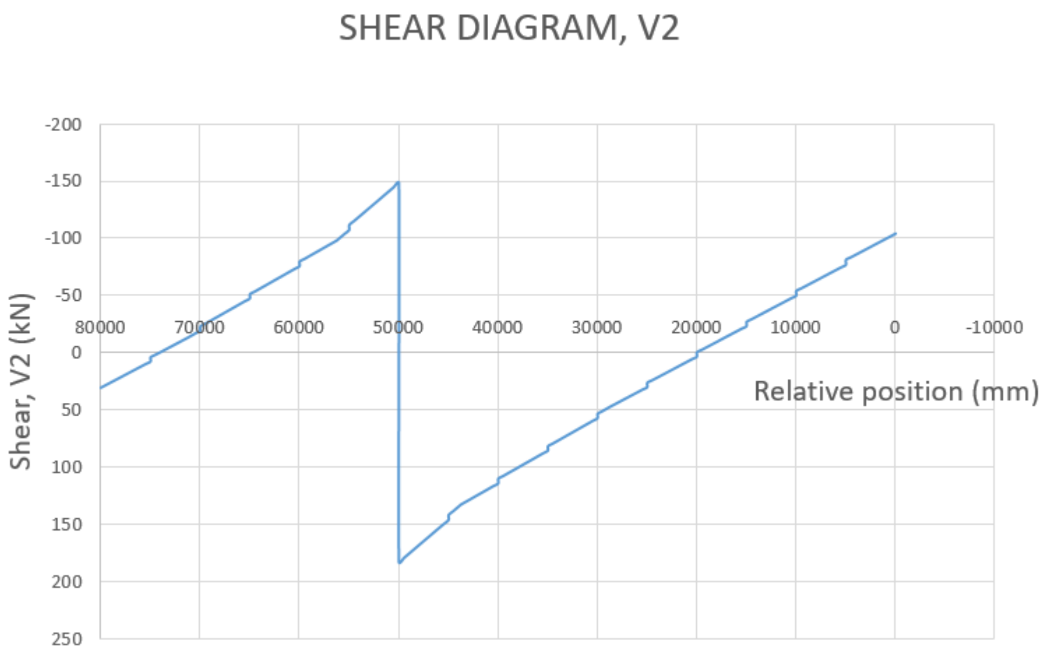


Figure 5.14: Side beam shear diagram

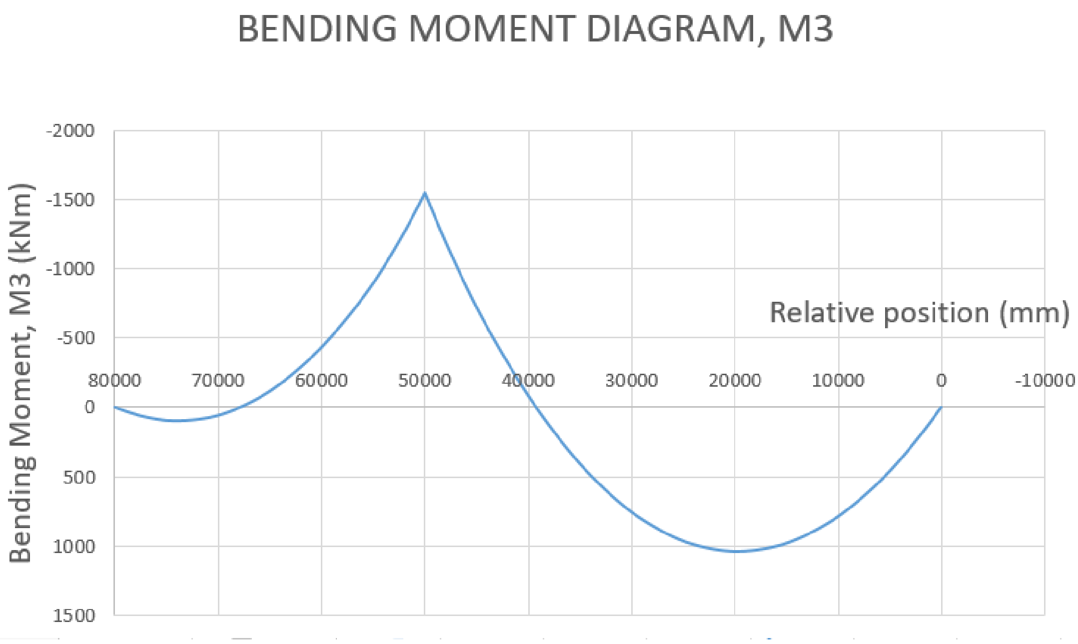


Figure 5.15: Side beam bending moment diagram

Consideration on structural analysis

Once that a first simple analysis considering only the self-weight was performed, the correctness of results obtained was checked. It is important to have an idea about the magnitude of stresses, such to obtain efficient results in terms of structural analysis. The loads effect magnitude has to be correct, only in this way the results make sense and can be used to solve design problems.

It was decided to solve a simple beam on three supports (two abutments and a pile, as the bridge is developed), to understand if the magnitude of loads is or not correct. The attitude of a structural engineer, that is not only a modeller, is to understand if the analysis and its analytical model are correct or present errors.

It was decided to solve this problem manually for a reason; it is important to understand that software have to be only a support to the work of engineers, they do not substitute them. A fundamental basis is to remember which is the traditional way of solving structures, understanding if problems they have solved are correctly brought to the end.

In the following prints shown in next page there are some approximate calculations that the author has done to understand and verify that the order of loads effects magnitude is correct. A statically indeterminate beam under the effect of a distributed load was considered. The value of this load comes from the biggest main girder section area of the bridge multiplied by steel weight. Therefore, the beam was solved using notion of structures theory about resolution of hyperstatic beams. Clearly, the results obtained do not correspond to the ones found using the structural analysis software. Only a beam section was considered, completely ignored the weight of bracing systems (although their contribute will be small); this very simplified manual model resolution allows to understand if important rough errors a present, an efficient manual check.

As it possible to understand seeing the following figures, magnitude values are correct and the tendency of these diagrams too. So, the model work and it could be exploited to realize a more complex structural analysis, using loads combination defined by legislation.

Nevertheless, it was decided to abort here the work using SAP2000. Reasons about this decision are connected to the complexity of interoperability problems confronted: these errors related to the way between software communicate each other do not allow to reach a good level of interoperability that permits to speed up and make easier the entire workflow. Definition of rigid frames, application of new rotation to local axes are all operations that represent an obstacle, especially when structures are more complicated. Moreover, being impossible to modify the analytical IFC model in the software for model authoring, all the operation have to be executed on the software for structural analysis, vanishing partially the aim of interoperability, that is the same InfraBIM methodology core point.

A more deepen analysis about this decision will be shown in the next chapter, where interoperability results in terms of structural analysis will be shown.

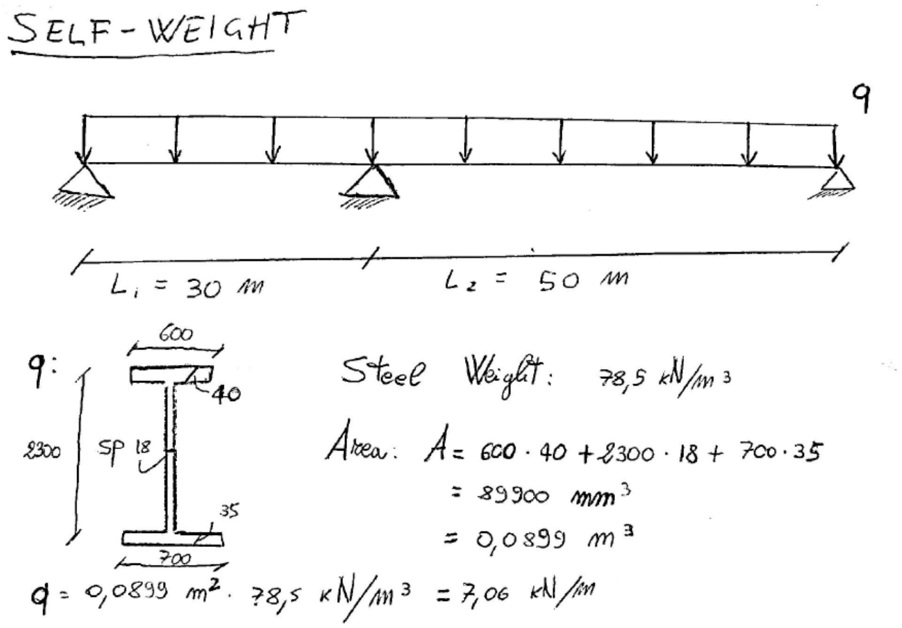


Figure 5.16: Print of hyperstatic resolution 1

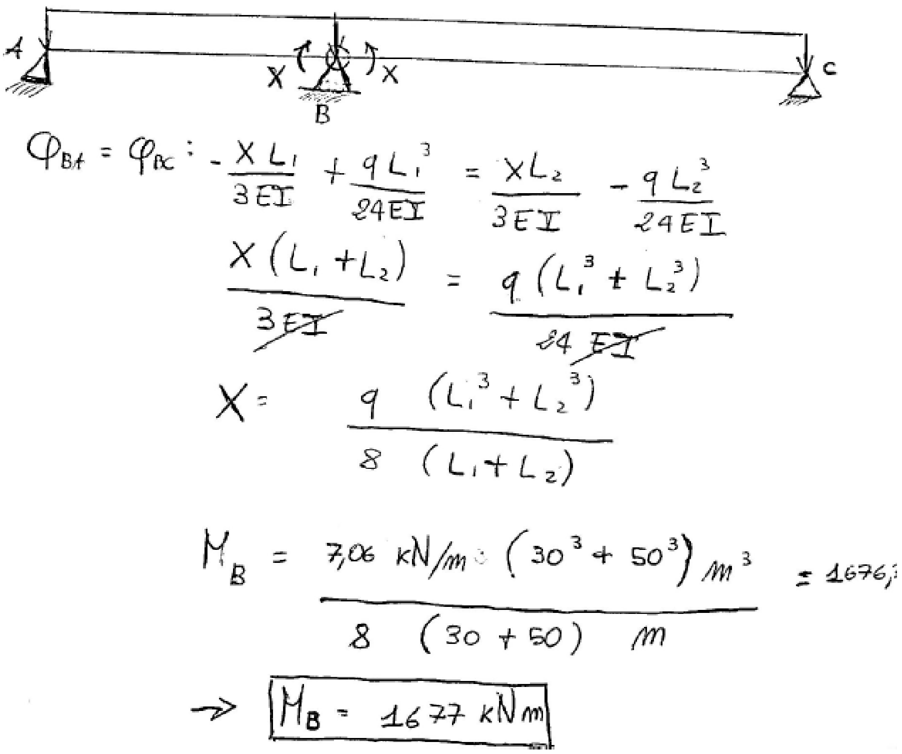


Figure 5.17: Print of hyperstatic resolution 2

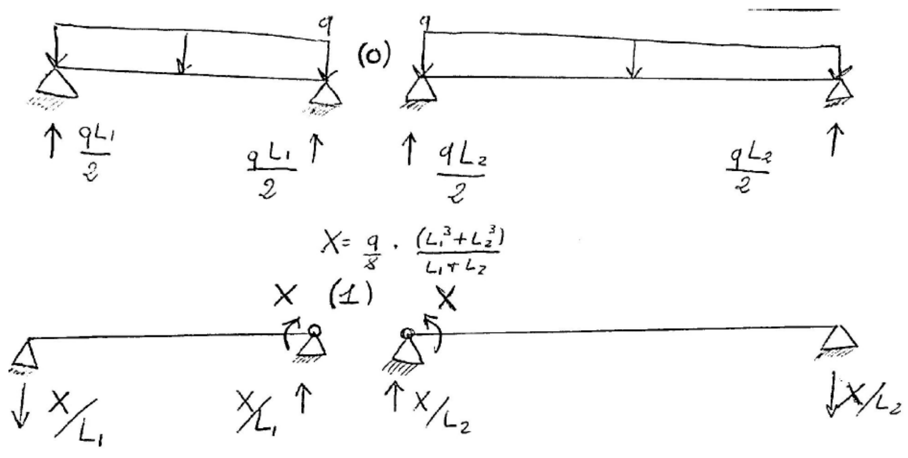


Figure 5.18: Print of hyperstatic resolution 3

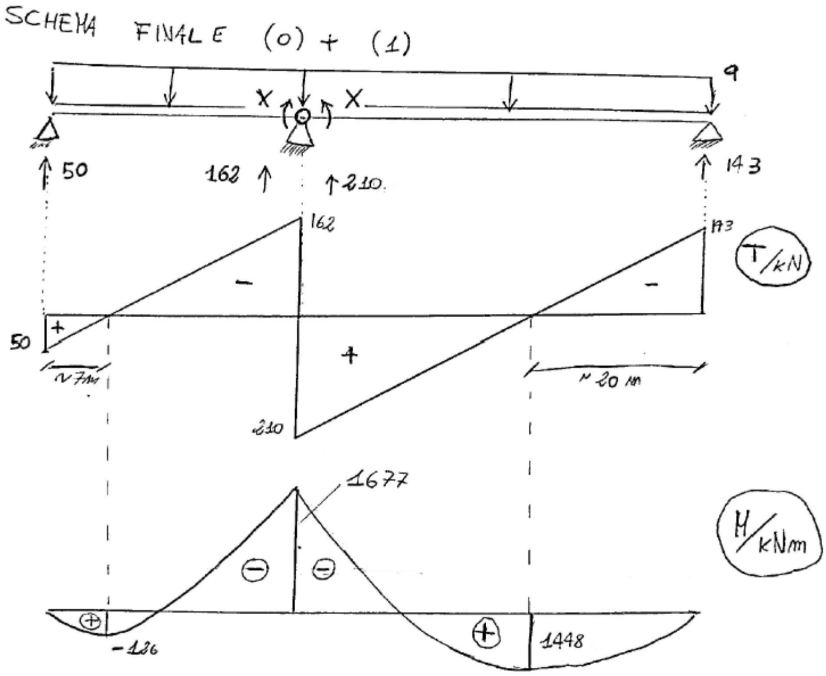


Figure 5.19: Print of hyperstatic resolution 4

5.2 Midas Civil 2019

The analytical model exported in Midas Civil contains all the adjustments taken in the previous chapter about interoperability problems.

To realize a more completed and structurally valid model it was decided to model the deck situated in the upper part too (as I have anticipated in chapter 3). The documentation does not provide information or geometrical data about this part of the bridge, so it was decided to model the deck creating three concrete beams in Tekla Structures, one for each steel beams, with some specific dimension. This is clearly a simplification of the real bridge, to create a better model it will be opportune define solid elements that are analytically not defined by only an axis. This kind of approximation taken allows the author to save time in second part of analysis about the definition of load. Moreover, although the information received about the bridge was referred only to the steel carpentry, structurally speaking it would be correct consider the structure as a composite structure of concrete and steel.

It is possible to define a composite structure of this type(if we want to realize a data exchange), both in Tekla Structures that in Midas Civil, but there is not a way to communicate this information inserted; probably this point has been completely solved in the last version of Tekla Structures (2019) that pays more attention to bridges (BRIM Information Models).

The two following images represent the model exported from Tekla Structures: one is the structural model and one is the referred analytical model defined in the Analysis and Design dialogue box (figures 5.20 and 5.21).

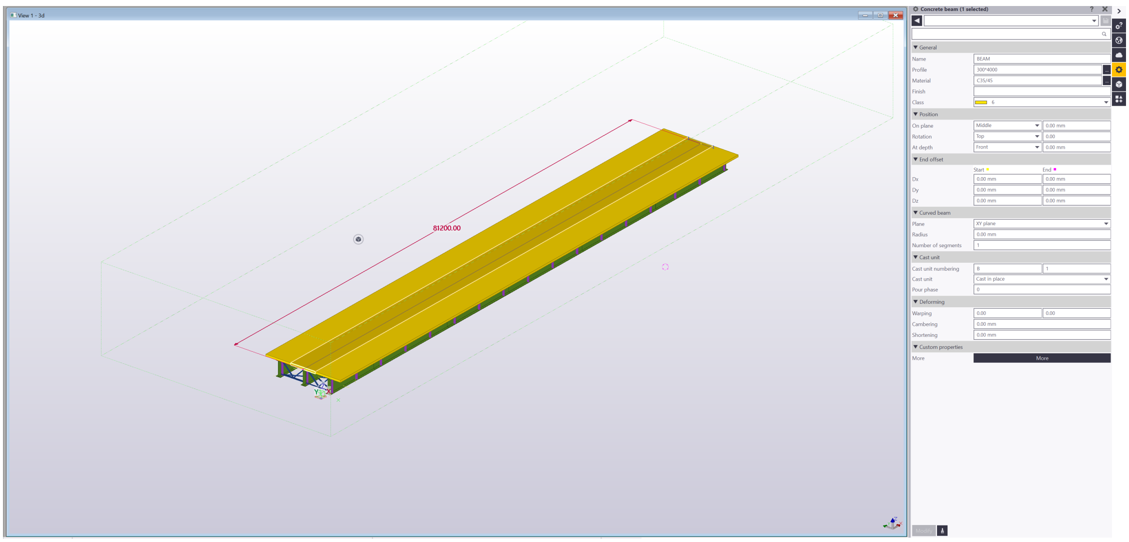


Figure 5.20: Final model exported from Tekla Structures with concrete deck (concrete beams)

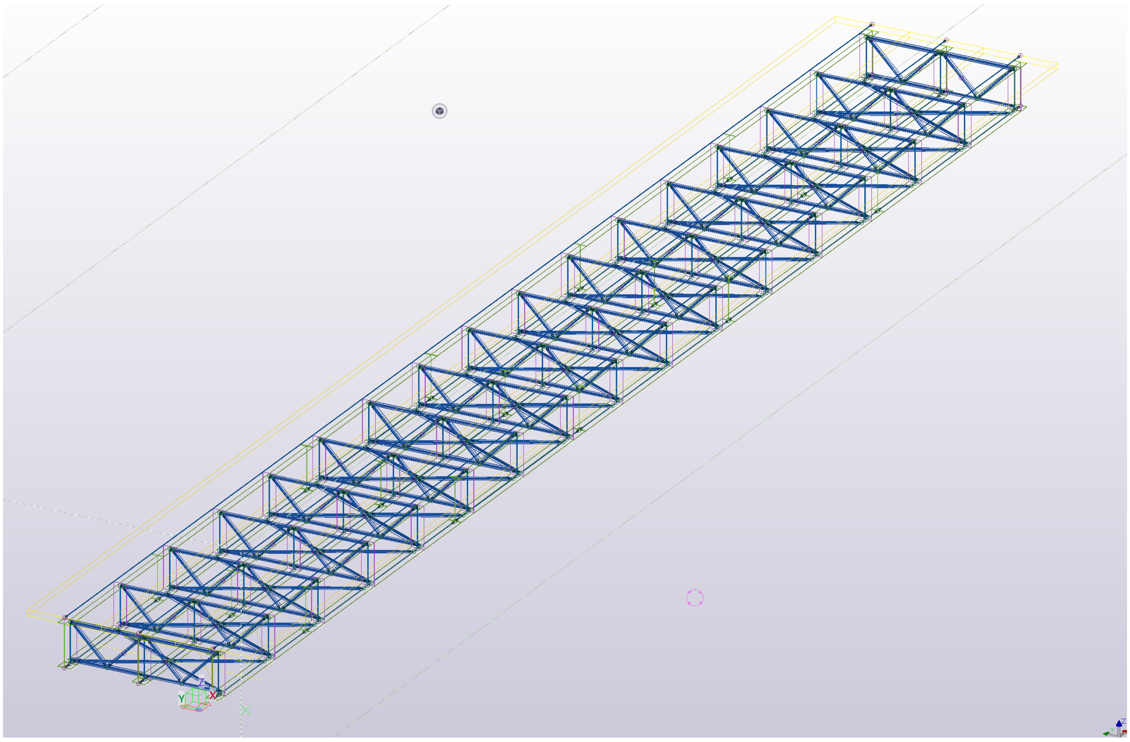


Figure 5.21: Final analysis and design model

In this following image there is the model imported in Midas Civil; just with a rapid look to the model we can understand that the interoperability level of direct link overcomes the one reached with the IFC file format.

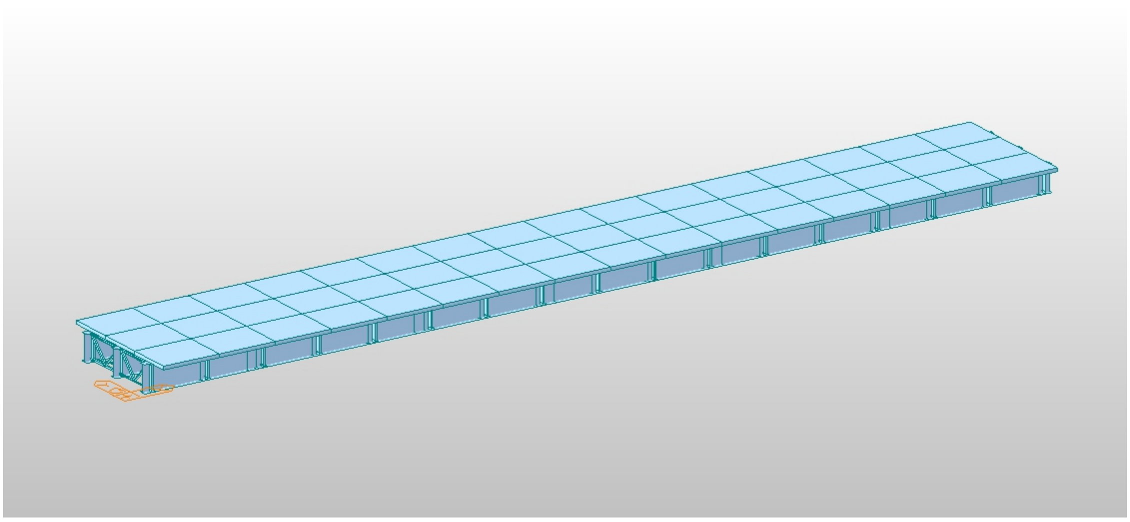


Figure 5.22: Imported model in Midas Civil

Looking the analytical model, it seems efficient; some adjustments are needed but they will not take a great amount of time. All these operations taken in Midas Civil will be reported in the next subsection.

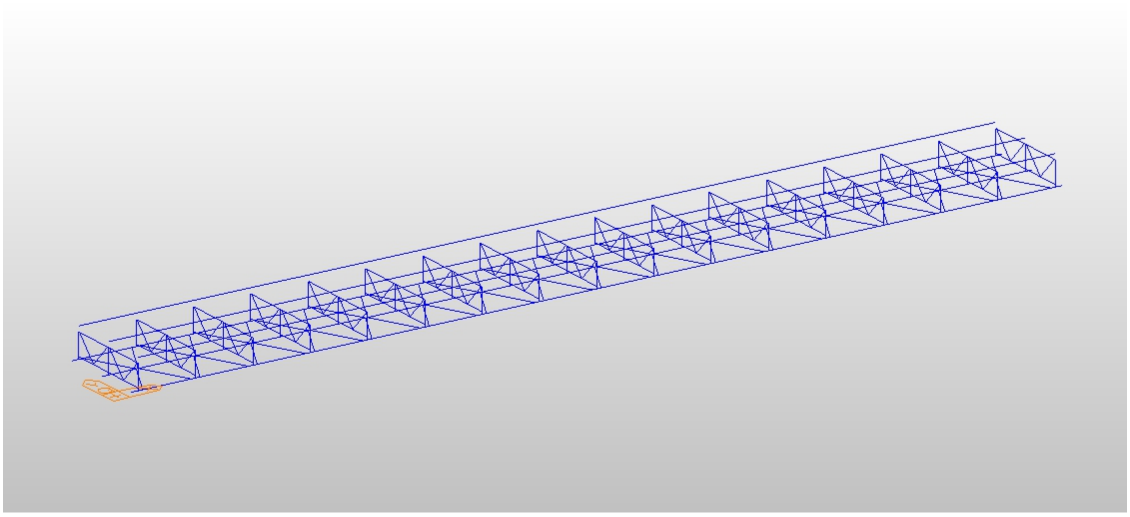


Figure 5.23: Imported analytical model in Midas Civil

5.2.1 Operations on structural analysis software

Analytical model checking

A first check was made about material and section of the bridge, verifying that all the exported objects were correct. It was necessary to modify some twin beams of the inferior bracing system that was imported as single beams, but this operation did not cost a great amount of time.

Moreover, as anticipated in the section dedicated to interoperability problems, user-defined main beams, have been modified: the profile subtype containing all the correct dimensions was not exported and so it was necessary to insert dimensions of wings in the structural analysis software (figure 5.24). Nevertheless, also this simple operation do not cost the author a great amount of time, it is a simple criticism that even a beginner modeller can made after a short time.

The last report that it is essential to make about this first checks on the model is that Midas Civil allows to change the offset, that is the position of beams axes (like it was possible in Tekla Structures). Modifying this setting it is possible to recreate the analytical model following and respecting structural engineers exigences.

To make this is sufficient to open the beam property window and then clicking on change-offset dialogue box (figure 5.25)

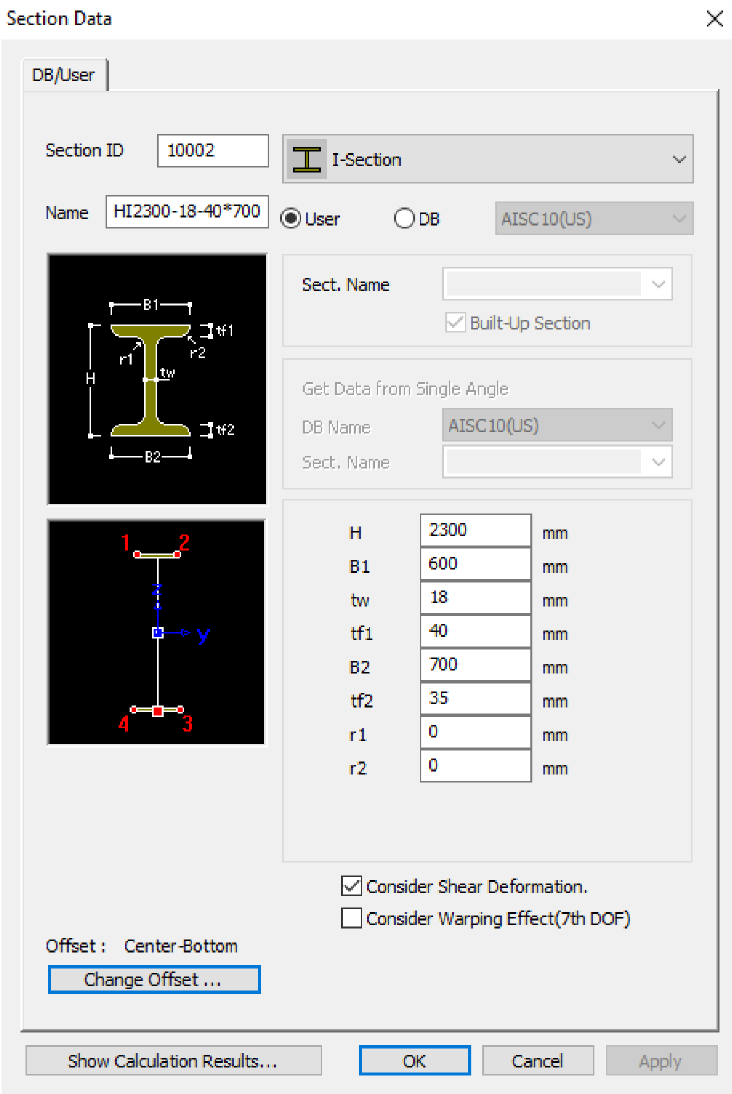


Figure 5.24: Section data properties

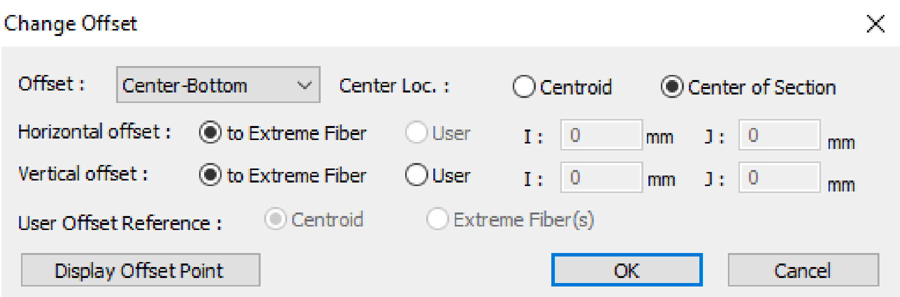


Figure 5.25: Change offset

Rigid Links

The definition of rigid links allows to connect elements that are separated in the analytical model in a way to perform the analysis.

Midas Civil allows to define simply rigid links between elements, selecting displacements and rotations that users want to lock. Being these composite structures, a rigid link was defined locking all the consented movements (this decision it will affect some structural analysis results).

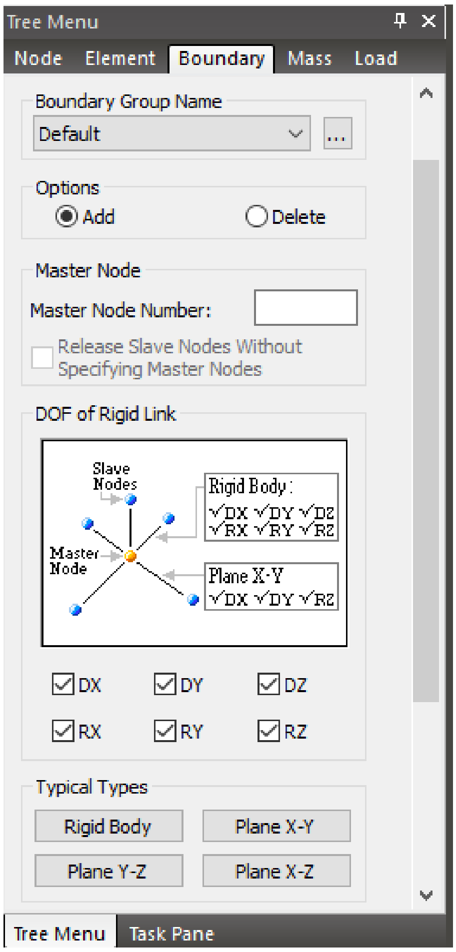


Figure 5.26: Rigid links definition

The insertion of rigid links was simply, it was only necessary to insert the first line, then the software allows to repeat the operation every time the user wants. This simple insertion option has allowed to save time, it was not necessary to define a new section as done in SAP2000, a great advantage offered by this software solution. The final result displayed is shown in figure 5.27.

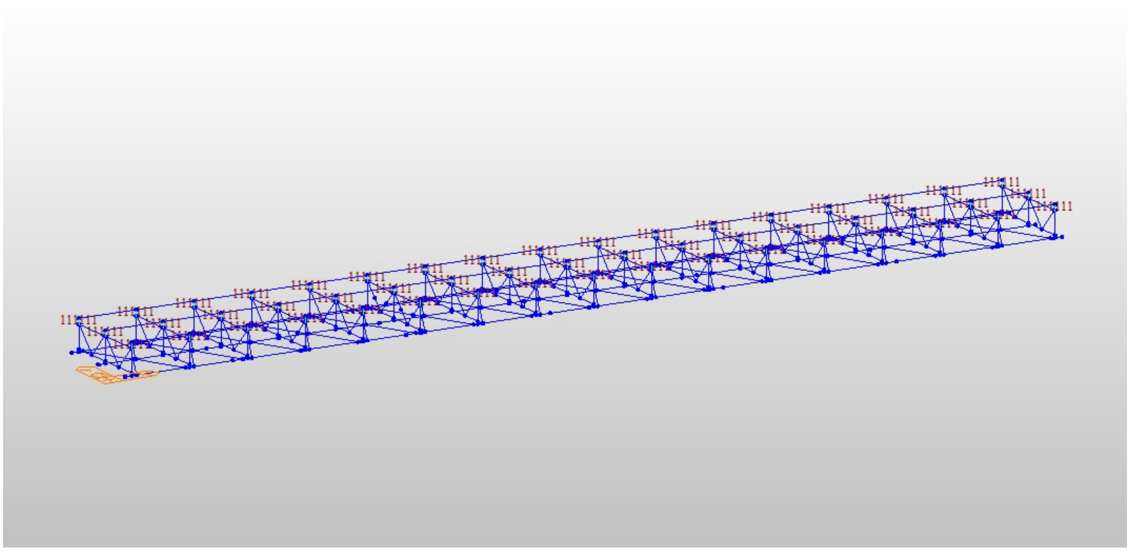


Figure 5.27: Rigid links displayed

Boundary conditions

As said in the section dedicated in Sap2000 for boundary conditions, they were defined in Midas Civil too; this reason was related to the same one made in that section. Infra-BIM methodology aim is exploiting more than one software solution, giving an help to engineers. Nowadays, being not possible resolution of problems by using only a software, it is possible to entrust to more than one program, exploiting their possibilities. To increase the process efficiency is good make operation related to structural analysis in the software dedicated to it. For this reason, the boundary condition definition and application was made in Midas.

Boundary conditions were inserted creating three new points under the beam axes, respectively for the two abutments and for the pile. Then every point was connected with beam inserting an elastic link, type rigid. This decision was not studied, however it was suggested me by software guides found in Midas Civil warehouse.

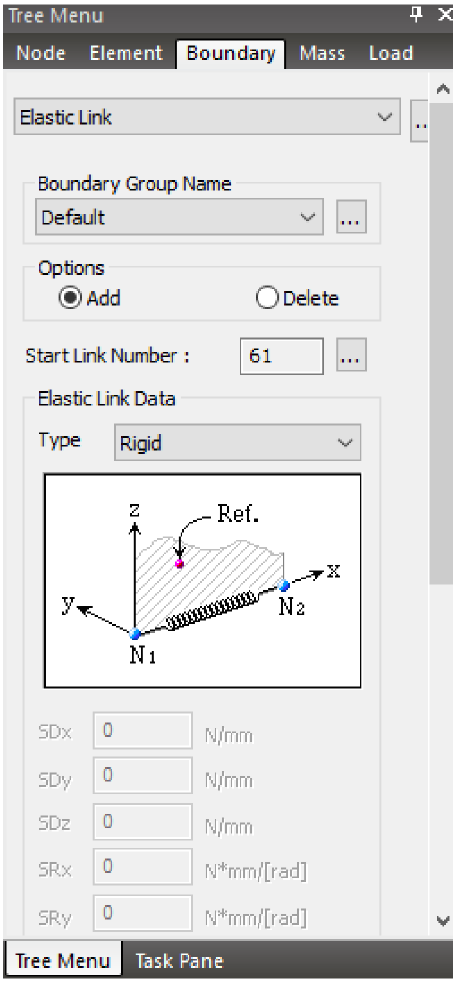


Figure 5.28: Elastic link definition

Once that all these elastic rigid links were created and inserted correctly, boundary conditions were applied: consented or not displacements were define respecting the position that have these points.

For abutments, on side beams were placed supports with fixed displacement on z, for the central one z and y. For the central pile, on side beams were fixed displacements on z and x, for the central on x,y and z.

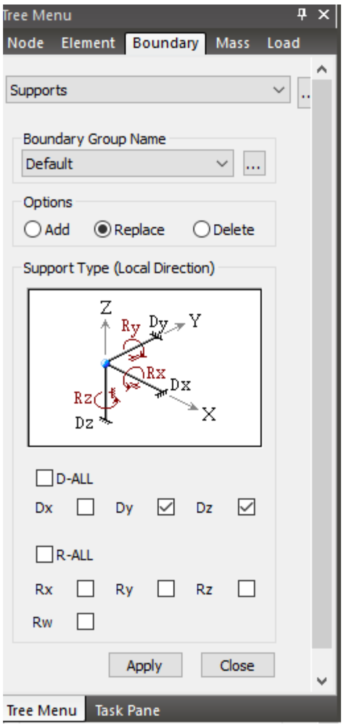


Figure 5.29: Support conditions definition

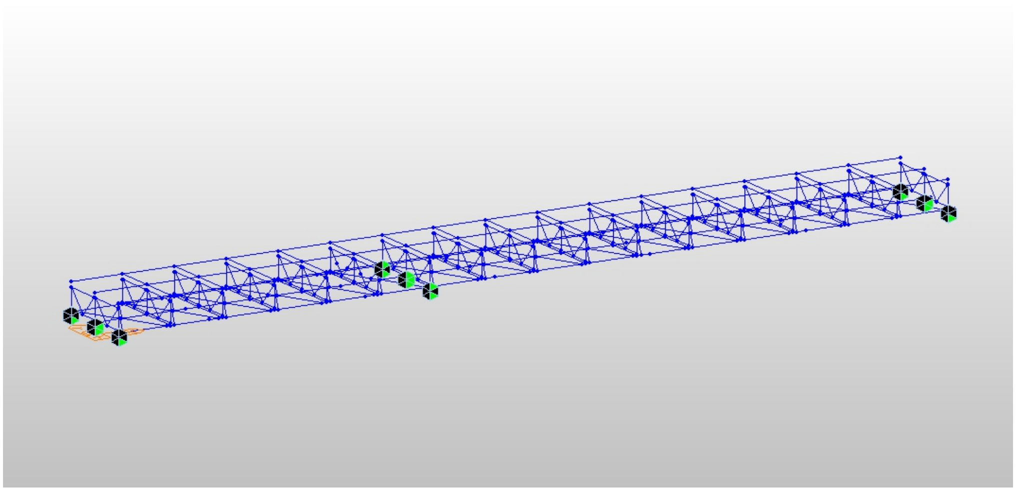


Figure 5.30: Model with boundary conditions displayed

5.2.2 Loads application and structural analysis

Static loads definition

Three Static Load Cases were defined in Midas Civil, considering different dead loads and following indications found in NTC2018 [5] about loads classification.

The first one is the self-weight of elements, imposing the gravity direction (-1, multiplied for the element weight calculated automatically by Midas Civil).

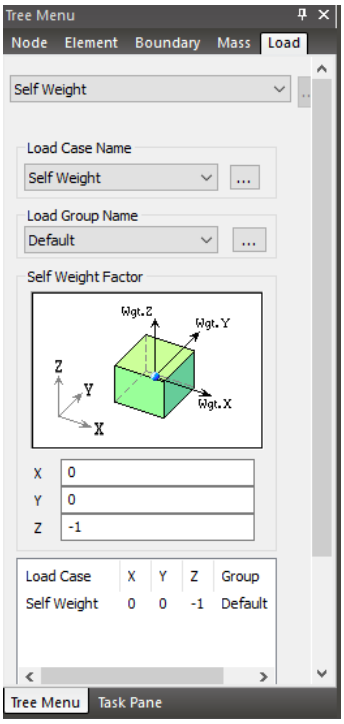


Figure 5.31: Self-weight definition

The second-one inserted is the load case related to the weight of parapets loads (figure 5.32). Load as a "Element Beams Load" were defined in Midas Civil and inserted the load value. Clearly, being these elements situated on the side of the bridge, the load was inserted only for side-beams.

Finally, the third one is the load related to pavement (figure 5.33) of the bridge. This load was defined too as a beam element load, making an important approximation, even because documentation did not contain information about the roads pavement. It was decided to insert a load defining it using these criteria: weight of pavement 23 kN/m^3 , and a thickness of 10 cm and a width of 8 m. Then it was divided the load, inserting a bigger contribute in the central beam, and lower contributes in the two side-beams (remembering always that this is a global test about a new methodology of work). Surely, the best option to define this typology of load is to create a floor load, but the insertion it will have been more complex (being an imported model and not a generated on the structural analysis software). Although this is an error that can affect accurate of the model, the aim of this thesis is defining a methodology for structural analysis, so this approximation can be considered valid.

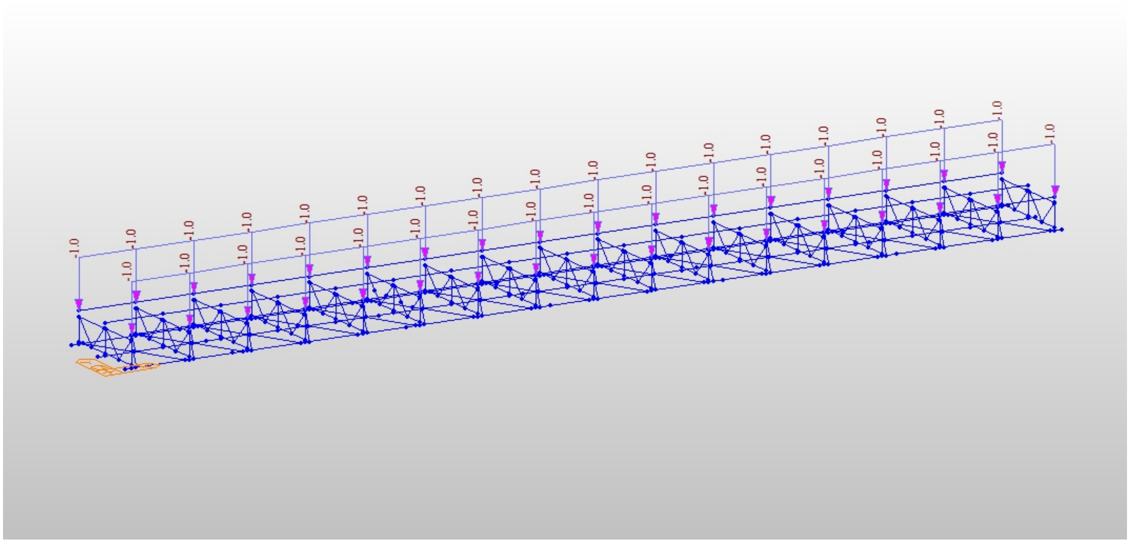


Figure 5.32: Parapet load

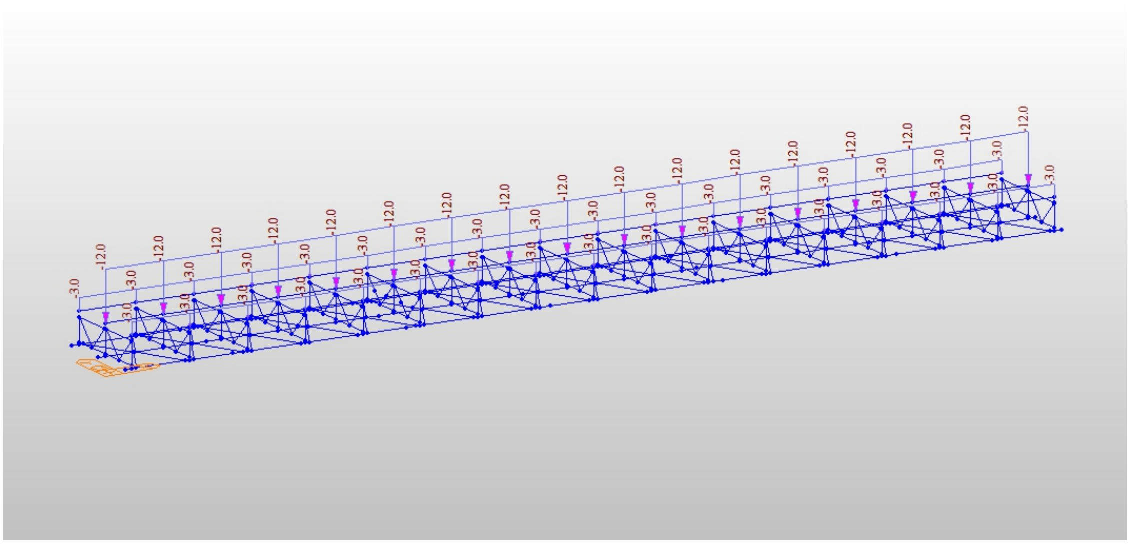


Figure 5.33: Pavement load subdivision

Moving loads definition

Before defining and applying traffic load, it was made a reference to the chapter 5 of NTC 2018 [5], the one dedicated to bridges; it is important to take always reference to the legislation active in order to define a valid scheme of loads.

In the subsection 5.1.3.3 there are defined vertical traffic moving load, Q1.

Widths of conventional lanes on the vehicle accessible roads and the maximum possible number (integer) of these lanes are indicated in the following prospect.

Fig. 5.1.1 - *Esempio di numerazione delle corsie*

Tab. 5.1.I - *Numero e larghezza delle corsie*

Larghezza della superficie carrabile "w"	Numero di corsie convenzionali	Larghezza di una corsia convenzionale [m]	Larghezza della zona rimanente [m]
$w < 5{,}40$ m	$n_l = 1$	3,00	(w-3,00)
$5{,}4 \le w < 6{,}0$ m	$n_l = 2$	w/2	0
$6{,}0$ m $\le w$	$n_l = \mathrm{Int}(w/3)$	3,00	$w - (3{,}00 \times n_l)$

Figure 5.34: Width of conventional lanes and maximum possible number
Source: NTC2018 [5]

The disposition and lanes enumeration should be determined in a way to induce worst design conditions. For each single design test the lanes number do consider loaded, their disposition on the vehicle accessible roads and their enumeration have to be chosen in a way that effects related to loads disposition result the most unfavourable.

The lane with the most unfavourable effect is enumerated as Lane 1; the lane which gives the next unfavourable effect is enumerated as lane 2.

For each lane design check and for each conventional lane are applied loads systems here defined for a total length end for a longitudinal disposition such to obtain the most unfavourable effect.

Variable traffic actions, comprehensive of dynamic effects, for this case study has been define by this load system, named load system 1 (5.1.3.3.3 [5]). This last is composed by loads concentrated on two axes in tandem, applied on pneumatic track in square shape and a late of 0,40 m, and by loads uniformly distributed as shown in figure 5.35.

This system have to be assumed as a reference both for global design checks, that for local design checks, considering only a tandem for each lane, disposed in the central lane axis. The tandem load, if exists, has to be considered entirely.

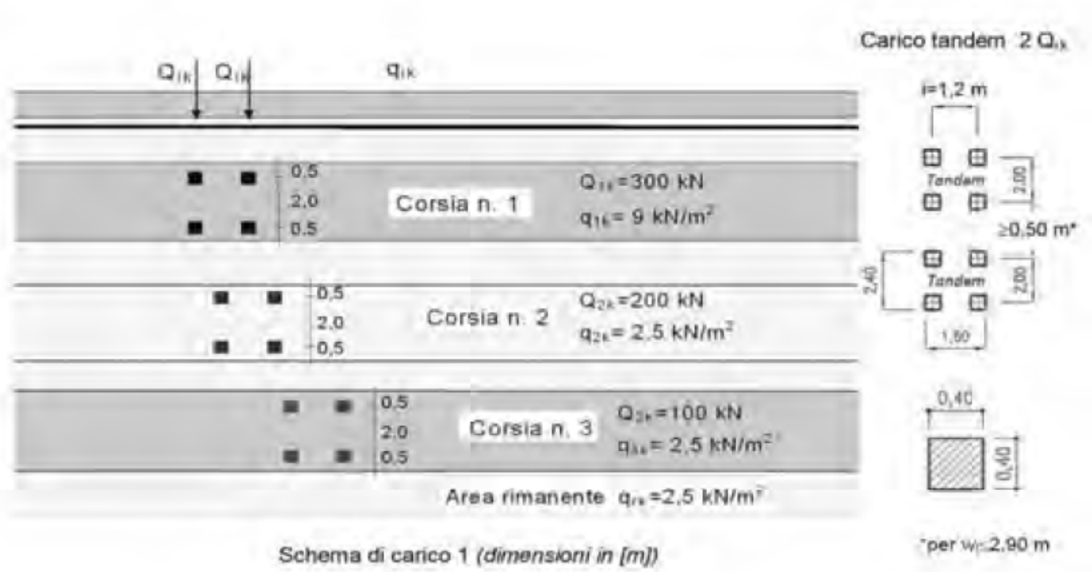


Figure 5.35: Load system 1
Source: NTC2018 [5]

The number of moving loads columns to consider in the calculation is the maximum compatible with the vehicle accessible surface width, holding in consideration that the conventional overall width is established for each lane in 3,00 m.

In each case, the lanes number should not be inferior to 2, unless that vehicle accessible surface width is less than 5,40 m.

Loads disposition and lanes number on the vehicle accessible surface will be, time after time, those which determine the unfavourable conditions of stress for the considered structure, frame or section.

Have to be considered, compatibly with the widths previously defined, the following load intensity:

Tab. 5.1.II - *Intensità dei carichi Q_{ik} e q_{ik} per le diverse corsie*

Posizione	Carico asse Q_{ik} [kN]	q_{ik} [kN/m²]
Corsia Numero 1	300	9,00
Corsia Numero 2	200	2,50
Corsia Numero 3	100	2,50
Altre corsie	0,00	2,50

Figure 5.36: Loads intensity
Source: NTC2018 [[5]]

The moving loads definition, specifically traffic loads, is probably the best part that is possible to define in the structural analysis software.

Clicking in the section related to the moving load, it is possible to set directly the Moving Load Code used, in our case, EUROCODE.

First of all, it was necessary to define some new elements and creating a new group, named "Cross Beam". This group has be created for the traffic loads application, and, a new material property has been assigned to the upper group (related to concrete deck). This new material has the modulus od elasticity of a concrete but a weight density equal to 0, such to keep the global behaviour of the structure. Their existence is useful to provide transversal rigidity to the bridge.

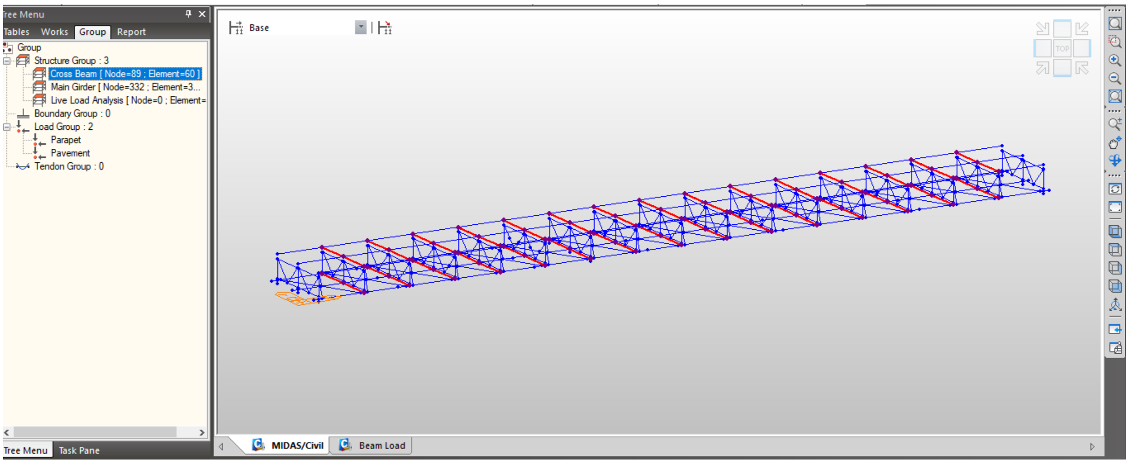


Figure 5.37: Cross beams group displayed

The creation of these cross beams was necessary for the definition of traffic line lanes. Indeed, for the generation of line lanes, in is necessary to insert the cross beam group for the vehicular load distribution. Once inserted this point, software creates the line lane, selecting two points that have to be positioned on a single beam. A new eccentricity has to be inserted to create other new lanes in the model, as reported in the above attached legislation [5].

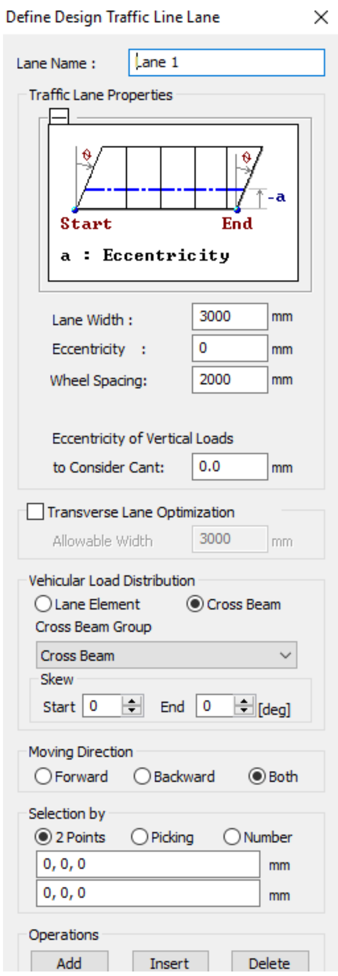


Figure 5.38: Define design traffic line lane

After the definition of traffic line lanes, they result so displayed:

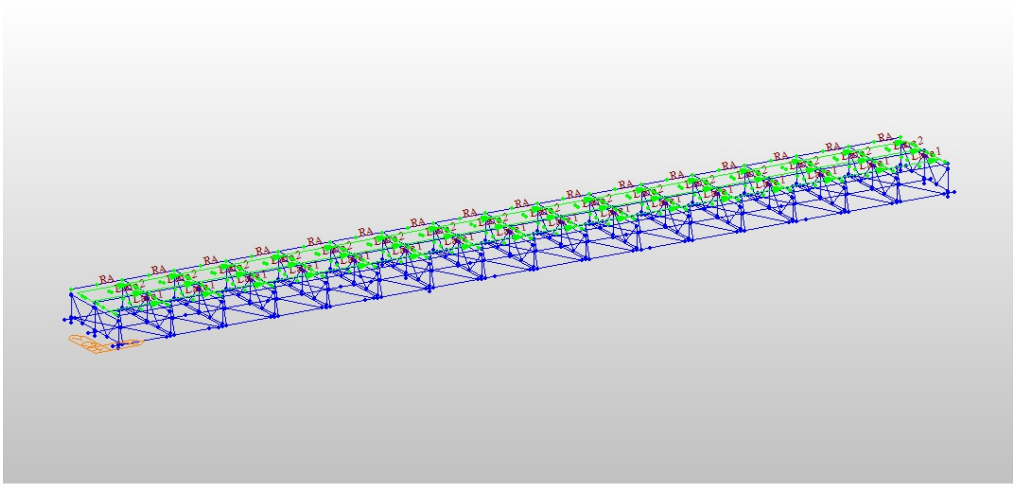


Figure 5.39: Traffic line lanes displayed

After that traffic line lanes are defined, it is opportune to insert a typology of vehicle; the structural software allows to insert standard vehicular loads following the chosen standards of legislation. In this case it was selected the definition contained in the EN 1991-2:2003 - RoadBridge, it contains all the input data related to Tandem System and UDL system (corresponding to the Italian legislation above described [5]). The definition with attached information and values is reported in figure 5.40.

This package definition contained in the software allows to speed up the workflow: it permits to insert vehicle effect in a very speed and automatic way, avoiding errors related to a wrong comprehension of legislations. Axial loads an uniformly distributed loads are contained in the software legislation package, allowing to avoid rough mistakes.

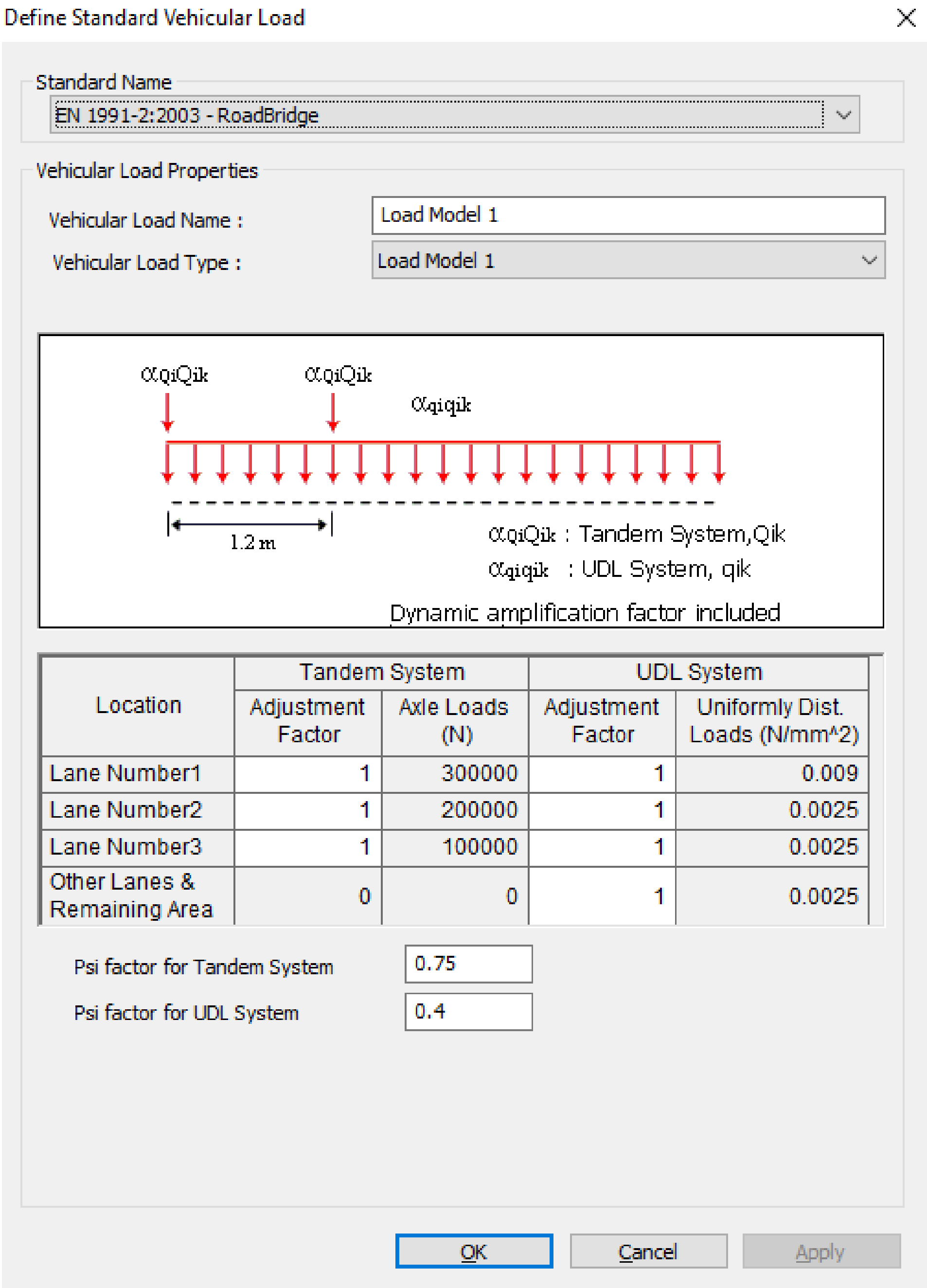


Figure 5.40: Define standard vehicular load

The final operation that it is necessary to do is defining the load case; it is opportune to define the vehicle model, and inserting the traffic lanes and remaining area in the opportune windows, in a way that the software will able to find this information by itself (figure 5.41).

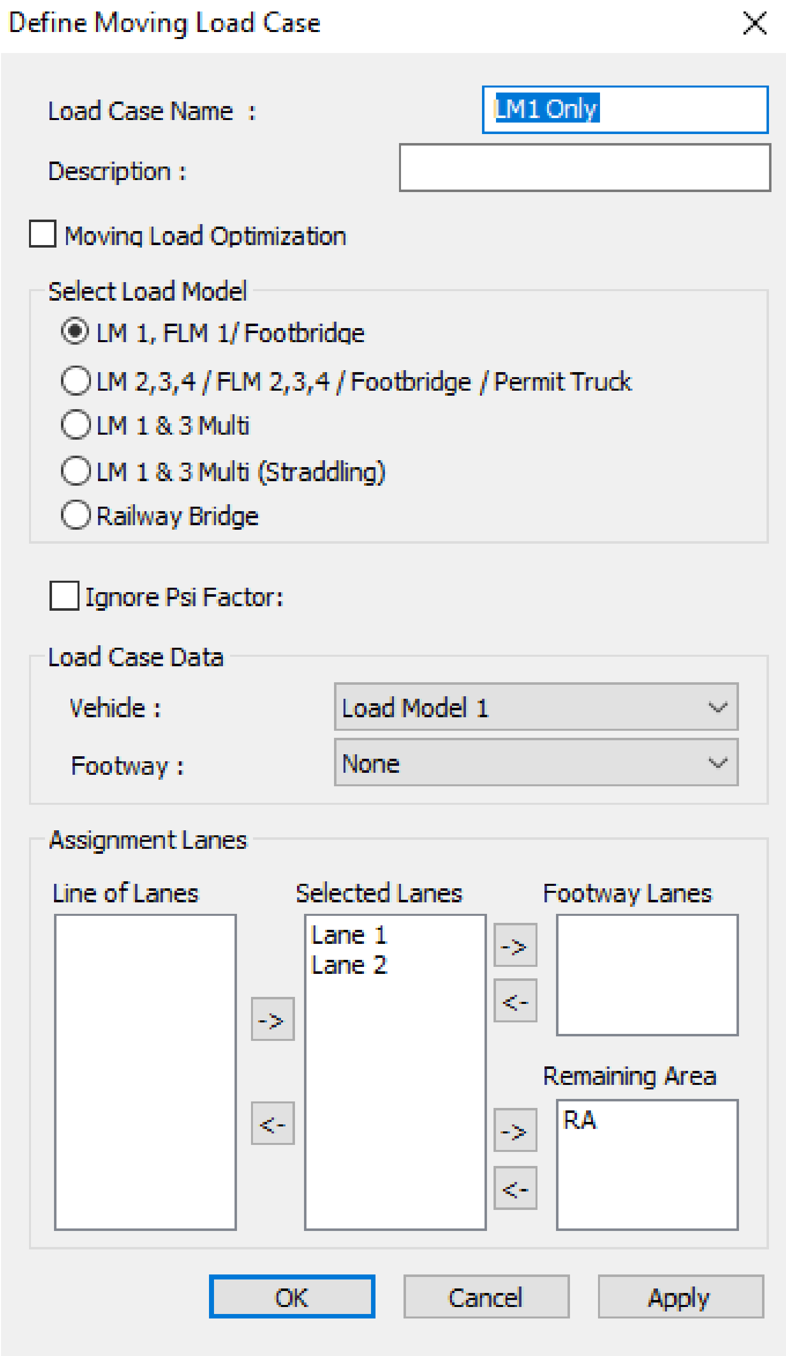


Figure 5.41: Define moving load case

Reached a complete definition of the load cases (it seems intricate but having a good knowledge about the bridge legislation it will result intuitive), it is opportune opening the window for moving load analysis control data.

In calculation filters the group that will be subjected to the effect of live loads was selected (indeed this group is named live load analysis). Clearly if the number of elements selected in these pre-analysis for traffic-load is bigger the analysis time could be increased.

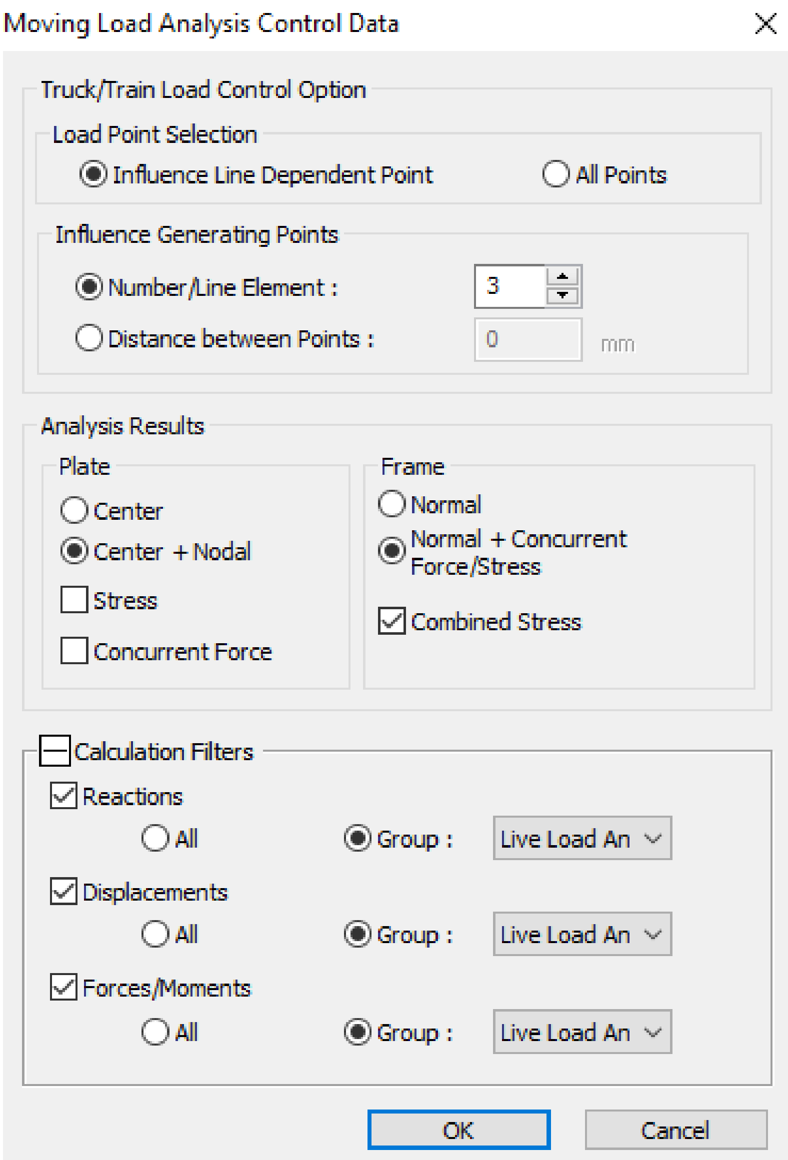


Figure 5.42: Moving load analysis control data

The group referred to the effect of live load is displayed here:

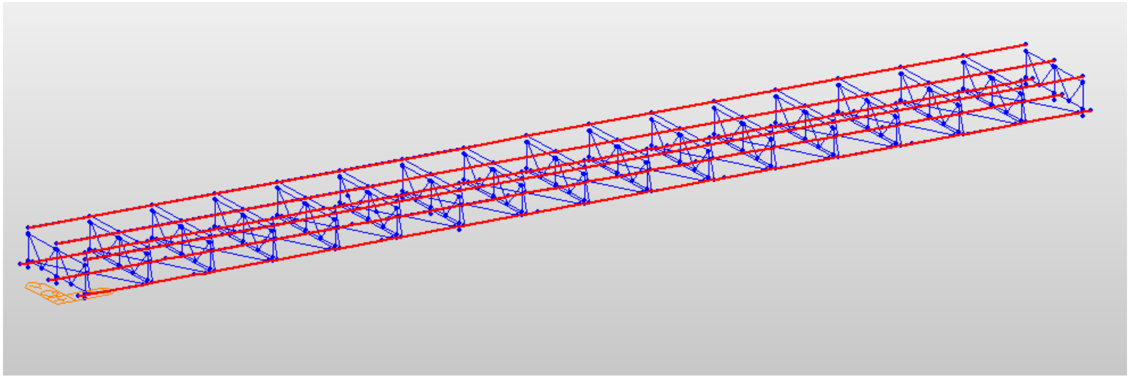


Figure 5.43: Live load analysis group

Once that all the setting about loads were made the analysis was ran. First, it was decided to study the effect of loads for elements self-weight, obtaining diagrams for bending moment and shear.

Therefore, a more accurate analysis was performed, inserting the effect of live loads and the contribute of permanent but not bearing loads (pavement and parapets). This second analysis was performed to the ULS combination of loads.

Effect of loads - Self-Weight

Once that the analysis was performed, the first point was to check the deformed shape of the bridge, confronting it with the one obtained in the precedent section dedicated to SAP2000.

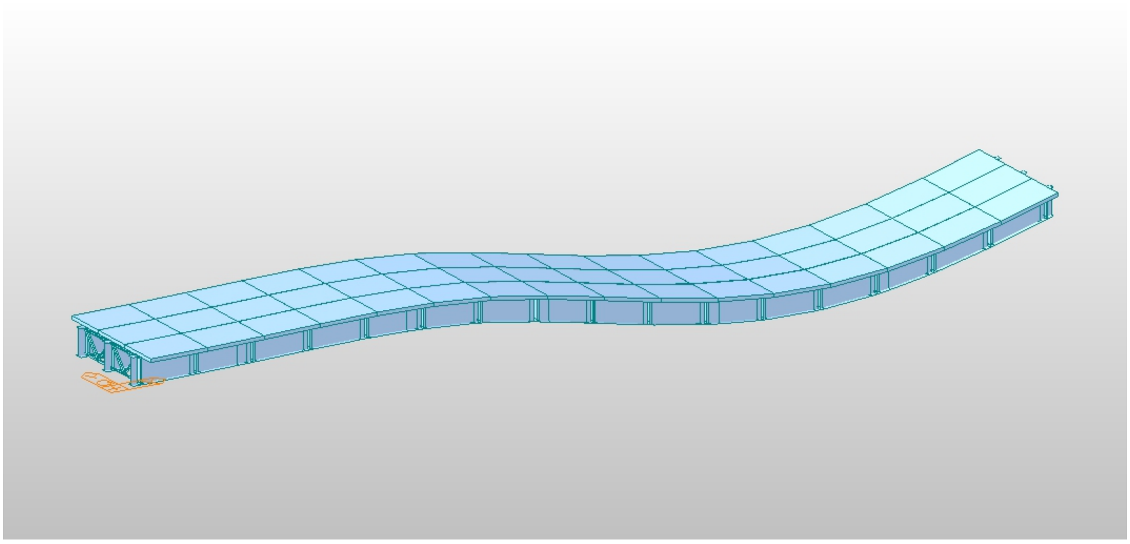


Figure 5.44: Bridge deformed-shape

It seems correct even after a qualitative confront with the one obtained in SAP2000.

Therefore, the self-weight effect will be shown: the bending moment diagram and the shear diagram of main girders. These two diagrams are shown in figures 5.45 and 5.46.

The shear development obtained could look like "strange", there are some segments which seem constant. This imprecision is due to a modelling choice, the decision of making a model of a composite section by using rigid links bring to this shape of the shear. Although its trend is strange some checks were made about values and the magnitude order resulted correct. These verifies have been made solving manually the structure, as made in the previous chapter, but with a different value for the distributed load; in this case it is obviously necessary to consider the contribute due to the presence of the concrete deck.

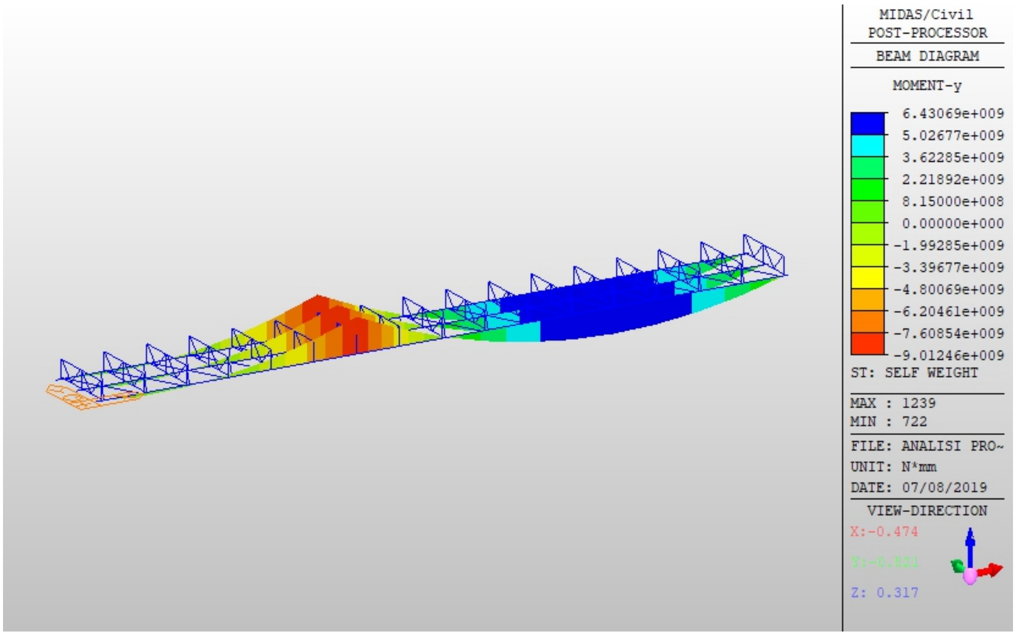


Figure 5.45: Main girders bending moment (Self-weight)

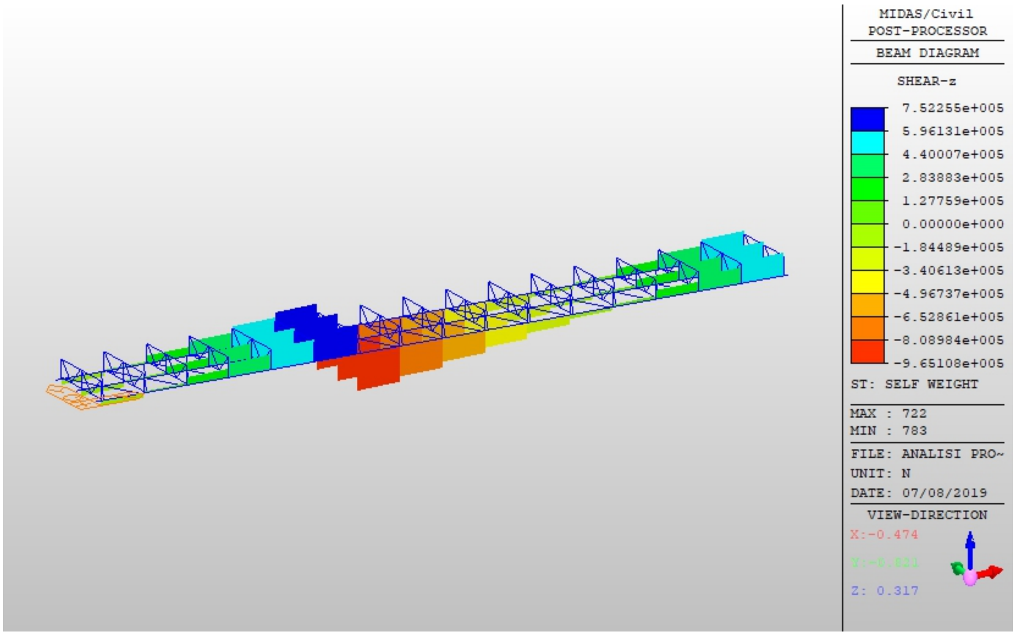


Figure 5.46: Main girders shear diagram (Self-weight)

Finally, for completeness of the work, graphical prints of the z displacements and of the bending- z beam stresses were reported:

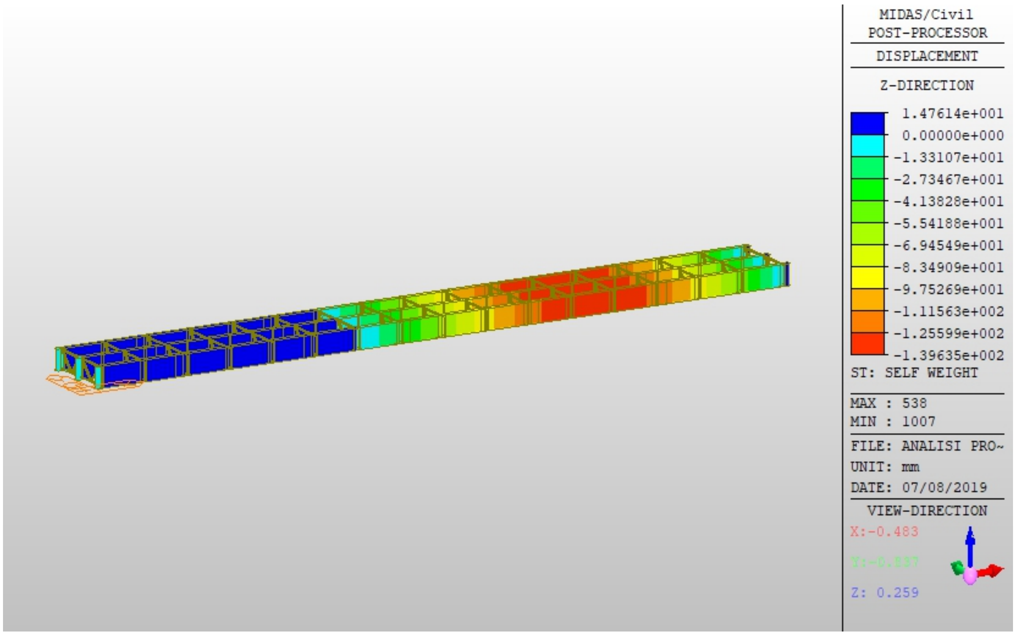


Figure 5.47: Z-direction displacements

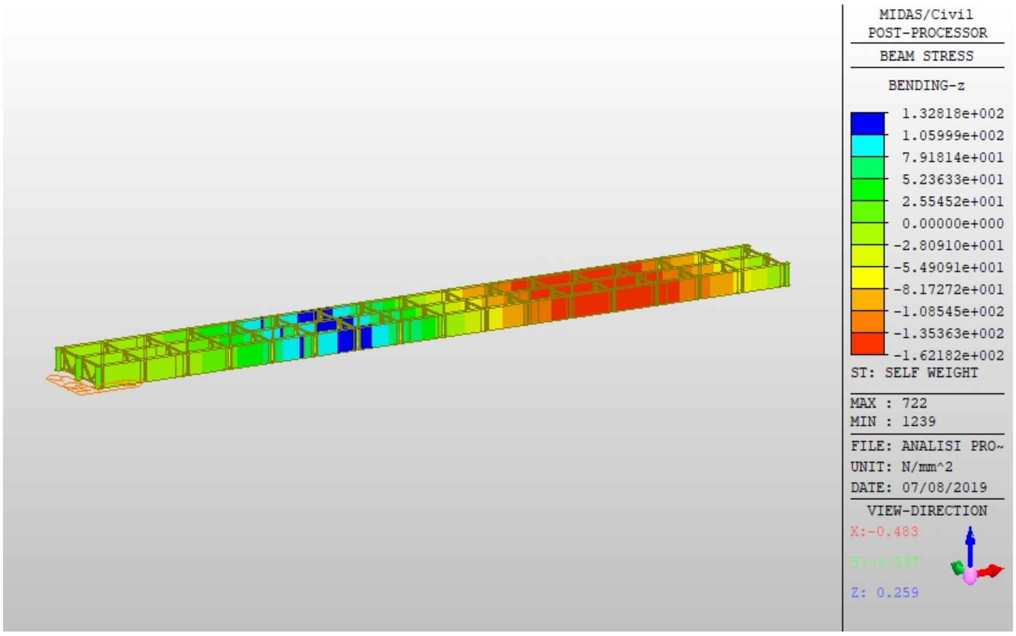


Figure 5.48: Bending-z beam stresses

Effect of ULS combination of loads

After performed a first structural analysis considering only the self-weight, it was decided to perform an analysis considering ULS (Ultimate Limit State) combination of loads.

The values of coefficients have been extracted from the NTC 2018 [5], chapter 5 and related to the 2, where ere provided partial coefficient values of action to assume in the analysis for effects of actions determination in design check at ULS.

Tab. 5.1.V – *Coefficienti parziali di sicurezza per le combinazioni di carico agli SLU*

		Coefficiente	EQU[1]	A1	A2
Azioni permanenti g_1 e g_3	favorevoli sfavorevoli	γ_{G1} e γ_{G3}	0,90 1,10	1,00 1,35	1,00 1,00
Azioni permanenti non strutturali [2] g_2	favorevoli sfavorevoli	γ_{G2}	0,00 1,50	0,00 1,50	0,00 1,30
Azioni variabili da traffico	favorevoli sfavorevoli	γ_Q	0,00 1,35	0,00 1,35	0,00 1,15
Azioni variabili	favorevoli sfavorevoli	γ_{Qi}	0,00 1,50	0,00 1,50	0,00 1,30
Distorsioni e presollecita-zioni di progetto	favorevoli sfavorevoli	$\gamma_{\varepsilon 1}$	0,90 1,00[3]	1,00 1,00[4]	1,00 1,00
Ritiro e viscosità, Cedimenti vincolari	favorevoli sfavorevoli	$\gamma_{\varepsilon 2}$, $\gamma_{\varepsilon 3}$, $\gamma_{\varepsilon 4}$	0,00 1,20	0,00 1,20	0,00 1,00

[1] Equilibrio che non coinvolga i parametri di deformabilità e resistenza del terreno; altrimenti si applicano i valori della colonna A2.
[2] Nel caso in cui l'intensità dei carichi permanenti non strutturali, o di una parte di essi (ad esempio carichi permanenti portati), sia ben definita in fase di progetto, per detti carichi o per la parte di essi nota si potranno adottare gli stessi coefficienti validi per le azioni permanenti.
[3] 1,30 per instabilità in strutture con precompressione esterna
[4] 1,20 per effetti locali

Figure 5.49: NTC values for ULS
Source: NTC2018 [5]

Therefore, here are reported coefficients for variable actions, related to road bridges and pedestrian bridges. These data have been inserted automatically by the software in figure (5.40).

As anticipated, the introduction of these coefficient is made by the software, saving time and allowing to obtain a good result in terms of efficiency. The connection with the actual legislation represents a good advantage that simplify and speed up the entire workflow.

Tab. 5.1.VI - *Coefficienti ψ per le azioni variabili per ponti stradali e pedonali*

Azioni	Gruppo di azioni (Tab. 5.1.IV)	Coefficiente ψ_0 di combinazione	Coefficiente ψ_1 (valori frequenti)	Coefficiente ψ_2 (valori quasi permanenti)
Azioni da traffico (Tab. 5.1.IV)	Schema 1 (carichi tandem)	0,75	0,75	0,0
	Schemi 1, 5 e 6 (carichi distribuiti	0,40	0,40	0,0
	Schemi 3 e 4 (carichi concentrati)	0,40	0,40	0,0
	Schema 2	0,0	0,75	0,0
	2	0,0	0,0	0,0
	3	0,0	0,0	0,0
	4 (folla)	--	0,75	0,0
	5	0,0	0,0	0,0

Figure 5.50: Coefficient for variable actions
Source: NTC2018 [5]

Once reported the Italian legislation for ULS loads combination, it is opportune to insert the coefficient values in the load combination dialogue box in Midas Civil.

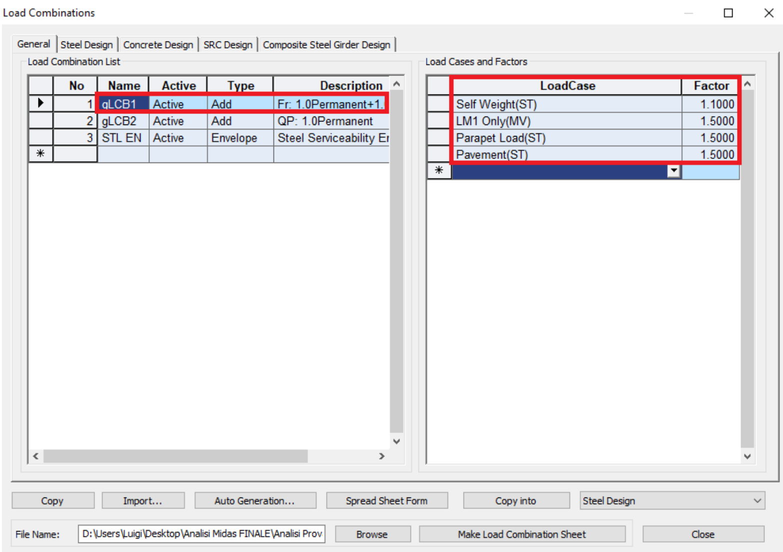


Figure 5.51: Load combination coefficients defined by NTC combination of loads [5]

Inserted these data, the software furnished results for ULS, that is its envelop. Thanks to the live load group insertion in the previous section, it is possible to obtain the ULS results in terms of forces in every section; moreover, these values can be reused for many different structural aims such as design or node checks.

The moment and shear diagrams will be shown, the ones which could have an interest in terms of structural analysis.

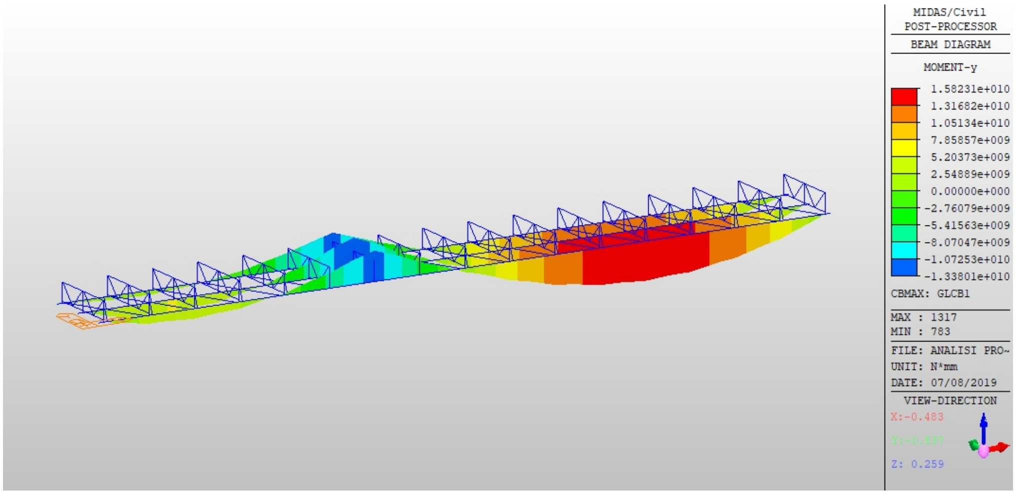


Figure 5.52: Moment diagram ULS loads combination envelop

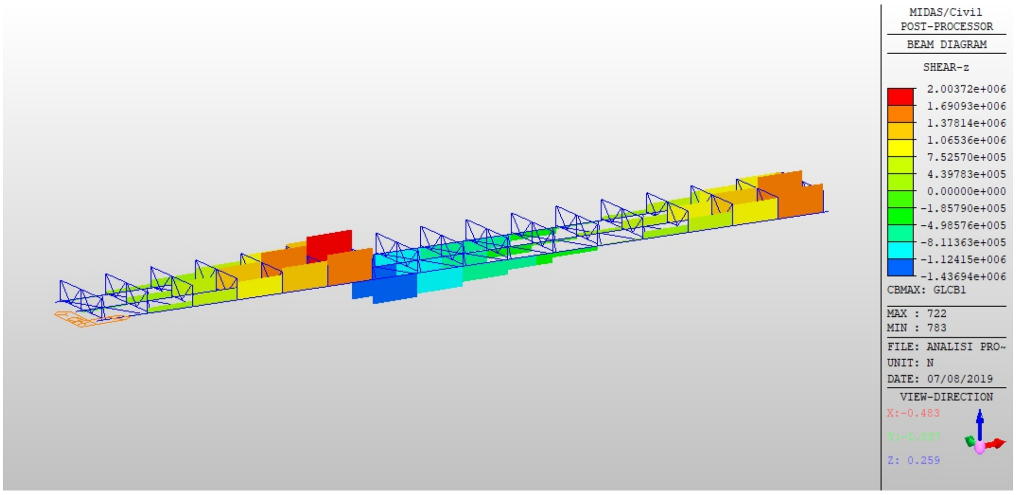


Figure 5.53: Shear diagram ULS loads combination envelop

Moreover, in the analysis results section of Midas Civil it is possible to interrogate the software using a function named Moving Tracer that allows to track, depending on the position inserted, the effect of live load on this structure by the definition found in the NTC 2018 [5].

For instance, the software is able to check which is the contribute of traffic loads in critical sections, such as the ones where some joints are present. In the following picture, there is an example of what said, that is the case in which the traffic load is located above the joint 4. Moreover, the moving load tracker provides the maximum bending moment value caused by the traffic load.

The choice of showing the effect of traffic loads in this exact point is not random:

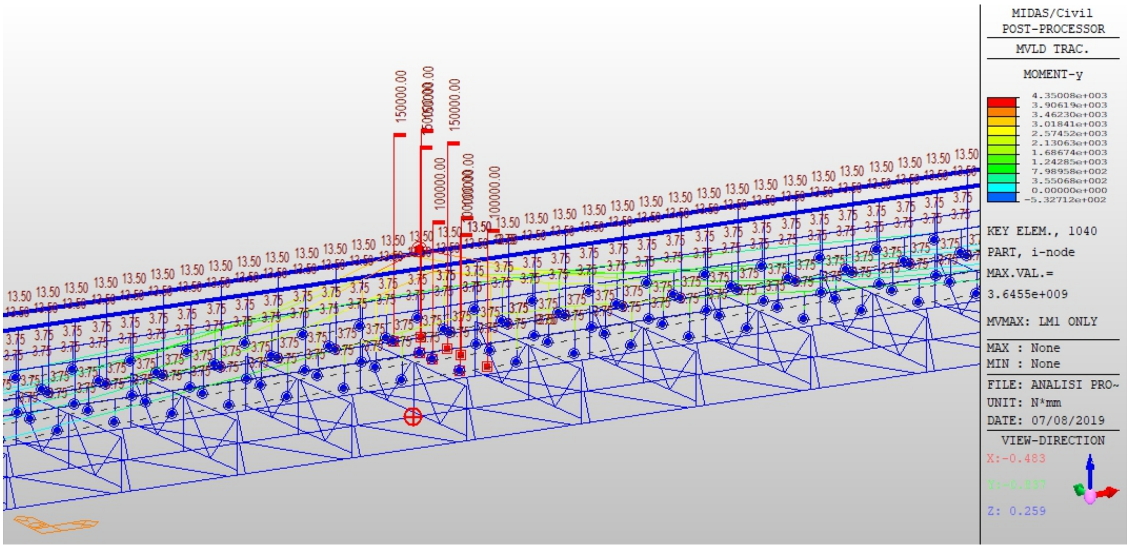


Figure 5.54: Moving load tracker, joint 4 position

as anticipated in previous parts of the thesis, the next point of this structural analysis is exploiting interoperability possibilities to move the study from a global structural analysis to a local one, particularly, in the node of the joint 4.

Considerations on structural analysis

In this case, it is not necessary spending many words about structural analysis obtained as made for SAP2000. Results are efficient in terms of structural analysis, possibilities offered by Midas Civil about loads definition are enormous; it is possible, even for new users, to insert parameter in a very intuitive environment such to realize structural analysis.

This aspect, added to the possibility of working adopting the BIM methodology, makes Midas Civil, probably, one of the best solutions for the definition of an efficient and functional workflow for structural analysis based on interoperability.

5.3 Idea StatiCa

5.3.1 Operations on structural analysis software

Once that the model was exported correctly, without any errors related to elements, their position and geometry, it was necessary to make some operations on the structural analysis software before performing the local structural analysis.

Material insertion

An operation that was essential to define in the structural analysis software is the material definition. Idea StatiCa did not recognize the one inserted in Tekla Structures and for this reason was necessary to assign manually it to the model exported. This lack is due to the not equal way of communication that present software belonging to different software-houses.

Welds

It was necessary to introduce some welds, in a way to (partially) adjust the model that will be analysed. The structural software allows to weld some elements clicking on the operation button and the selecting operations needed.

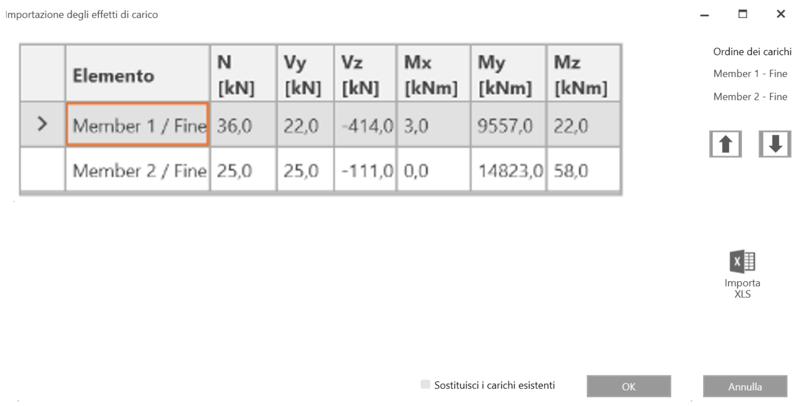
It was decided to introduce welds for those plates that presented a strange deformation; this means that exported plates, that were recognized in the custom component in Tekla but not in Idea StatiCa, were bolted to wings and to other play, such to avoid a insensate deformed shape. This represents probably the worse definition error, something was introduced only to permit the data exchange.

Figure 5.55: Weld 1

5.3.2 Structural analysis

Reached this point, Idea StatiCa allows to insert loads effect values from excel: they are necessary to perform an analysis on a joint at partial restored state. It was decided by the author to run an analysis with the joint at partial restored state to test another type of interoperability, the one related two different structural analysis software.

Actually, it is not correct naming this one as an interoperability data exchange passage, because it does not happen by using any plugin or any file format. The data exchange is possible thanks to an excel sheet file extracted from Midas Civil structural analysis: then it is necessary to copy data and import them in Idea StatiCa, clicking on the XLS import button present in the project window:



	Elemento	N [kN]	Vy [kN]	Vz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
>	Member 1 / Fine	36,0	22,0	-414,0	3,0	9557,0	22,0
	Member 2 / Fine	25,0	25,0	-111,0	0,0	14823,0	58,0

Figure 5.56: XLS table import

These loads are applied to two member element ends: member 1 and member 2, that is beam 1 (resistant one) and member 2 (connected one).

Once that loads effect were inserted, it was checked the parameters used for mash definition. This last one was automatically defined by the FEM software. Its dimension in this case is small and related to the analysed connection dimensions. Because of this reason, the software set by itself the mash dimension.

Modello e mesh

Lunghezza di default dell'elemento standard [h]	1,5
Lunghezza di default dell'elemento con sezione cav	2
Divisione della superficie dell'elemento cavo circola	64
Divisione degli archi dell'elemento cavo rettangolar	3
Numero di elementi sull'ala o flangia dell'elemento	8
Numero di elementi sull'ala più grande dell'element	16
Numero di iterazioni di analisi	25
Conteggio delle divergenze	3
La misura minima dell'elemento [mm]	10
La misura massima dell'elemento [mm]	50

Figure 5.57: Modello and mash settings

Checked that the mash automatic dimension has sense and is correct for the model dimensions, another check was made about distances consented between bolts and between bolts and plate edges (defined in NTC2018[[5]]).

Distanza tra i bulloni [d]	2,2
Distanza tra i bulloni e il bordo [d]	1,2

Figure 5.58: Setting check

Verified these settings the joint analysis at partial restored state was launched and stresses calculated.

The new method about components (CBFEM - Component Based Finite Element Model) allows a rapid analysis of joints. The model FEM, as said, is automatically created. The analysis is a no-linear one: load increments are applied gradually and the stresses state calculated. In this case the joint had to resist the total load applied (the analysis in not at complete recovery of resistance).

The following image 5.59 represents the result obtained for the joint analysis, equivalent stresses for effects of ULS loads combination are shown.

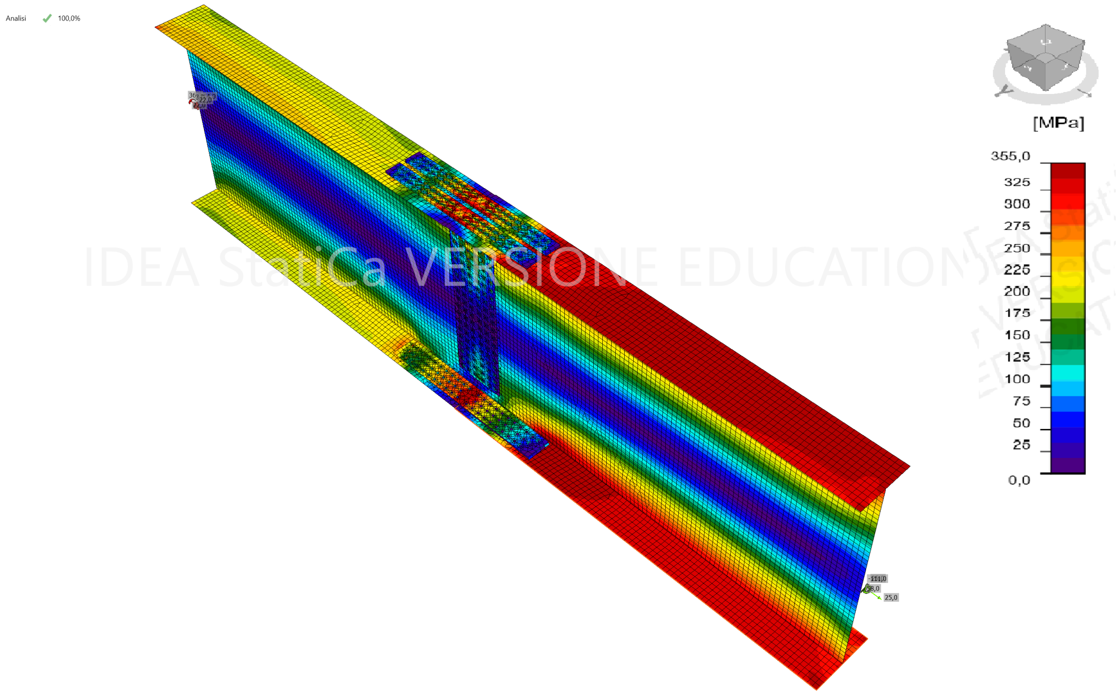


Figure 5.59: Joint equivalent stresses for ULS loads combination effect

And then its deformed shape:

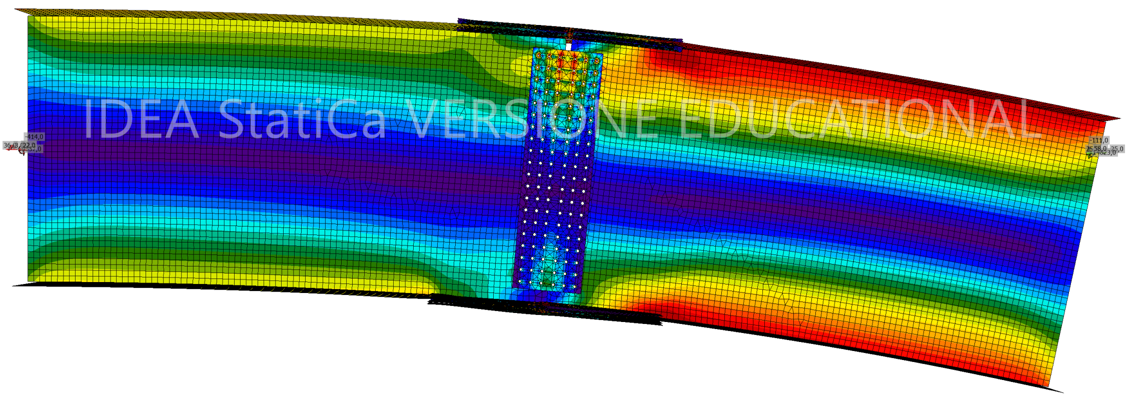


Figure 5.60: Joint deformed shape with stresses

By a simple check of obtained results, it is possible to understand which bolts will be the most stressed, and predisposed to a possible break (if badly designed). The software offers even possibilities about design checks, controlling the plastic deformation level (maximum value of 5 %), but these outputs of the software were not studied.

Considerations on structural analysis

As final result of this section, it is essential to make some considerations about the results obtained in terms of structural analysis. It was possible to execute a first simple analysis, studying equivalent stresses which affect the connection.

Main problems were found in the connection definition, it was not easy to define it, many adjustments were needed. For this reason, the results obtained can contain some errors, due to a bad definition and modelling of the connection: this issue is related to interoperability problems previously discussed. If the custom component definition problem will be solved, a better level of analysis will be possible using this methodology.

Chapter 6

Results

6.1 Structural BIM modelling

The structural BIM model has been realized thanks to the carpentry tables provided by *Cordioli&C.*, they contain all the information and data about steel elements (beams, bolts, plates) which compose the bridge, needed to realize a correct modelling.

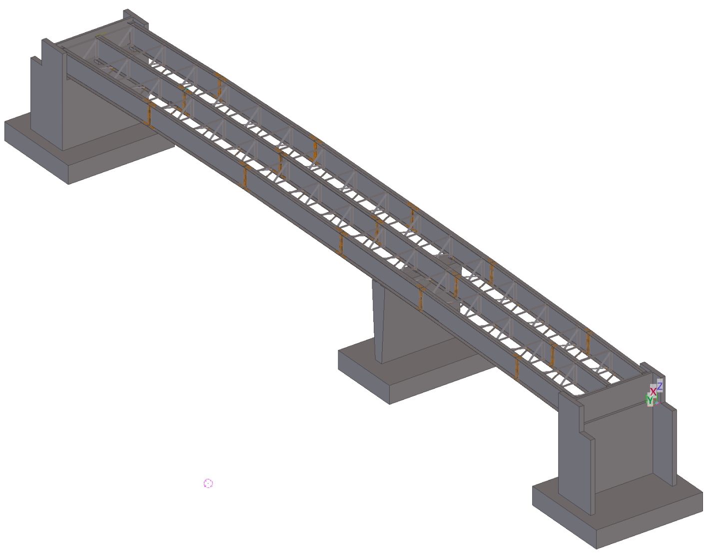


Figure 6.1: Structural BIM model

The structural modelling software, *Tekla Structures 2018*, is a powerful tool for creation of structural BIM models. It allows to insert elements with many information using an input element system based on grids and levels. These inserted elements are classified by the software in profiles which can be modified in a way to insert elements with not-standardized dimensions. Moreover, it is possible to change in a very simple way these elements positions, managing all the structural modelling in a 3D view (intuitive environment for new users), while the attached data can be visualized under the shape of “abacuses”, allowing to users a double check about the correctness of information inserted.

The phase of modelling is probably the most important for the global workflow result, it represents the basis for all the following operations and interoperability tests. It is important to create a structural BIM model correctly, in a way to save time in workflow advanced phases extracting data from the model.

To create a good structural model in Tekla Structures it is necessary to:

- Define a initial system of grids and levels to make easier the elements insertion in a 3D view, avoiding positioning errors that can slow down the process;

- define immediately not standardized profiles, to make easier the model creation; it is important to check the correctness of inserted data, it is important to not forget that these elements will be exported in other software, they represent the workflow nourishment;

- interrogate the Analysis & Design Dialogue Box provided by Tekla Structures, when the data exchange way is realised by a direct link. It allows to manage the analytical model already from first modelling phases, allowing to export a good model in structural analysis software. It is essential to avoid the creation of eccentricities that can take to rigid links generation and pay attention to nodes where many beams flow into them.

6.2 Interoperability for structural analysis

This section has been divided in parts depending on the typology of data exchange used; its aim is trying to define results in shape of a guide to avoid interoperability errors and give solution to criticisms that can compromise the methodology applied.

6.2.1 SAP2000 v20 - IFC

The model exportation in *SAP2000 v20* was executed using the IFC file format 2x3, export type Coordination View 2.0.

The analytical model obtained in SAP2000 contains many problems, because it is not possible to manage it in first modelling phases in Tekla Structures. This point is a flaw in the methodology definition, it is not possible, by actual technologies, to handle this part in structural modelling software.

The aim of this thesis is to provide a guide for critical modelling points, which ones can compromise the methodology. The following table was defined to summarize them:

Critical points	Summarized resolution
Beams local axes rotation	Assigning a new rotation to local axes in SAP2000
Analytical beams axes position	Creation of rigid links (rigid frames)
Boundary conditions	Application directly in structural analysis software

Table 6.1: Modelling guide for interoperability critical points

Resolutions to these critical points are here explained as conclusion of the work; as repeated before, all the produced modifies are taken in structural analysis software; this point is an important limitation to the methodology.

- *Rotation of beams axes*

  It is possible to assign the rotation to beam local axes. It was necessary to repeat this operation many times, it is not an intuitive resolution method but it works. The time for this operation is conditioned by the definition of local axes around to which is realised the rotation.

- *Position of analytical beams axes*

  It is possible to define rigid frames (fictitious elements) with the aim of unifying elements which are not connected each other. It was necessary to create some zones for bracing plans, named rigid-zones by the author, to permit a good structural analysis with a deformed-shape which did not present problems. Even this second point is quite intricate but at least it works correctly without any errors. The copy command allows to facilitate the process once that a first system of beams connection has been created (this function only works having a license).

- *Boundary conditions*

  Boundary conditions have to be defined in the software for structural analysis; this is not properly a limitation. Really, the fact that boundary conditions insertion has been made in SAP2000 is not a disadvantage. Software for structural analysis allow to manage the boundary insertion, simply selecting which displacements are fixed and which not. In this decisions engineers come in play, deciding how to manage the analytical model to obtain good results.

6.2.2 Midas Civil 2019 - Direct Link

The exportation realised by Direct Link between *Tekla Structures 2018* and *Midas Civil 2019* works surely better than the one executed using the IFC file format. Using the

Analysis and Design Dialogue Box is possible to modify the position of analytical axes obtaining a model without any problems after the exportation. In the structural analysis software, it was necessary to make modifies which have not affected the methodology, on the contrary they have enhanced it.

Even this time critical points and relative solutions were summarized in a table, trying to define a guide for this typology of exportation.

Critical points	**Summarized resolution**
Position of analytical beams axes	TS Analysis and Design Dialogue Box
User-defined beams	Modifying elements dimensions in Midas
Boundary conditions	Application in structural analysis software
Loads definition and application	Application in structural analysis software

Table 6.2: Modelling guide for interoperability critical points

The resolution to these points are here explained and discussed, they represent the work conclusion. Modifies taken by the author, as anticipated, concern both software, the one dedicated to model authoring and the one for structural analysis. This fact represents already a result of how the methodology really works, a union of possibilities represents all the potentiality that a correct infraBIM methodology carries to the workflow.

- *Position of analytical beams axes*

  It is possible to realize a good analytical model in the Analysis and Design dialogue box. At this modelling phase, it is important to pay attention to two fundamental points. First, it is necessary to avoid the creation of rigid links between beams; these automatically generated elements are not recognized in Midas Civil, it is important to avoid their creation moving beams axes positions using tools furnished by the software. Second, it is important to pay attention to beams which flow into a single node, these can produce the generation of other rigid links or eccentricities that can affect the exportation efficiency.

- *User-defined beams*

  As explained in the chapter dedicated to interoperability, the plugin does not allow to export main girders elements. To solve this problem it was necessary to introduce some data in the structural analysis program. It is important to remember that this problem occurs only when beams wings have different dimensions each other.

- *Boundary conditions*

  It is sufficient seeing what written about the same issue presented in the precedent subsection dedicated to *Sap2000 v20*.

- *Loads definition and application*

  It is possible to define loads and load combinations in Tekla Structures. The author decision was to make this operation in the structural analysis software because this point was not considered as a disadvantage. In software for structural analysis, the loads definition is very simple and intuitive. They offer the possibility of inserting static or moving loads interrogating the dialogue box dedicated to loads. Moreover, Midas Civil contains a package where it is possible to define, manage and combine load combinations according to legislations. In this workflow phase engineers have to intervene, deciding which loads is opportune to consider and which not.

6.2.3 Idea StatiCa

To realize the model exportation and perform a first simple local structural analysis, it was necessary to increase the BIM structural model LOD up to 400. Once that the model was defined with more details, it was necessary to create a custom component containing information which could be understood by the structural analysis software, that is *Idea StatiCa*. The effect of loads have been extracted from the other structural analysis software used, Midas Civil.

Critical points	**Summarized resolution**
Definition of a valid custom component	Correct modelling in TS
Unnecessary plates	Operations in structural analysis software
Effect of loads insertion	Exported from Midas Civil

Table 6.3: Modelling guide for interoperability critical points

Also in this case, adopted modifies and operations concern all used software; it means that the workflow includes both the program for model authoring that the ones for structural analysis, increasing InfraBIM methodology potentiality. Main problems, concerning the connection definition are here reported with their respective (partial) resolution.

- *Definition of a valid custom component*

  This one is surely the biggest interoperability problem for local structural analysis. It was necessary to model the joint such a way that allowed to recognize the connection both in Tekla that in Idea StatiCa. To (partially) solve it, it was necessary to model the node not exactly how it appears in steel workshop tables, some adjustments were needed.

- *Unnecessary plates*

  This critical issue is strongly connected to the last one; Tekla Structures allows to define a valid custom component only in the way described in chapter 4, and for this reason some plates were exported and they resulted without holes in Idea StatiCa. To solve this criticism it was made an operation, inserting welds to avoid an inexactly deformed shape of the connection.

- *Effect of loads insertion*

  This operation represents a good advantage, it is possible to insert effect of loads calculated in another structural analysis software in shape of an excel table. Probably the best input option for BIM collaboration furnished by Idea StatiCa, without using a BIM data exchange file format.

6.3 InfraBIM methodology evaluation for structural analysis

6.3.1 Operative timings confront

The overall of executed operations needed to perform a good exportation in the software for structural analysis has cost a certain amount of time. In this section a global idea of time needed to realize a good exportation for a global structural analysis was provided. The local one has not been considered because its workflow is too specific and its modelling can not be considered as a standard for all the connection typologies.

In the first test about interoperability between Tekla Structures and Sap2000, 471 elements have been exported, while in the second one with Midas Civil 474 (due to the presence of three concrete beams).

Using the IFC file format, it was not necessary to define timings related to the analytical model modifies in model authoring software, it is not possible to modify the analysis model until the exportation is not finalized.

Using a direct link, it was possible to make some pre-export operations, timings are summarized in this table:

Operations	**Modified elements [%]**	**Elements**	**Time**	**Min/El**
Analytical check	80	380	**240**	0,63

Table 6.4: Pre-exportation timings, Analysis & Design Dialogue Box

Once that the model was exported, it was necessary to make some adjustments, with different efforts depending on the data exchange used. Following tables report results about time needed to effectively make all the operations on structural analysis programs. In these tables, timings related to the research of solution have been considered.

Operations	Elements	Modified elements	Time	Min/El
New local axes definition	Frames	471	180	0,38
Material assignation	Frames	471	30	0,06
Rigid links	Links	960	180	0,19
Boundary conditions	Joints	9	5	0,55
Loads	Frames	471	5	0,01
Total	-	-	**400**	-

Table 6.5: Post-exportation time, SAP2000 v20

Operations	Elements	Modified elements	Time	Min/El
Profile	Beams	30	20	0,30
Rigid Links	Links	57	15	0,26
Boundary conditions	Nodes	9	5	0,55
Fictitious elements	-	16	1	0,06
Loads	Beams	474	20	0,04
Total	-	-	**61**	-

Table 6.6: Post-exportation time, Midas Civil 2019

Checking data reported in tables, the direct link efficiency overcomes IFC possibilities: working on the analytical model on Tekla permits to save time and speed up the workflow. Resume timings table is here reported.

Phase	Sap2000	Midas Civil 2019
Pre-export	0	240
Post-export	400	61
Total	**400**	**301**

Table 6.7: Resume timings table

6.3.2 Data-exchange evaluation

In this subsection will be given information about the data exchange level that is possible to reach, depending on the typology of software used.

First, it will be reported operations incidence about modelling in a structural analysis software. This table gives an idea about general steps that a structural engineer has to make before performing an analysis.

Operations	Percentage incidence [%]
Geometrical modelling	50
Profiles definition	20
Material definition	1
Boundary conditions definition and application	5
Rigid links definition	4
Loads definition and application	20

Table 6.8: Operations percentage incidence

Defined main operations, data-exchange tables are shown, one for *SAP2000 v20* and one for *Midas Civil 2019* containing results in percentage. This confront has been made to understand which data exchange, objectively, allows a better interoperability.

Operations	Incidence [%]	TS - Sap2000 [%]	Weight [%]
Geometry	50	60	30
Profiles	20	100	20
Materials	1	0	0
Boundary conditions	5	0	0
Rigid links	4	0	0
Loads	20	0	0
Total	100	-	**50**

Table 6.9: Data exchange percentages, Tekla Structures 2018 - SAP2000 v20

Operations	Incidence [%]	TS - Midas Civil [%]	Weight [%]
Geometry	50	100	50
Profiles	20	90	18
Materials	1	100	1
Boundary conditions	5	0	0
Rigid links	4	0	0
Loads	20	0	0
Total	100	-	**69**

Table 6.10: Data exchange percentages, Tekla Structures 2018 - Midas Civil 2019

This data are about the percentage of information which it is possible to export in a way to avoid the repetition related to data input. How aspected, the results obtained, once that percentages have been assigned, remark that *Midas Civil 2019* allows a better data exchange with *Tekla Structures 2018*, using the plugin provided by the two software-houses.

The IFC file format permits only to reach a weighted percentage of 50 %, there are even limitations which do not allow to make easier the entire workflow.

The same analysis about interoperability has been made for Idea StatiCa, showing first operations for a structural bolted connection modelling:

Operations	**Percentage incidence [%]**
Connection geometry definition	5
Materials definition	1
Profiles definition and application	40
Bolts definition and application	50
Effect of loads	4

Table 6.11: Operation percentage incidence

Now, as made before, it will be shown a table containing information about exportation percentage for every operation needed. This final output is necessary to have an overall idea of the data exchange quality.

Operations	**Incidence [%]**	**Data exchange [%]**	**Weight [%]**
Geometry	5	100	5
Materials	1	100	1
Profiles	40	0	0
Operations	50	90	45
Effect of loads	4	100	4
Total	100	-	**55**

Table 6.12: Data exchange percentages, Idea StatiCa

In this case, the worst result in terms of interoperability related to profiles definition was due to the impossibility of exporting immediately the connection from *Tekla Structures 2018* to *Idea StatiCa*, some modifies were requested to the connection recognition. If software-houses would develop better this option, the interoperability level could reach a weighted percentage early of 100 %.

Finally, it has been shown a table containing information about weighted percentages for every data exchange typology. The final resume table is here shown:

	SAP2000 v20	**Midas Civil 2019**	**Idea StatiCa**
Weighted percentage [%]	50	69	55

Table 6.13: Resume table

Chapter 7

Conclusions

The target of this thesis was to evaluate and study interoperability between BIM software for model authoring and software for structural analysis, applying the method to an existing infrastructure, an overpass.

Once that the case studied assigned was analysed, all the operations needed to obtain a BIM model ready to be exported on calculation software have been defined, following an approach based on standardised and time saving operations. By this way, it has been possible to define a BIM methodology, studied, modelled and adapted to the case study, allowing a good management of a big quantity of data which always engineers have to handle in infrastructure design processes.

Two data-exchange typologies have been evaluated, giving an accent to criticisms and possibilities of each one and showing guidelines to overcome worse obstacles. Finally, results have been given in terms of data-exchange percentage, with a particular eye also to timings, establishing the path that involves the less loss of data.

Interoperability for structural analysis offers some possibilities, but they result even improvable; nowadays, this data transfer is under study, software-houses are establishing the basis for new interoperability levels, where the data loss in transfers is reduced at the minimum, permitting a continuous flow of information from global to local analysis. Limitations exist but in next years, all these barriers will be surely erased, data exchanges are in continuous evolution. Other new interoperability tests and researches about new software implementations will be requested.

Nevertheless, BIM possibilities in structural analysis are many and all related to interoperability: exploiting potentiality of this concept is possible to avoid mistakes in the model definition and repetitions, starting from an analytical model which, no matter how simple, represents a starting point for following studies and analysis.

Anyway, it is also correct to make a consideration about the role that engineers have to keep within the workflow. Although interoperability levels are destined to increase, it is not possible to think that a perfect and correct analytical model is exportable from a BIM one, engineers have to modify them such a way to give the best answer in terms of structural analysis and time efficiency.

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