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BIM as a tool for Structural Health Monitoring

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Ringraziamenti

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Abstract

The number of structures that have reached the end of their service life and are in a serious aging and deterioration conditions are increasing day by day. On the other hand, the new constructions are larger and subjected to higher load conditions. In order to deal with these issues Structural Health Monitoring (SHM) plays a key role in the AEC industry both for the control of the builded heritage and for the new constructions realization process ensuring a higher safety level. In parallel with this innovation process the use of innovative tools occurs for the management of the great amount of data. Furthermore the application of new generation smart sensors S3 has been tested for the realization of the monitoring system.

For this purpose Building Information Modelling (BIM) is useful with its capability to store data and manage all the aspects related to a project starting from the design, through the construction and until the maintenance phase. The aim of the thesis work is to elaborate an automatic SHM design process for the monitoring of bridges with the help of the BIM potentialities.

The methodology has been designed and tested with the help of two case studies: a simple three storey building and the Stura bridge that is an important infrastructure with a strategic role in the connection between the city of Turin and the Caselle International Airport. The workflow started with the creation of the Revit model of a generic building that has been exported in Robot in order to perform a structural analysis and then the results has been organized in Excel files. Subsequently, with the use of the Revit integrated visual programming language Dynamo, different scripts have been created for the automatic placement of the sensors in the model according to different monitoring levels. After the first design, the scripts have been adapted in order to work properly on a bridge by applying them on the model of the Strura bridge. In addition, in order to test further the suitability of the BIM methodology to the SHM purposes, some models of real monitoring systems have been realized in the Revit environment.

The result of the study is a digital twin of the monitored items containing the elements of the SHM system that could be used as a “flight recorder” of the structure and an automatic routine for the creation of a monitoring mechanism that could be applied to different bridge typologies. During the elaboration of the process some problems related to interoperability problems among softwares have been encountered but the introduction of the SHM components in the BIM environment is the most logical development and currently one of the main trend in the evolution of the construction and design process. This thesis is expected to be a starting point for future researches aimed at improving the suitability and efficiency of the developped system.

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Introduction

The Structural Health Monitoring (SHM) has become in the recent years a fundamental instrument for AEC industry in order to obtain higher safety levels during the entire lifecycle of the structures starting from the design and construction stages and obviously during the exercise phase. A continuous monitoring of the structure plays a key role for the design of an efficient maintenance plan and could prevent the occurrence of catastrophic collapses, a danger that is high due to the increasing number of deteriorated structures that are subjected to higher loads.

In tamdem with the many benefits of the SHM systems application come new issues related to the storage, management and interpretation of the measured data. In particular the amount of data is huge and need to be filtered in order to obtain useful informations on the health of the structure.

Building information modelling (BIM) has proved to be a suitable solution for the management of the informations due to its ability to create efficient digital representations of structures such as bridges. With its many features, among other the visual programming language Dynamo included in Revit, the BIM methodology appears to be the best solution to obtain the aim of this thesis work: an automatic routine for the design of a SHM system for bridges.

The work is subdivided in 6 sections. The first part is dedicated to a theoretical introduction of the Structural Health Monitoring systems and of the BIM methodolgy. The second chapter explains the elaboration of the routine applied to a simple case study of a three storey building that has been used to test the efficiency of the various steps. In particular the work is developed starting from a Revit model, exported in Robot for the structural analysis, and the results are organized in a series of Excel sheets.

The files have been used to place the components of the SHM system in the Revit model with the help of Dynamo scripts. Different scripts have been designed in order to allow the user to choose between an automatic sensor placement and a manual selection of the monitored elements.

Also a script for the placement of the rebars that contains the sensors has been created. Another important aspect that has been treated is the one related to the electricel connections between the SHM components.

The third one is dedicated to the explanation of how a set of deformation data has been simulated in order to fill the sensors parameters. The fourth section is related to the adaptation process of the scripts to the second and main case study: the Stura bridge.

Then, in the fifth section various SHM applications has been discussed. In particular three examples are shown: two case are related to an innovative SHM system with smart S3 sensors and the other one is a classic monitoring system with accelerometers.

In conclusion, in the sixth part, the final considerations on the results of this thesis work are contained. Moreover are explained the future developments that need to be done in order to complete the process and obtain an efficient design system.

Chapter 1: Theoretical Introduction

1.1 Structural Health Monitoring

1.1.1 Historical context

Through the last century the amount of civil infrastructures that have been builded is impressive and strictly related to processes of expansions of the cities and the industrialization of many countries. The result of this evolution is a building heritage composed of structures with many different design and construction approaches. In particular the codes and specifications developped through the years due to progresses in the scientific research.

Most of the existing structures built in the past centuries were not designed considering the evolution of structural damage through the life cycle, in particular in Europe where it is possible to find constructions aged hundreds of years and still on service.

Even the structures from the last few decades, that have been built taking into account the effects of internal actions, could have reached the end of their service life and the accessibility and the residual resistances of materials need to be carefully evaluated.

Regarding to bridges the safety issue is even more pressing both for the strategical importance of this type of strucutures and for the average health condition of the european heritage. In fact the possibility to overcome natural obstacles makes this type of constructions a key element in the transport networks with fundamental importance in the fieldsof economics and connections. For this reason it is crucial to avoid failure or partial damaging of bridges that could lead to a longlasting closure of the transport network and consquently to huge economical losses. Another fundametal issue is the risk for human life that needs to be avoided in any possible way.

As regards the health state of the bridges in Europe a great part of them has been built after the World War II and has now reached the end or the life cycle. An interesting study, developped by the European Union BRIME, concerning to this theme has shown that the percentage of bridges with structural defects is 39% in France, 37% in Germany, 30% in United Kingdom and 26% in Norway.

Even if Italy is not considered in the previous study, the same situation can be assumed as two recent collapse of the Morandi’s Bridge in Genova (2018) and the Albiano-Magra Bridge near Massa (2020) has shown. The two cases previously named are examples of the need of renovation in the usually applied monitoring and maintenance routines and techniques.

Given these problems, on April 2020 the Minister of Transport Infrastructure of Italy has published the new guidelines for risk classification and monitoring of bridges (Italia, Ministero delle Infrastrutture e dei Trasporti, Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti, 2020).

The aim of the new guidelines is to establish a multilevel method for monitoring in order to define a general procedure for damage detection and risk evaluation for existing bridges.

As a consequence of this situation, the Structural Health Monitoring (SHM) earns a fundamental role in the process of evaluation of structural damage and risk analysis because allows to store and analyse great amount of data both historical and real time. This new monitoring methodology, in contrast to the traditional monitoring techniques based on visual inspections directly on site, is not dependent on the human eye and its subjectivity and allow the user to have informations also on the internal zones of the structures that would not be visible.

The Structural Health Monitoring is based on the concept of using sensors such as inclinometers, accelerometers, strain gauges and others to obtain a permanent and continous monitoring of the structure with particular attention to the critical zones. The data are collected and used to evaluate the evolution of critical phenomena in order to prevent collapses.

The SHM was born in the field of aviation and aerospace but in last few years, due to the advances in the implemented technology and the decrease of the cost of sensors, the number of application in civil engineering has grown.

The main characteristics of a SHM system should be:

-Low cost

-Able to obtain continuos evaluations

-Sensitive to low damage levels and various types of damage

-Insensitive to measurement noise and environmental conditions changes

1.1.2 Definition

According to Farrar and Worden in “New Trends in Vibration Based Structural Health Monitoring (2007)”, SHM is described as:

“The process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure is referred to as structural health monitoring (SHM). This process involves the observation of a structure or mechanical system over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of system health.”.

Another good defintion of SHM is contained in the publication by Radulescu et al "The Role of Structural Health Monitoring for the Design of the Life Cycle of Constructions" that states:
"The Structural Health Monitoring is a non – destructive in-situ sensing and evaluation method that uses a variety of sensors attached to or embedded in a structure to monitor the structural response, to analyze the structural characteristics for the purpose of estimating the severity of damage or deterioration and evaluating the consequences, thereof on the structure in terms of response, capacity, and service-life."

The main difference between traditional monitoring and SHM consists in a continuos assessment of the structure behaviour and damage evolution, in contrast to the periodical inspections on site performed in the past. The function of the systems is not only the record and collection of data but also the analysis in order to plan the maintenance during the life cycle of the structure.

1.1.3 Components of the SHM system

Even if the composition of the SHM systems is subjected to continous evolution due to the technological innovations the main components are:

- Sensors
  The sensors are the core elements of the system and the choice of appropriate technologies related to the parameter that need to be monitored (strains, temperature, displacements, deformations…). The variety of sensors in the market is wide and the designer choice will be influenced by many factor such as durability, cost, accuracy and power requiements. Another central point related to sensing devices is the right placement that should be designed according to the aim of the monitoring system.

- Data acquisition system (DAS)
  The Data acquisition system is the components that rules the sensor network and decides when and how the measurements need to be taken. Each sensor has to be connected to the DAS that will be located near or inside the structure. Another task performed by the DAS is the conversion of the signal obtained from the sensors from analog output into engineering language.
  The connection between the sensor network and the data acquisition system coud be realized in two different ways:

  -Wired connection: is the traditional way and in the past used to be the most economical by far. This type of technology could be subjected to electromagnetic interferences that are partially solved with the use of shielded cables. On the other hand, the use of non conventional cables raises the cost of the system

-Wireless connection: is a usefull technology that can be used when the extension of connections is wide, usually in structures of big dimensions. This solution is nowadays still more expensive, even if the cost of this solution is reduced in the last years, and is characterized by a lower pace of transmission.

- Communication system

The communication system carries out the transmission of data from the DAS to the processing station that could be placed in a different location. With this component the user is also able to control the sensors, by means of the DAS, remotely. This kind of transmission could be performed both with wires (telephone line, optic fibers) or wireless (radio or wi-fi trnasmission technologies).

- Data processing and storage

The data processing step is fundamental in order to clean the signals from noise, errors and other inaccuracies that could affect the subsequent analysis step. This task is executed automatically by a computer that applies some algorithms. Once the data are cleaned, a routine for the strage will be executed. The storing is crucial in order to obtain a chronological history of the structural behaviour of the monitored element that could be consulted in the future. Some problems related to this phase are the need of an efficient storing procedure that could be understood by different users and professional figures and the incresing amount of stored data due to continuos monitong that requires huge memory. Nowadays also could storage are used.

- Data analysis

The aim of the data analysis is to evaluate the collected informations that are useful for deciding on the health of the structure and envy possible allert when the setted thresholds are overcome.

This is one of the most important step in the SHM process because summarize the collected data in order to reach the goal of the monitoring process and define the health of the structure.

A possible SHM configuration is shown in the following picture from the article "*Different Techniques of Structural Health Monitoring*" by Raj Dharma et al (2013).

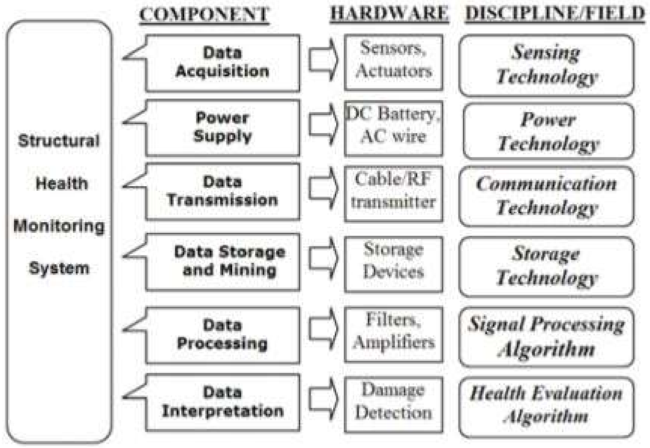


Figure 1. Components of a Structural Health Monitoring system

1.1.4 Sensor typologies

The sensor typologies that are used depend on the type of data that the designer wants to collect and on the characteristics of the structure and obviously of the SHM system. The main quantities that coul be measured in a monitoring system are:

- Strains
- Displacements
- Accelerations
- Rotations
- Temperature

In this thesis work we will study the design of an SHM system composed by strain sensors. The typologies of strain sensing devices usually applied in monitoring systems are: foil strain gauges, vibrating wire strain gauges, optical fibre and smart sensors (S3).

- The foil strain gauges are composed by a sheet that is glued to the surface of the structure or welded and deforms solidly with it. The deformation is read and then sent through the wires to the readout device. In some structures, such as casted in place concrete structures, the foils are embedded. The sensors measurements are performed in the sheet's orientation direction and is based on the linear relationship between the linear expansion of a conductor and its electrical resistance.

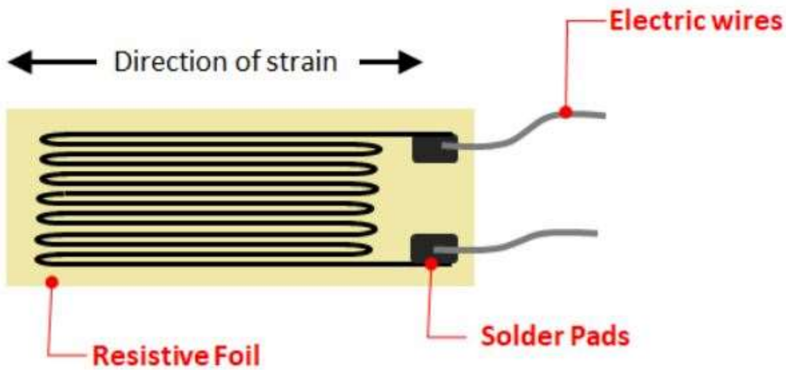


Figure 2. Foil strain gauges scheme. Source: https://learnchannel-tv.com/sensor/wheatstone-bridge/wheatstone-bridge-with-strain-gauge/

- The vibrating wire strain gauges are compose by a thin steel wire contained in a sealed steel tube tense between two anchorages attached to the structure. The anchorages could be directly welded to rebars and steel surfaces or embedded in concrete. The sensing devices working method is based on the analysis of the vibrating frequency of the wire. If the srecture is subjected to a deformation the distance between the two anchorages will change and also the vibrating frequency measure after an elettromagnetic pulse the is used to stimulate the wire. From the change of the frequency the strain is calculated.

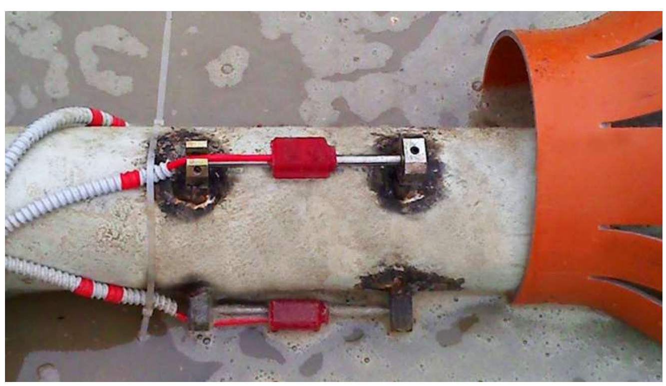


Figure 3. Vibrating wire strain gauges. Source: https://www.sisgeo.com/products/strain-gauges-and-thermometers/item/vibrating-wire-strain-gauges.html

- The optical fibre sensors are one of the innovative techniques of strain detection and are composed by long cables (the fibres) exposed to periodic ultraviolet light emissions that propagate through the lenght of the sensors. The reflected signal is analysed and is possible to discover differences between the reflection pattern in the undeformed and deformed stage. From the study of the pattern changes the value sof deformation can be obtained.

The advantages of this type of solutions are the easy of connection to the structure (usually the fibres are glued directly on the monitored surface), the compactness and immunity to elettromagnetic ineterferences. On the other hand, there are also some disadvantages such as the variability of measurements due to thermal variations, the high cost of the sensors and the log-term stability of fibres in a concrete environment due to chemical and mechanical impact of the concrete.

Figure 4. Example of fibre optic sensors glued on a beam specimen for a bending test. Source: http://trussitn.eu/wp-content/uploads/2017/06/ESR11-at-ESREL2017.pdf

- Smart sensors S3 are an innovative technology that has been recently developed (Tondolo 2016) and is based on the use an hard PCB and a barometric pressure sensor placed in a cavity drilled directly in the reinforcing bar. The sensor is connected to a soft PCB outside the cavity that is able to connect with the acquisition system. The cavity is sealed and the wire is placed in a dedicated slot along the rebar.

  The strain evaluation is based on the ideal gas law starting from the pressure values measured by the barometric sensor. This solution belongs to the family of MEMS (Micro Electro-Mechanical Systems) and is characterized by a low cost

that allows the designer to develop a diffused SHM system with a considerable number of sensors.
This type of sensors will be considered in the following SHM design process due to his favorable properties.

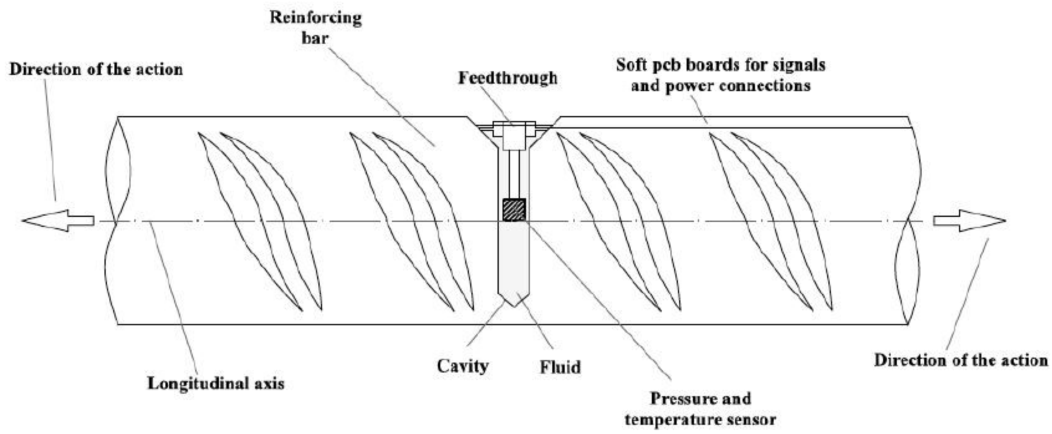


Figure 5. Smart sensor S3 scheme. Source: F. Tondolo, A. Cesetti, E. Matta, A. Quattrone, D. Sabia. Smart reinforcement steel bars embedded with low-cost MEMS sensors for strain monitoring.

1.2 Building Information Modeling

1.2.1 Historical context

Even if the construction industry plays a key role in global economics in the last few years has suffered an important crisis and is characterized by a huge financial waste due to the inefficiencies and waste of the construction and maintenance processes. According to the Construction Industry Institute in the USA the non added value related to the construction business is up to 57% and an urgent change of direction need to be considered by the different stakeholders in order to reduce the losses.

The AEC world has, moreover, an important role in the environmental issues. In fact, according to the U.S. National Building Information Modeling Standard, facilities consume up to 40% of the world’s energy. And so, consistently with the global trend of sustainability that has spread in many fields in the last decade, a more environmentally compatible building process needs to be developed.

Another critical point of the process is the need of a simple and unique way of exchanging files and informations among the different professional figures starting from a shared central model that could be used by the users with many different softwares in a circular way instead of a fragmented linear communication that requires more time and promotes the risk of errors and loss of data.

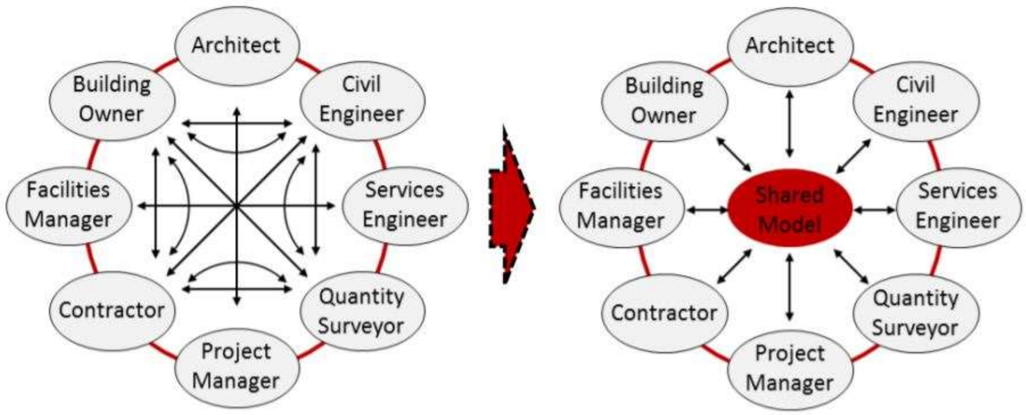


Figure 6. Comparison between traditional method and BIM. Source: A. Osello. Lecture: From CAD to BIM. New opportunities for the AEC industry.

At the start or the 21st century, because of the need of modernization and thanks to the development of the internet connection, a new construction and design methodology was born: Building Information Modelling (BIM). It is an ensemble of concepts and practices improved by innovative information technologies and design softwares that helps the stakeholders to reduce inefficiency and waste in the design and construction phases as well as in life cycle of the facility.

1.2.2 Definition

The concept of BIM may be interpreted with a double meaning, as a work process (Building Information Modeling) or as a way to represent the designed project (Building Information Model) even if the first interpretation has a more wide and general meaning and could be considered as the best way to define the concept.

According to the U.S. National Building Information Modeling Standard BIM is *"an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle."*

Another interesting definition is provided by the softwarehouse Autodesk, one of the top companies in the AEC software industry, that defines BIM as "*a process that begins with the creation of an intelligent 3D model and enables document management, coordination*

and simulation during the entire lifecycle of a project (plan, design, build, operation and maintenance).
BIM is used to design and document building and infrastructure designs. Every detail of a building is modeled in BIM. The model can be used for analysis to explore design options and to create visualizations that help stakeholders understand what the building will look like before it's built. The model is then used to generate the design documentation for construction."

And furthermore, according to Osello: *"As an activity, BIM is composed by the set of processes applied to create, manage, derive and communicate information among stakeholders at various levels, using models created by all participants to the building process, at different times and for different purposes, to ensure quality and efficiency throughout the entire building lifecycle.*
Instead, the building information model is an unambiguously defined digital representation of the physical and functional characteristics of a facility."

Figure 7. Example of operations involved in the BIM process. Source: https://blogs.opentext.com/why-level-3-building-information-modeling-is-about-to-change-everything/

The BIM methodology could be applied not only to the new structures but also to the existing facilities. This branch of the BIM is called HBIM (H stands for Heritage or Historic) and allows to efficiently manage the huge heritage of structures present in all the european countries and particularly in Italy.

For this type of approach the remote sensing technologies, such as laser scanner, are fundamental to reconstruct the 3D model, especially in case of ancient structure when accurate blueprints are not available.
According to Murphy in "*Historic building information modelling (HBIM)" : "Historic Building Information Modelling (HBIM) is a novel solution whereby interactive parametric objects representing architectural elements are constructed from historic data, these elements (including detail behind the scan surface) are accurately mapped onto a point cloud or image based survey.".*

1.2.3 BIM dimensions

The BIM methodology is able to handle all the step of the design and construction of the structures and allow the stakeholders to manage and plan the maintenance during the entire life-cycle. Due to the multiple abilities of this process a division in different "dimensions" is usually considered:

- **1st dimension**

The first dimension corresponds to the concept from which the project starts. This step related to the study of the location, the definition of the tentative geometry and a first costs analysis.

- **2nd dimension**

In this dimension the general characteristics of the project are defined such as materials, loads applied, structural scheme and 2D drawings. The amount of informations collected comapred to the previous level is higher.

- **3rd dimension**

With the informations previously determined a 3D digital model is created. Many different professional figures are involved in the production of the model that is in continuos evolution due to a dynamic process. The aim of this step is to obtain the As-built model.

- **4th dimension**

It is the temporal dimension. The evaluation of a time schedule of the design and construction process and of the facility's life cycle is contained in this dimension. Also time-space conflict analysis is performed. With BIM softwares, such as Revit, is possible to realize visualization of the different construction phases.

- **5th dimension**

It is related to the costs analysis and estimation. The final aim is to maintain the expenses within the fixed limits. In this step the amount of materials and the fees comparisons are realized.

- **6th dimension**

In this dimension the sustainability of the structure during the life cycle is evaluated taking into account energy estimations and other requirements. Simulations are performed to choose better technologies and obtain time and costs optimizations.

- **7th dimension**

Is the dimension of the facility manage during time and contains informations about the health state and the technical specification and the maintenance plans. This dimension is fundamental for infrastructures that are characterized by a service life of up to 100 years. The costs of construction and maintenance depends on the structural scheme that has been chosen during the planning phase and for this reason the decisions made in the planning and design stage are crucial.

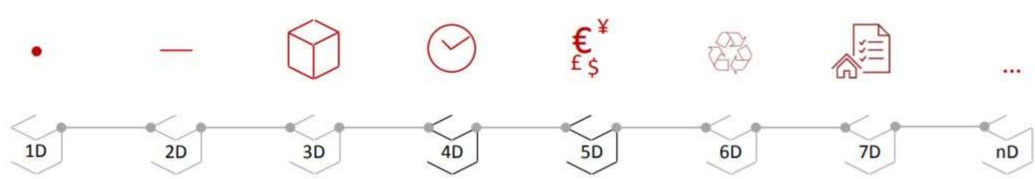


Figure 8. BIM dimensions. Source: A. Osello. Lecture: From CAD to BIM. New opportunities for the AEC industry.

1.2.4 Interoperability

The design of a structure is a complex process that involves many different professional figures belonging to different disciplines. The aim is to obtain a shared model that can be modified by each user with different softwares. For this reason is fundamental to optimize the exchange of informations between the various softwares and minimize the losses. This concept is key for the BIM process and is called *interoperability.*

The interoperability among softwares, according to the AFUL working group, is: *"Interoperability is a characteristic of a product or system, whose interfaces are* *completely understood. With respect to software, the term interoperability is used to describe the capability of different programs to exchange data via a common set of exchange formats, to read and write the same file formats, and to use the same protocols"*.

Even if this is one of the main issue in BIM and the softwarehouses have made many progresses in the process, interoperability is still a great issue and passing the model from a software to another causes very frequently data losses. This problem is present also between softwares produced by the same company and once it will be solved a great step to a more efficient methodology will be done.

Figure 9. Example of interoperability between different softwares.

In order to define some standard rules for the design with BIM was born Building Smart, a no-profit organization that manages to improve the collaborative design and construction of buildings and infrastructures. The association is constitued by several members such as softwarehouses, governative institutions and design and construction companies.

One of the main results of the work of the group is the definition of a standard format for the exchanging of data: the Industry Foundation Classes (IFC).

According to Building Smart, IFC is: *"a standardized, digital description of the built environment, including buildings and civil infrastructure. It is an open, international standard (ISO 16739-1:2018), 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."*

1.2.5 Diffusion of BIM

The BIM methodology usage is higly increasing in many countries all over the world. This diffusion is helped by dedicated government policies such as the one of Italian Minister of Infrastructure and Transport that with the DM01/12/2017 n.560 has gradually implemented the obligation of the BIM for projects over a certain amout of costs. The aim of this policy is to extend the obligation to every project in 2025.

Around the world many countries has already fully adopted the BIM method and are taking adavantage of it including the scandinavian countries (Norway, Denmark and Finland), anglo-saxon countries and Singapore (that is a leading country in technology innovation and implementation).

In particular some of them, such as Australia, US and Denmark, have already established the use of BIM in public projects as mandatory and other ones have developped dedicated standard rules to support this adoption process. One of the main examples is the ensamble of rules created by the British Standard Institute in United Kingdom that fixed some progressive steps to help the transition process from the traditional method towards BIM.

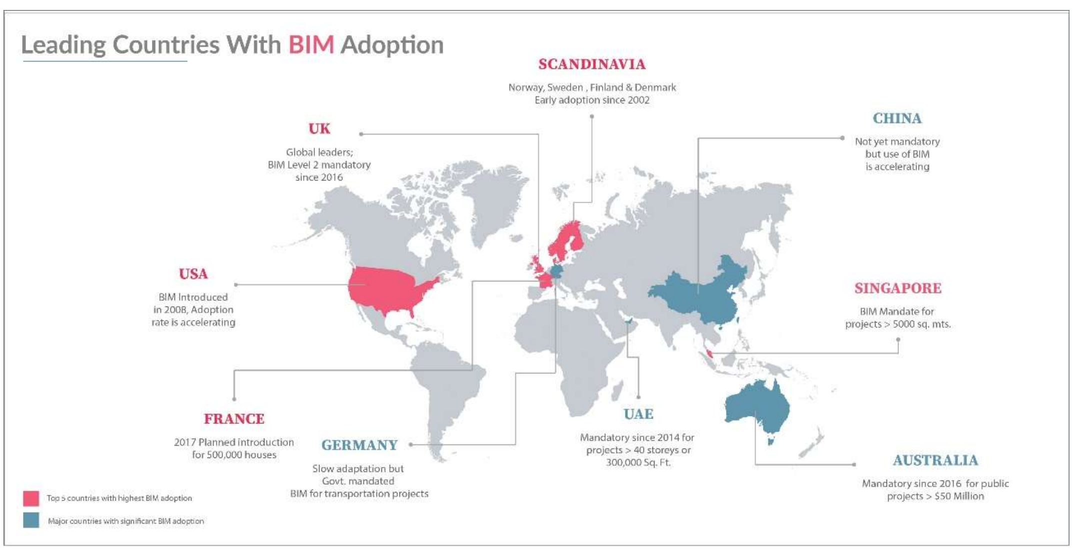


Figure 10. BIM diffussion around the world. Source: https://www.united-bim.com/leading-countries-with-bim-adoption/

Chapter 2: Elaboration of the SHM system

2.1 Goal of the thesis work

The aim of the thesis is the elaboration of an automatic method for the positioning of the components of the Structural Health Monitoring System in order to control the key zones of the structure and also to optimize the electrical wired connections and the data logger positions. In order to accomplish this task the BIM method will be used and a digital representation of the system will be created.

In particular the system is conceived for the monitoring of a new bridge structure with the application of a smart sensor S3 that are inserted in cavities drilled in the rebar of the structural elements that will be monitored.
The leading parameter for the choice fo the monitored structural parts is the bending moment and three different types of SHM level:

- low level of monitoring: each element with bending moment higher than the 70% of the max bending moment will be monitored

- medium level of monitoring: each element with bending moment higher than the 60% of the max bending moment will be monitored

- high level of monitoring: each element with bending moment higher than the 50% of the max bending moment will be monitored

This aspect of the process will be discussed more in depth later.
After the definition of the monitored elements a code for the automatic placement of the sensors into the digital twin model needs to be defined.

The final goal of the of the work is to obtain a faithful digital representation of the monitored structure containing the components of the SHM mechanism.
With this model the user will be able to check the timeline of values of the monitored quantities directly by clicking on the istances of the sensors in order to control the health conditions of the bridge.

The main concept is to create a system that will work in the same way a flight data recorder works for an airplane in order to collect and record all the needed information for state of health evaluations.

2.2 First case study

In order to set up the previously described system a simple structure has been designed on the software Autodesk Revit. In particular a simple multistorey building has been chosen instead of a bridge, that is the type of structure that will be monitored at the end of the process, because at first a more regular shape will help the design of the SHM system.

The structure is a three storey building characterized by plan and elevation irregularities and different cross section shapes of the structural members in order to have a great variety of geometries to deal with in SHM model. For example also some inclined beams are present in the building.

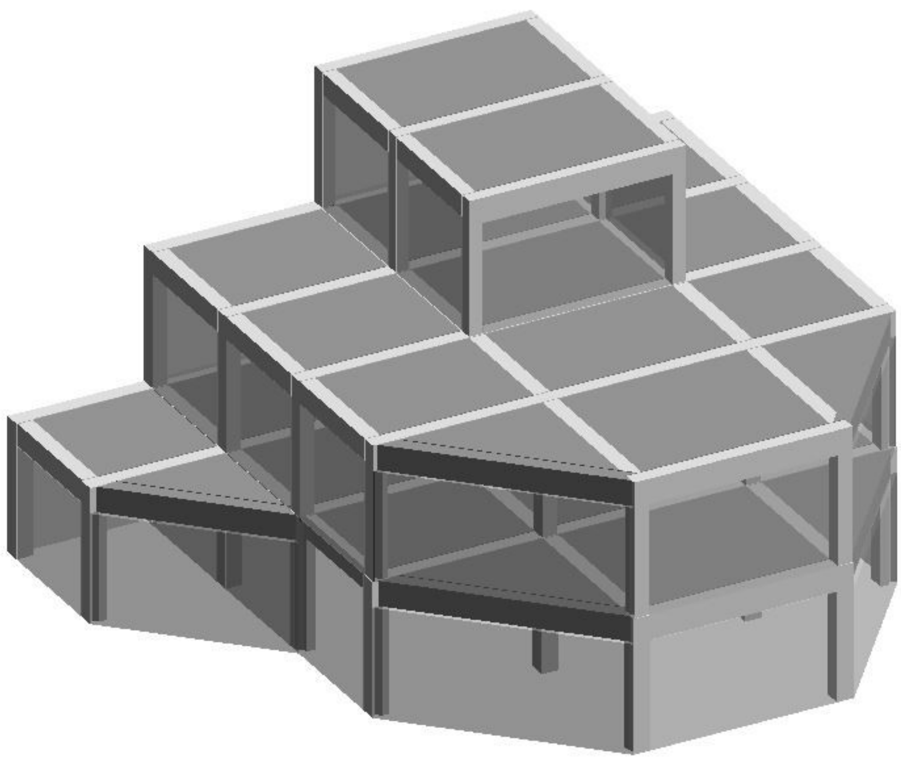


Figure 11. Revit representation of the monitored structure.

The frame of the structure is composed by many different cross sections:

- Beams: 450 mm x 650 mm, 450 mm x 750 mm, 400 mm x 750 mm, 400 mm x 650 mm;
- Columns: 400 mm x 400 mm, 450 mm x 450 mm, 500 mm x 500 mm;
- Floor: 300 mm;

The items that will be monitored are the columns and the beams.
In the following immages are shown a frontal prospect and first floor plan of the buildings directly obtained from Revit model.

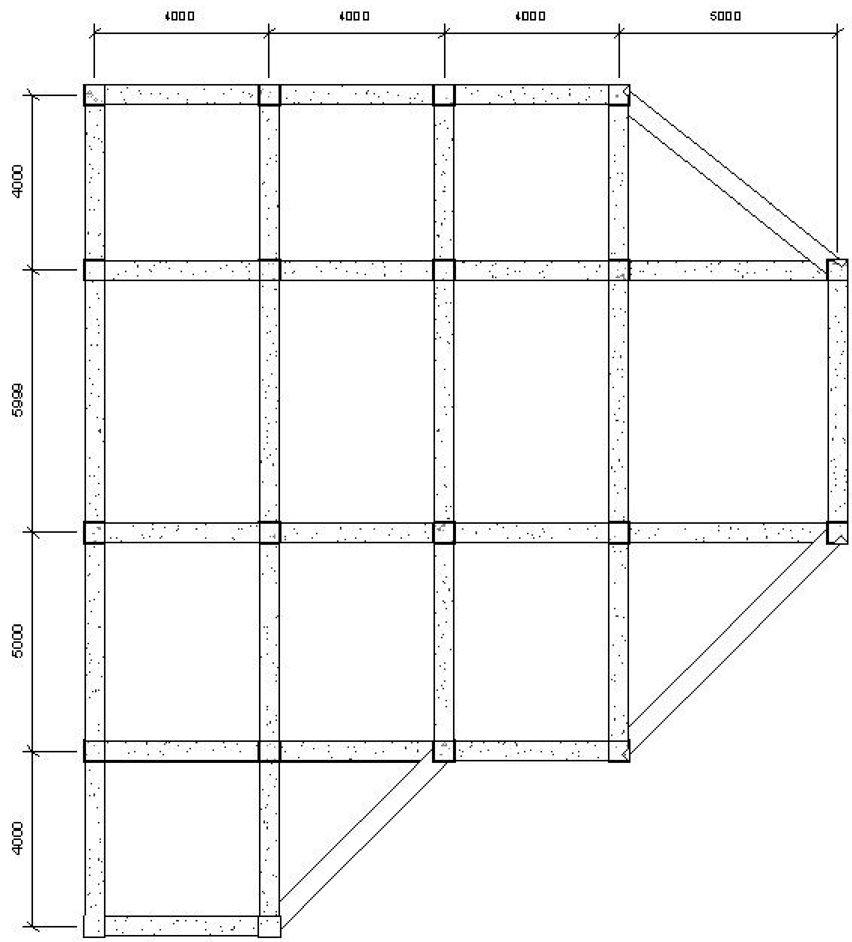


Figure 12. Plan view of the building’s first floor.

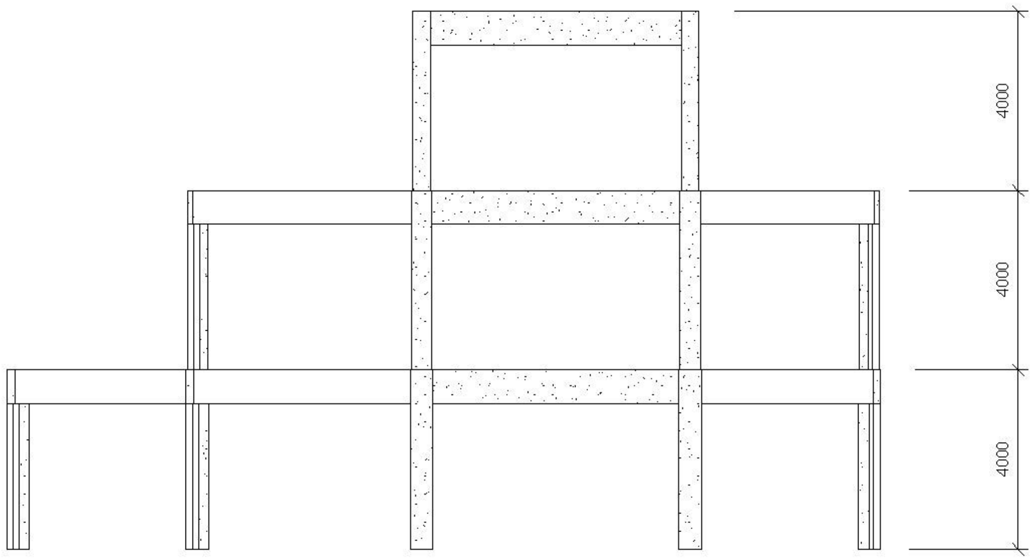


Figure 13. Prospect of the building.

2.3 Set up of the sensor family in Revit

The following step of the procedure is the design of the Revit family of the sensors. The first idea was to create directly a Smart Bar family composed by the rebar and the sensors contained.

The design of the sensor is based on the idea of the division in 5 different sections: the two extremities, the central part and two transition zones. The division is ruled by the distribution of the bending moment as the one of the following picture.

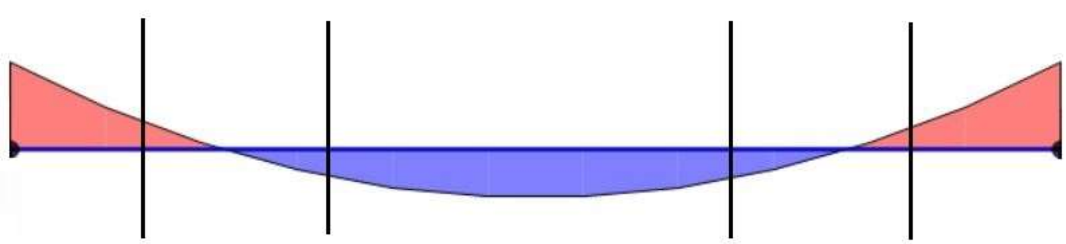


Figure 14. Bending moment distribution in a beam.

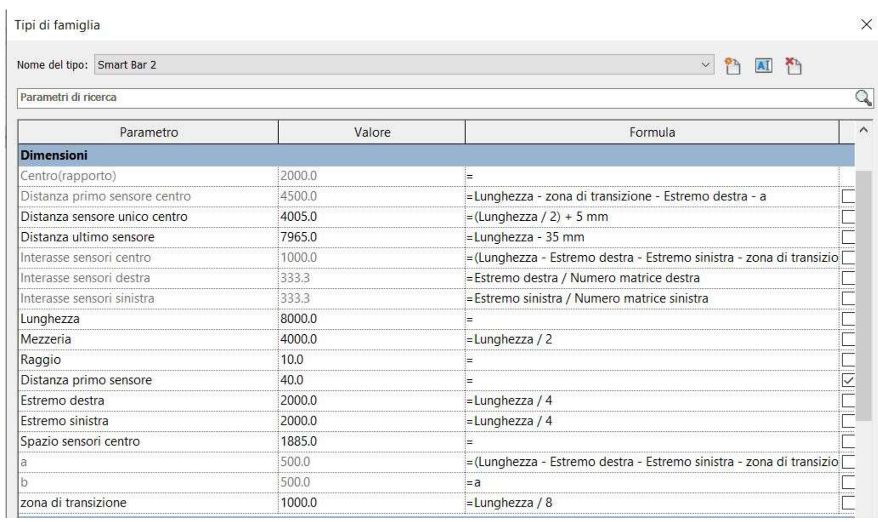
The two external sections and the central one are the more interesting parts of the beam, because are subjected to the higher stresses, and will host the sensor arrays.

The family is composed by two different components: the bar that is represented as an elongated cylinder and the S3 sensor that are displayed as cubes (10 mm x 10 mm x 10 mm) placed with their center on the axis of the bar.

The main characteristic of this Revit family is the possibility of changing the dimensions of the bar and the layout of the sensors in the different sections. For this purpose a set of parameters has been created.

The parameters belongs to different categories:

- Dimension parameters
- Lunghezza, Raggio: change the dimensions of the bar
- Estremo destra, Estremo sinistra, Centro, Zona di transizione: control the dimensions of the different sections of the bar
- Distanza primo sensore destra, Distanza primo sensore sinistra, Distanza primo sensore centro: define the position of the first sensor of the array for each monitored sector
- Interasse sensori destra, Interasse sensori sinistra, Interasse sensori centro: set the distance between the sensor of an array in function of the lenght of the sector and of the number of sensor


Tipi di famiglia

Nome del tipo: Smart Bar 2

Parametri di ricerca

Parametro	Valore	Formula	
Dimensioni			
Centro(rapporto)	2000.0	=	
Distanza primo sensore centro	4500.0	=Lunghezza - zona di transizione - Estremo destra - a	☐
Distanza sensore unico centro	4005.0	=(Lunghezza / 2) + 5 mm	☐
Distanza ultimo sensore	7965.0	=Lunghezza - 35 mm	☐
Interasse sensori centro	1000.0	=(Lunghezza - Estremo destra - Estremo sinistra - zona di transizio	☐
Interasse sensori destra	333.3	=Estremo destra / Numero matrice destra	☐
Interasse sensori sinistra	333.3	=Estremo sinistra / Numero matrice sinistra	☐
Lunghezza	8000.0	=	☐
Mezzeria	4000.0	=Lunghezza / 2	☐
Raggio	10.0	=	☐
Distanza primo sensore	40.0	=	☑
Estremo destra	2000.0	=Lunghezza / 4	☐
Estremo sinistra	2000.0	=Lunghezza / 4	☐
Spazio sensori centro	1885.0	=	☐
a	500.0	=(Lunghezza - Estremo destra - Estremo sinistra - zona di transizio	☐
b	500.0	=a	☐
zona di transizione	1000.0	=Lunghezza / 8	☐

Figure 15. Dimension parameters of the Smart Bar family.

- Visibility parameters

  The array of sensor are affected by a numerical problem: is not possible to set the number of sensors equal to 1. The problem is solved performing a workaround: a single element is placed over the first element of each array and some visibility parameters are setted in order to make disappear the array or the single element according to the number of wanted sensor.

  The parameters are:

Visibilità		
Visibilità matrice d	☑	=if(Numero sensori destra > 1, 1 = 1, 1 = 0)
Visibilità matrice s	☑	=if(Numero sensori sinistra > 1, 1 = 1, 1 = 0)
Visibilità singolo elemento c	☑	=if(Numero sensori centro = 1, 1 = 1, 1 = 0)
Visibilità matrice c	☐	=if(Numero sensori centro > 1, 1 = 1, 1 = 0)
Visibilità singolo elemento d	☐	=if(Numero sensori destra = 1, 1 = 1, 1 = 0)
Visibilità singolo elemento s	☐	=if(Numero sensori sinistra = 1, 1 = 1, 1 = 0)

Figure 16. Visibility parameters of the Smart Bar family.

- Other parameters

Are used to set the number of sensors for each array.

Altro			
Numero sensori centro	1	=	☐
Numero matrice centro	2	=if(Numero sensori centro < 2, 2, Numero sensori centro)	☐
Numero matrice destra	6	=if(Numero sensori destra < 2, 2, Numero sensori destra)	☐
Numero matrice sinistra	6	=if(Numero sensori sinistra < 2, 2, Numero sensori sinistra)	☐
Numero sensori destra	6	=	☐
Numero sensori sinistra	6	=	☐

Figure 17. Other parameters of the Smart Bar family.

The following images represent a possible sensor layout of the Smart Bar with 6 sensors for both the external sectors and 5 sensors in the central one.

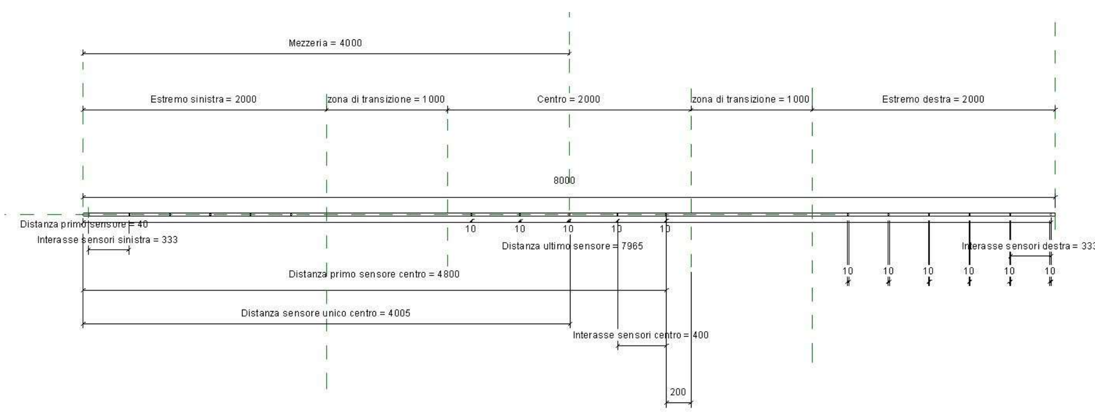


Figure 18. Possible layout of the sensors in the rebar.

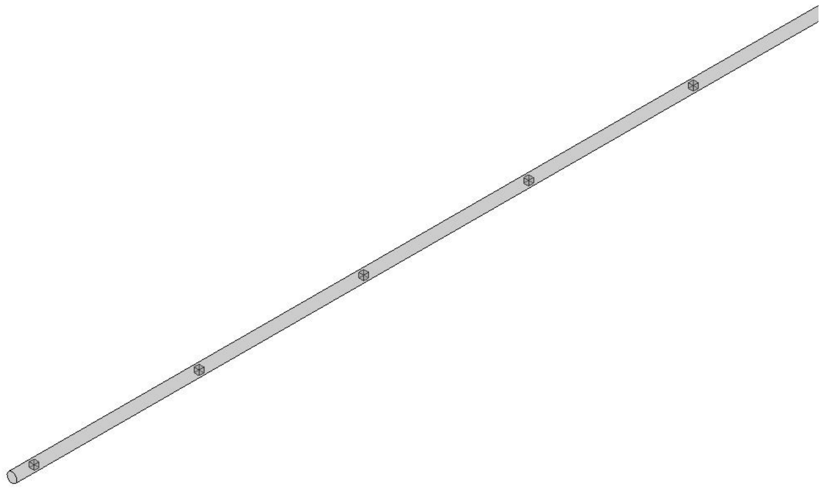


Figure 19. External portion of the Smart Bar.

After a more accurate analysis on the best way to place the sensors in the model some issues have appeared and so a new typology of sensor family has been created.

This new family contains only one sensor that is represented, as in the previous one, by a cube (10 mm x 10 mm x 10 mm) placed with his center on the axis of the bar. In this solution the rebar will be displayed as a separated family.

The position of the sensor is controlled by an Excel file that will be described later.

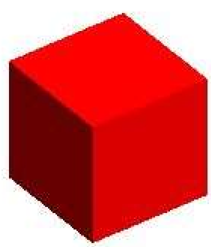


Figure 20. Single sensor family in Revit.

The type of family that has been chosen is "Dispositivi dati" and an electronic connector has been added to a face of the cube to allow the user to connect with other electronic devices in order to create circuits.

The parameters of the sensor family are:

- Allineamento: defines the position in the cross section of the element and could be "Estradosso" or "Intradosso" in the beams and "pp", "pn", "np" or "nn" in the columns where "p" means a positive displacement and "n" means a negative displacement both with respect to the center of the cross section.

- Armatura host: defines the identification code of the rebar that will host the sensor. The identification code is composed by the number of the structural element that contains the rebar and the position of the rebar in the cross section ("Estradosso" or "Intradosso" in the beams and "pp", "pn", "np" or "nn" in the columns).

- Elemento host: is the number of the structural element that contains the sensor.

- Posizione locale: defines the location of the sensor along the rebar in order to individuate the right position. The unit of measurement is meters.

- Deformazione: the family contains 10 parameters with the same characteristics that are creted with the aim to contain the values of deformations that are obtained by the measurements of the sensors.

Allineamento	Estradosso
Armatura host	56/Estradosso
Deformazione 01	0.000000
Deformazione 02	0.000000
Deformazione 03	0.000000
Deformazione 04	0.000000
Deformazione 05	0.000000
Deformazione 06	0.000000
Deformazione 07	0.000000
Deformazione 08	0.000000
Deformazione 09	0.000000
Deformazione 10	0.000000
Elemento Host	56
Posizione locale (m)	2.500000

Figure 21. Parameters of the Revit sensor family.

2.4 Workflow

Once the sensor family has been created the following step is the design of a routine for the setting of the parameters and the placing of the sensors in the Revit model of the monitored structure.

The workflow starts from the architectural model in Revit that can be exported in a structural analysis software in order to evaluate the stresses in all the elements of the structure. The result of the analysis will be a table of values of bending moments related to the ID of the structural element and to the position of the section along the element. For each element the table should display :

-Min Bending Moment

-Max Bending Moment

-Values of Bending Moment at the start and end of the element

-ID of the structural element

-Length of the structural element

Once obtained the table can be exported in Excel in order to select the elements with higher stress values which are the ones to be monitored. Then, with Dynamo, the sensors are placed in the Revit model in the previously identified structural elements.

Two other Dynamo scripts will be created: one for the placement of the rebars that contain the sensors in the monitored structural elements and other one for the manual positioning of the sensors in the elements chosen directly by the user.

2.5 Structural model on Autodesk Robot

For the elaboration of the structural model the software Autodesk Robot has been chosen due to its good interoperability with Revit. The good interaction among the two softwares, that are developped by the same softwarehouse, allows a simple transition from the model in Revit to the structural one with a plug-in contained in the menu "Analizza".

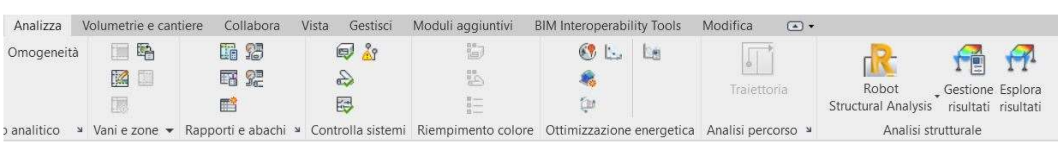


Figure 22. Robot Structural Analysis link in Revit.

With a simple click on the link button the model is exported in Robot and converted in a structural representation.

Even if the connetion works appropriately some errors and imperfection appears and need to be corrected manually. On the other hand create from the beginning a new structural model will require much more time and for this reason the use of the link function seemed to be the best solution for this task.

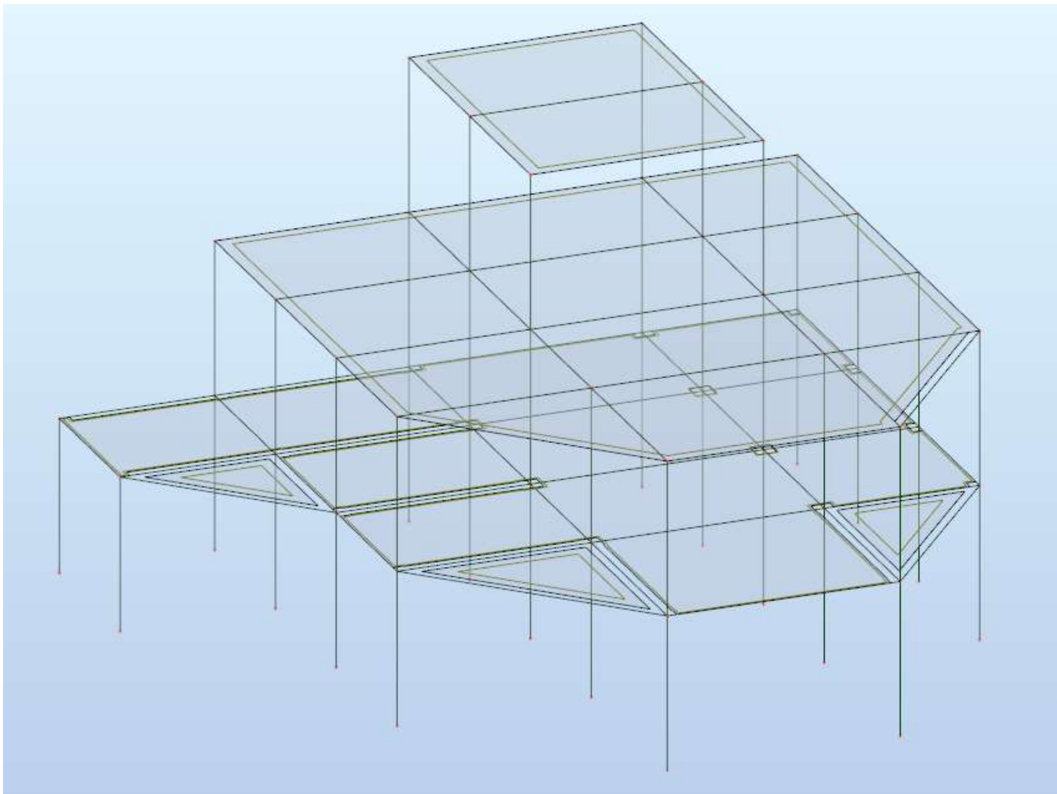


Figure 23. Structural model obtained by exportation from Revit.

In this case study, after the exportation, some errors happened and needed to be fixed manually. In particular the main error is the material of the structural elements that is not recognized in the Robot model and has been setted again manually.

Another imperfection is the lack of the constraints at the base of the ground floor columns and even in this case the problem is solved rapidly by manual setting.

Then the next step was to define load combinations for the structural analysis.

The load cases used for the combinations are:

- dead load (DL): contains the weight of the structure,
- live load (LL): contains the imposed load of 2kN/m^2 according to NTC2018 and is ditributed on the area of the three floors,
- snow load (SNOW): is a distributed load of 0,8 kN/m^2 obtained considering the building located in "Zona I" and surrounded by higher constructions or natural

elements. The load is distributed on a part of the second floor and on the third one beacuse are the ones exposed to weather conditions.

$$q_s = q_{sk} \cdot \mu_i \cdot C_E \cdot C_t$$

dove:

q_{sk}	è il valore di riferimento del carico della neve al suolo, di cui al § 3.4.2;
μ_i	è il coefficiente di forma della copertura, di cui al § 3.4.3;
C_E	è il coefficiente di esposizione di cui al § 3.4.4;
C_t	è il coefficiente termico di cui al § 3.4.5.

Figure 24. Snow load calculation according to NTC2018.

- accidental load (ACC): is a concentrated load of 7 kN located in the midspan of a first floor beam. The load is used to simulate the presence of a heavy machine like ones used in hospitals and is obtained acording to NTC2018.

With the previous load cases have been created 6 load combination (3 for the SLU and 3 for the SLE):

- SLU1 (live load dominant): 1,3xDL + 1,5xLL + 1,5x0,7xSNOW + 1,5x0,7xACC
- SLU2 (snow load dominant): 1,3xDL + 1,5xSNOW + 1,5x0,7xLL + 1,5x0,7xACC
- SLU3 (accidental load dominant): 1,3xDL + 1,5xACC + 1,5x0,7xLL + 1,5x0,7xSNOW
- SLE RARA: 1,0xDL + 1,0xLL + 0,7xSNOW + 0,7xACC
- SLE FREQUENTE: 1,0xDL + 0,7xLL + 0,2xSNOW + 0,8xACC
- SLE QUASI PERMANENTE: 1,0xDL + 0,6xLL + 0,2xSNOW + 0,8xACC

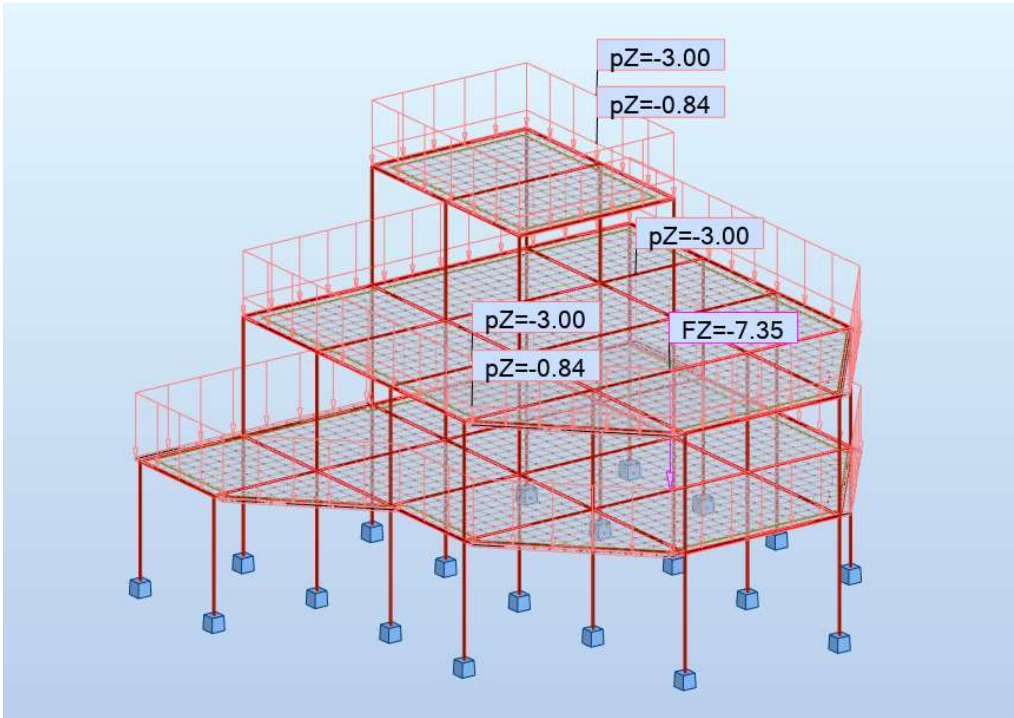


Figure 25. Load combination SLU1. The value of the loads are already multiplied by the combination coefficients.

Once the combination were setted, the following step was to run the analysis in Robot. The software calculate the structure in a few seconds and then the results are available. In particular the user can choose from a dedicated menu the typology of solutions for each load combination and customize the visualization of the stress diagrams.

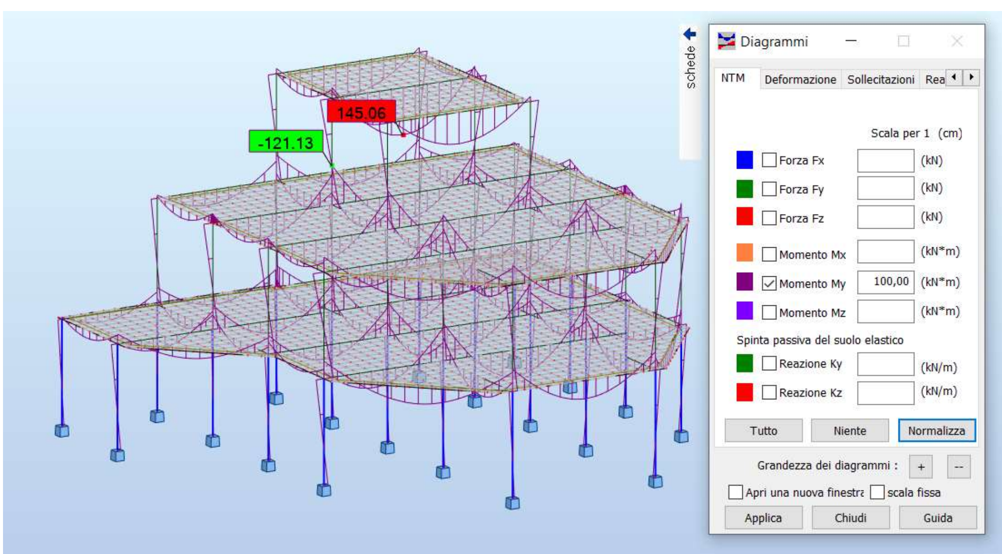


Figure 25. Bending moment diagram of the structure under the load combination SLU1.

As regards the management of the results, Robot allows the user to create tables of data that could be customized according to the different needs by choosing the wanted informations and adding or deleting columns.

Even if for the purpose of this thesis work the most interesting values are the one of the bending moment all the data of forces and moments have been selected for the creation of table of results and also two columns with the number and the lenght of the corresponding structural element.

In particular the number of the structural element is fundamental in order to relate the data to the structural element in Revit because after the exportation Robot renumbered the elements with a different order.

In addition the number of points for each element in which the forces and moments are calculted has been setted to 8.

Forze - Condizioni: 9a14

Elemento/Punto/Condiz.	FX (kN)	FY (kN)	FZ (kN)	MX (kNm)	MY (kNm)	MZ (kNm)	Nome	Lunghezza (m)
1/ 1/ 9 (C)	880,47	-0,50	4,16	-0,00	-5,56	-0,85	8	4,00
1/ 1/ 10 (C)	839,59	-0,44	3,88	-0,00	-5,19	-0,74	8	4,00
1/ 1/ 11 (C)	826,53	-0,46	3,84	-0,00	-5,14	-0,77	8	4,00
1/ 1/ 12 (C)	655,73	-0,38	3,08	-0,00	-4,12	-0,63	8	4,00
1/ 1/ 13 (C)	605,29	-0,36	2,83	-0,00	-3,79	-0,60	8	4,00
1/ 1/ 14 (C)	593,31	-0,35	2,76	-0,00	-3,69	-0,58	8	4,00
1/ 2/8/ 9 (C)	875,83	-0,50	4,16	-0,00	-3,19	-0,56	8	4,00
1/ 2/8/ 10 (C)	834,95	-0,44	3,88	-0,00	-2,98	-0,49	8	4,00
1/ 2/8/ 11 (C)	821,89	-0,46	3,84	-0,00	-2,95	-0,51	8	4,00
1/ 2/8/ 12 (C)	652,16	-0,38	3,08	-0,00	-2,36	-0,41	8	4,00
1/ 2/8/ 13 (C)	601,72	-0,36	2,83	-0,00	-2,17	-0,39	8	4,00
1/ 2/8/ 14 (C)	589,73	-0,35	2,76	-0,00	-2,11	-0,38	8	4,00
1/ 3/8/ 9 (C)	871,19	-0,50	4,16	-0,00	-0,81	-0,27	8	4,00
1/ 3/8/ 10 (C)	830,30	-0,44	3,88	-0,00	-0,76	-0,24	8	4,00
1/ 3/8/ 11 (C)	817,24	-0,46	3,84	-0,00	-0,75	-0,25	8	4,00
1/ 3/8/ 12 (C)	648,59	-0,38	3,08	-0,00	-0,60	-0,20	8	4,00
1/ 3/8/ 13 (C)	598,15	-0,36	2,83	-0,00	-0,55	-0,19	8	4,00
1/ 3/8/ 14 (C)	586,16	-0,35	2,76	-0,00	-0,54	-0,18	8	4,00
1/ 4/8/ 9 (C)	866,54	-0,50	4,16	-0,00	1,56	0,02	8	4,00
1/ 4/8/ 10 (C)	825,66	-0,44	3,88	-0,00	1,46	0,01	8	4,00
1/ 4/8/ 11 (C)	812,60	-0,46	3,84	-0,00	1,45	0,01	8	4,00
1/ 4/8/ 12 (C)	645,02	-0,38	3,08	-0,00	1,16	0,01	8	4,00
1/ 4/8/ 13 (C)	594,57	-0,36	2,83	-0,00	1,07	0,02	8	4,00
1/ 4/8/ 14 (C)	582,59	-0,35	2,76	-0,00	1,04	0,02	8	4,00
1/ 5/8/ 9 (C)	861,90	-0,50	4,16	-0,00	3,94	0,31	8	4,00
1/ 5/8/ 10 (C)	821,02	-0,44	3,88	-0,00	3,68	0,26	8	4,00
1/ 5/8/ 11 (C)	807,96	-0,46	3,84	-0,00	3,64	0,28	8	4,00
1/ 5/8/ 12 (C)	641,45	-0,38	3,08	-0,00	2,92	0,23	8	4,00
1/ 5/8/ 13 (C)	591,00	-0,36	2,83	-0,00	2,69	0,23	8	4,00
1/ 5/8/ 14 (C)	579,02	-0,35	2,76	-0,00	2,62	0,22	8	4,00
1/ 6/8/ 9 (C)	857,26	-0,50	4,16	-0,00	6,32	0,59	8	4,00
1/ 6/8/ 10 (C)	816,37	-0,44	3,88	-0,00	5,89	0,51	8	4,00
1/ 6/8/ 11 (C)	803,32	-0,46	3,84	-0,00	5,84	0,54	8	4,00
1/ 6/8/ 12 (C)	637,88	-0,38	3,08	-0,00	4,68	0,44	8	4,00
1/ 6/8/ 13 (C)	587,43	-0,36	2,83	-0,00	4,31	0,44	8	4,00
1/ 6/8/ 14 (C)	575,45	-0,35	2,76	-0,00	4,20	0,42	8	4,00
1/ 7/8/ 9 (C)	852,61	-0,50	4,16	-0,00	8,69	0,88	8	4,00
1/ 7/8/ 10 (C)	811,73	-0,44	3,88	-0,00	8,11	0,76	8	4,00

Figure 26. Results table from Robot analysis.

2.6 Data management on Excel

Once the table has been created, Robot allows the exportation to Excel where the data have been used to choose the monitored elements and the sensors positions.

The data were divided in two different Excel files, one for the columns and one for the beams due to the different location of the stress concetration zones. In fact for the beams the monitored sectors are three (the two extremities and the midspan zone) and for the columns the zones subjected to major bending moment are only the top and the bottom.

2.6.1 Beams Excel file

The file is composed by 8 different sheet: "Inviluppi", "Momenti travi", "50", "60", "70", "Dynamo50", "Dynamo60" and "Dynamo70".

The Excel sheet called "Inviluppi" has been created to obtain the envelope of the forces and moments.

In particular, for each one of the eight sections in which the structural elements are divided, the envelope contains the maximum value (in absolute value) of forces Fx, Fy and Fz and bending moments Mx, My and Mz considering the 6 different load combinations.

Name	Length (m)	Inviluppo FX (kN)	Inviluppo FY (kN)	Inviluppo FZ (kN)	Inviluppo MX (kNm)	Inviluppo MY (kNm)	Inviluppo MZ (kNm)
68	4	-2,75	0,09	50,57	-2,53	-23,37	0,04
68	4	-2,48	0,01	39,33	-2,35	3,66	0
68	4	-2,23	0	23,66	-1,98	23,25	-0,01
68	4	-2,02	0	5,22	-1,51	32,5	0
68	4	-1,85	0	-14,02	-1,02	29,99	-0,01
68	4	-1,72	0,01	-32,21	-0,58	15,8	-0,01
68	4	-1,6	-0,02	-47,27	-0,23	-8,41	0
68	4	-1,52	-0,13	-57,26	0,06	-39,36	0,06
64	4	-3,09	-0,05	53,31	1,73	-22,84	-0,01
64	4	-2,66	0	39,66	1,53	4,79	0,01
64	4	-2,38	0	23,66	1,35	24,53	0,01
64	4	-2,15	0	4,87	1,14	33,71	0
64	4	-1,97	0	-14,73	0,91	30,89	0,01
64	4	-1,82	0	-33,19	0,69	16,19	0,01
64	4	-1,7	0,02	-48,37	0,47	-8,63	0
64	4	-1,61	0,08	-58,38	0,26	-40,23	-0,03
69	4	-1,54	0,26	51,51	-0,77	-37,88	0,12
69	4	-1,52	0,05	41,58	-0,55	-10,2	0,01
69	4	-1,5	0	26,57	-0,27	10,77	-0,01
69	4	-1,48	0	8,49	0,07	21,76	-0,01
69	4	-1,47	0,01	-10,58	0,43	21,17	-0,01
69	4	-1,45	0,01	-28,68	0,75	8,97	-0,01
69	4	-1,44	0	-43,72	0,99	-13,21	-0,01
69	4	-1,43	-0,09	-53,71	1,18	-42,14	0,03

Figure 27. Envelope of forces and moments for beams.

Then the sheet called "Momenti travi" is used to collect together the values of the envelop in a way that is convenient in order to be recalled by the succesive sheets.

The following sheets are the result of the main idea on which the Structural Health Monitoring System construction is based: the division in three different monitoring levels.

In fact, starting from the maximum value of bending moment recorded in the structure, the three monitoring levels are designed in order to control:

- All the elements with a bending moment higher than the 50% of the maximum bending moment (High SHM Level),
- All the elements with a bending moment higher than the 60% of the maximum bending moment (Medium SHM Level),
- All the elements with a bending moment higher than the 70% of the maximum bending moment (Low SHM Level).

With this purpose, three different Excel sheets have been created: “50”, “60” and “70”.

The structure of each sheet is the same and for this reason only one of them will be described.

Considering the sheet “50”, all the bending moment data are collected in a column with the number of the element and the length and filtered with respect to a percentile (50%) of the maximum bending moment of the beams. If the maximum bending moment in a beam is lower than the fixed threshold the correspondent lines are setted as empty.

In order to collect together the elements that need to be monitored has been used a filter that neglect all the empty cells of the interested columns.

Name	MY (kNm)	Length (m)	Max (kNm)
51	-93,37	6,00	102,30
51	-16,49	6,00	102,30
51	40,60	6,00	102,30
51	70,42	6,00	102,30
51	69,12	6,00	102,30
51	36,72	6,00	102,30
51	-22,93	6,00	102,30
51	-102,30	6,00	102,30
54	0,00	6,00	104,07
54	-16,91	6,00	104,07
54	39,57	6,00	104,07
54	68,91	6,00	104,07
54	67,32	6,00	104,07
54	34,82	6,00	104,07
54	-24,79	6,00	104,07
54	-104,07	6,00	104,07
57	-103,59	6,00	116,61
57	-19,67	6,00	116,61
57	43,50	6,00	116,61
57	77,90	6,00	116,61
57	76,03	6,00	116,61
57	37,88	6,00	116,61
57	-29,01	6,00	116,61
57	-116,61	6,00	116,61

Figure 28. Filtered data of monitored beams.

Once obtained the information on the monitored beams, a further subdivision has been made in three different levels of Structural Health Monitoring:

- Level 1: beams with bending moment higher than 50% and lower than 60% of the maximum,
- Level 2: beams with bending moment higher than 60% and lower than 70% of the maximum,
- Level 3: beams with bending moment higher than 70%.

For each level a different spacing of the sensors is considered in order to have an higher density of sensors in the zones of the beam subjected to higher bending moments.

In particular for Level 1 hase been chosen an interaxis of 1 m, for Level 2 of 0,5 m and for Level 3 of 0,25 m.

Then the length of each beam was divided in 5 parts:

- two external sectors of length equal to 1/4 of the length of the beam,
- a central sector with a length equal to 1/4 of the length of the beam,
- two transition sectors with a length of 1/8 of the length of the beam.

After the calculation of the length of each portion the number of sensors contained is obtained by simple multiplicaion of the length by the interaxis correspondent to the monitoring level.

The sensors are located mainly in the external and central sections and the number is ruled by the level of monitoring that depends in turn to the maximum value of bending moment in the beam. For this reason the interaxis in the monitored portion of a beam is always the same and is not possible, for istance, to have a different spacing in the external sector compared to the central one.

This decision was made in order to not weigh down the process of calculation and placing of the sensors.

Concerning to the transition zones a different rule has been setted: if the beam is longer than 5 m a single sensor will be placed in the middle of the each transition portion.

This setting was designed in order to avoid an excess of sensors in short beams both for costs efficiency and lack of usefulness.

Smart Bar Parameters			
Length left section (m)	1,375	N. sensors left	6
Length central section (m)	1,375	N. sensors center	6
Length right section (m)	1,375	N. sensors right	6

Figure 29. Example of sectors length and number of sensors calculation.

The final part of the Excel sheet is related to the calculation of sensor positions.

The position depends on the thickness of the concrete cover, half the width of the column adjacent to the monitored beam and the value of the interaxis that depends on the level of monitoring defined previously.

In the following figure are represented the position of the sensors in a beam with a length of 6 m and a bending moment higher than the 70% of the maximum bending moment (Level 3).

		Posizione sensori (mm)				
1	2	3	4	5	6	sensori intermedi
300,00	550,00	800,00	1050,00	1300,00	1550,00	1968,75
3625,00	3375,00	3125,00	2875,00	2625,00	2375,00	4031,25
5700,00	5450,00	5200,00	4950,00	4700,00	4450,00	

Figure 30. Position of the sensors in the monitored beam.

2.6.2 Columns Excel file

The file is composed by 8 different sheet: “Inviluppi”, “Momenti travi”, “50”, “60”, “70”, “Dynamo50”, “Dynamo60” and “Dynamo70”.

The Excel sheet called “Inviluppi” has been created to obtain the envelope of the forces and moments.

In particular, for each one of the eight sections in which the structural elements are divided, the envelope contains the maximum value (in absolute value) of forces Fx, Fy and Fz and bending moments Mx, My and Mz considering the 6 different load combinations.

Case/Bar/Point	FX (kN)	FY (kN)	FZ (kN)	MX (kNm)	MY (kNm)	MZ (kNm)	Name	Length (m)	Inviluppo FX	Inviluppo FY	Inviluppo FZ	Inviluppo MX	Inviluppo MY	Inviluppo MZ
1/ 1/ 9 (C)	880,47	-0,5	4,16	0	-5,56	-0,85	8	4	880,47	-0,5	4,16	0	-5,56	-0,85
1/ 2/8/ 9 (C)	875,83	-0,5	4,16	0	-3,19	-0,56	8	4	875,83	-0,5	4,16	0	-3,19	-0,56
1/ 3/8/ 9 (C)	871,19	-0,5	4,16	0	-0,81	-0,27	8	4	871,19	-0,5	4,16	0	-0,81	-0,27
1/ 4/8/ 9 (C)	866,54	-0,5	4,16	0	1,56	0,02	8	4	866,54	-0,5	4,16	0	1,56	0,02
1/ 5/8/ 9 (C)	861,9	-0,5	4,16	0	3,94	0,31	8	4	861,9	-0,5	4,16	0	3,94	0,31
1/ 6/8/ 9 (C)	857,26	-0,5	4,16	0	6,32	0,59	8	4	857,26	-0,5	4,16	0	6,32	0,59
1/ 7/8/ 9 (C)	852,61	-0,5	4,16	0	8,69	0,88	8	4	852,61	-0,5	4,16	0	8,69	0,88
1/ 2/ 9 (C)	847,97	-0,5	4,16	0	11,07	1,17	8	4	847,97	-0,5	4,16	0	11,07	1,17
2/ 3/ 9 (C)	825,61	-0,5	-5,82	0	7,77	-0,83	13	4	825,61	-0,5	-5,82	0	7,77	-0,83
2/ 2/8/ 9 (C)	820,97	-0,5	-5,82	0	4,44	-0,55	13	4	820,97	-0,5	-5,82	0	4,44	-0,55
2/ 3/8/ 9 (C)	816,32	-0,5	-5,82	0	1,12	-0,26	13	4	816,32	-0,5	-5,82	0	1,12	-0,26
2/ 4/8/ 9 (C)	811,68	-0,5	-5,82	0	-2,21	0,02	13	4	811,68	-0,5	-5,82	0	-2,21	0,02
2/ 5/8/ 9 (C)	807,04	-0,5	-5,82	0	-5,54	0,31	13	4	807,04	-0,5	-5,82	0	-5,54	0,31
2/ 6/8/ 9 (C)	802,39	-0,5	-5,82	0	-8,86	0,59	13	4	802,39	-0,5	-5,82	0	-8,86	0,59
2/ 7/8/ 9 (C)	797,75	-0,5	-5,82	0	-12,19	0,87	13	4	797,75	-0,5	-5,82	0	-12,19	0,87
2/ 4/ 9 (C)	793,11	-0,5	-5,82	0	-15,51	1,16	13	4	793,11	-0,5	-5,82	0	-15,51	1,16
3/ 5/ 9 (C)	498,4	7,25	-3,71	0	4,95	9,51	12	4	498,4	7,25	-3,71	0	4,95	9,51
3/ 2/8/ 9 (C)	493,76	7,25	-3,71	0	2,83	5,37	12	4	493,76	7,25	-3,71	0	2,83	5,37
3/ 3/8/ 9 (C)	489,11	7,25	-3,71	0	0,71	1,23	12	4	489,11	7,25	-3,71	0	0,71	1,23
3/ 4/8/ 9 (C)	484,47	7,25	-3,71	0	-1,41	-2,91	12	4	484,47	7,25	-3,71	0	-1,41	-2,91
3/ 5/8/ 9 (C)	479,83	7,25	-3,71	0	-3,53	-7,05	12	4	479,83	7,25	-3,71	0	-3,53	-7,05
3/ 6/8/ 9 (C)	475,18	7,25	-3,71	0	-5,65	-11,19	12	4	475,18	7,25	-3,71	0	-5,65	-11,19
3/ 7/8/ 9 (C)	470,54	7,25	-3,71	0	-7,77	-15,33	12	4	470,54	7,25	-3,71	0	-7,77	-15,33
3/ 6/ 9 (C)	465,9	7,25	-3,71	0	-9,89	-19,47	12	4	465,9	7,25	-3,71	0	-9,89	-19,47

Figure 31. Envelope of forces and moments for beams.

A sheet called "Momenti colonne" like the one the beam's Excel file is used reorder the values of the envelope.

The following sheets are organized on three SHM levels as for the beams ones. In particular the sheets are:

- "50": all the structural elements with a bending moment higher than 50% if the max bending moment in the structure are considered,
- "60": all the structural elements with a bending moment higher than 60% if the max bending moment in the structure are considered,
- "70": all the structural elements with a bending moment higher than 70% if the max bending moment in the structure are considered.

Also for the columns a further subdivision has been made in three different levels of Structural Health Monitoring:

- Level 1: beams with bending moment higher than 50% and lower than 60% of the maximum,
- Level 2: beams with bending moment higher than 60% and lower than 70% of the maximum,
- Level 3: beams with bending moment higher than 70%.

For each level a different spacing of the sensors is considered in order to have an higher density of sensors in the zones of the beam subjected to higher bending moments.

In particular for Level 1 hase been chosen an interaxis of 1 m, for Level 2 of 0,5 m and for Level 3 of 0,25 m.

The main difference with respect to the beams file is the subdivision of the length of the columns. Each column is subdivided in three portion with a legth of 1/3 of the total length of the element.

In the top and base sectors the number of sensors contained is calculated by simple multiplicaion of the length by the interaxis correspondent to the monitoring level.

In the central portion is placed only one sensor in the middle of the lenght of the column because is a part of the structural element that is subject to low bending moment and is not particularly interesting for monitoring purposes.

Smart Bar Parameters			
Length Down section (m)	1,08	N. sensors Down	2
Length up section(m)	1,08	N. sensors up	2

Figure 32. Example of sectors length and number of sensors calculation.

The final part of the Excel sheet is related to the calculation of sensor positions.

The position depends on the thickness of the concrete cover, the width of the beam located on top of the monitored column and the value of the interaxis that depends on the level of monitoring defined previously.

In the following figure are represented the position of the sensors in a column with a length of 4 m and a bending moment higher than the 60% of the maximum bending moment (Level 3).

		Posizione sensori (mm)				
1	2	3	4	5	6	sensori intermedi
80	580					2000
3170	2670					

Figure 33. Position of the sensors in a monitored colum.

2.7Automatic sensors positioning in Revit model with Dynamo

2.7.1 Dynamo and visual programming

Dynamo is an open source visual programming platform belonging to Autodesk softwares. Can be used as an independent software or as a plug-in that is contained in the visual programming section of the Revit menu.

Figure 34. Dynamo logo. Source: https://primer.dynamobim.org/it/

During the design process a lot of visual and geometric relationship are created according to a workflow that leads the designer from the concept to the result. This process is, in fact, an algorithm and programming could help to solve the task in a more formal and smart way.

This work method is called visual programming and is very usefull to solve problems in great projects saving time that cuold be spent better.

In particular Dynamo can be used to create geometries in the Revit environment or to place revit families in a wanted location and many other features.

The Dynamo interface is simple and userfriendly and is composed by a workspace and a side menu that contains the nodes and packages.

The nodes are the functions that are used to create the algorithm and packages are group of nodes that are gathered together because of their capability to solve similar tasks.

Some packages are contained by default in Dynamo and other can be downloaded. Dynamo is an open source software and the users community is usefull to find packages and node that are developped by members.

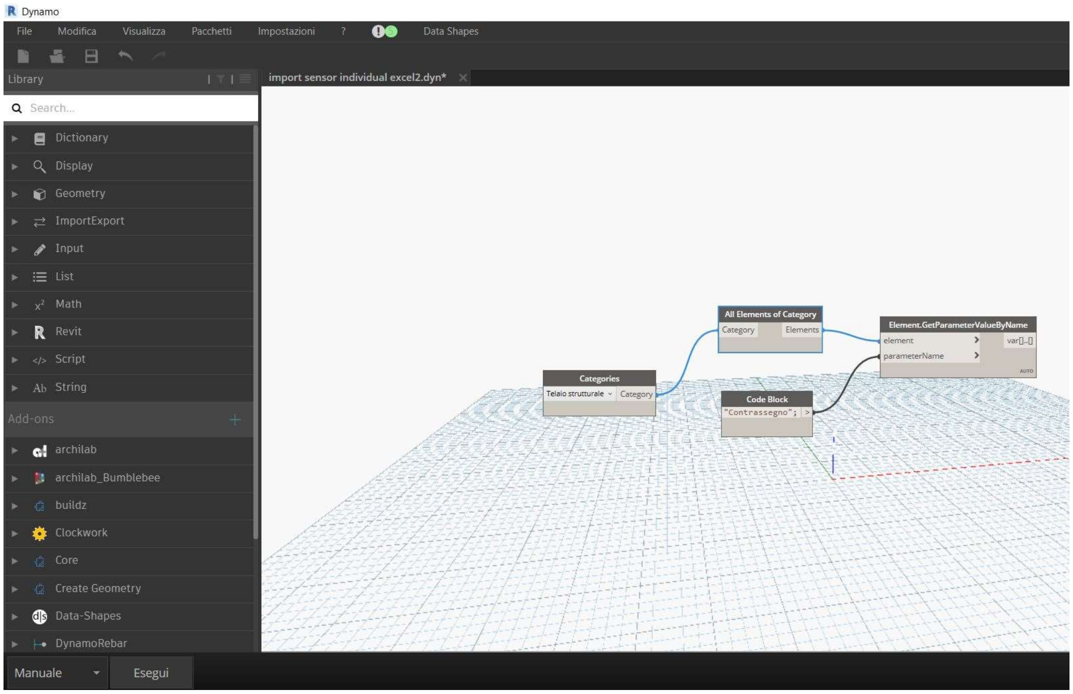


Figure 35. Example of the Dynamo interface.

The script can be creted by adding the needed node by the menu and connecting them together with wires. Each node applies a function to the input data and gives back an output data thata can be connected to another node.

The possibility to visualize the functions and their connections enables a simple working method and for this reason the Dynamo language is much easier than the other programming languages.

2.7.2 Automatic sensor placement script

The role of Dynamo in the workflow of the Structural Health Monitoring system design is to elaborate the sensor position calculated in Excel files previously described in order to place the sensor instances in the Revit model of the building.

2.7.2.1 SHM level selection

The script designed for the case study of the three storey building starts with a group of nodes dedicated to the selection of the monitoring level. In particular are used three nodes from the package Data Shapes (TextNote Data, RadioButtons Data and MultipleInputForm ++) in order to create an interface that allows the user to select between three different monitoring levels:

- High monitoring level: each structural element with bending moment higher than 50% of the maximum bending moment in the structure will be monitored,
- Medium monitoring level: each structural element with bending moment higher than 60% of the maximum bending moment in the structure will be monitored,
- Low monitoring level: each structural element with bending moment higher than 70% of the maximum bending moment in the structure will be monitored.

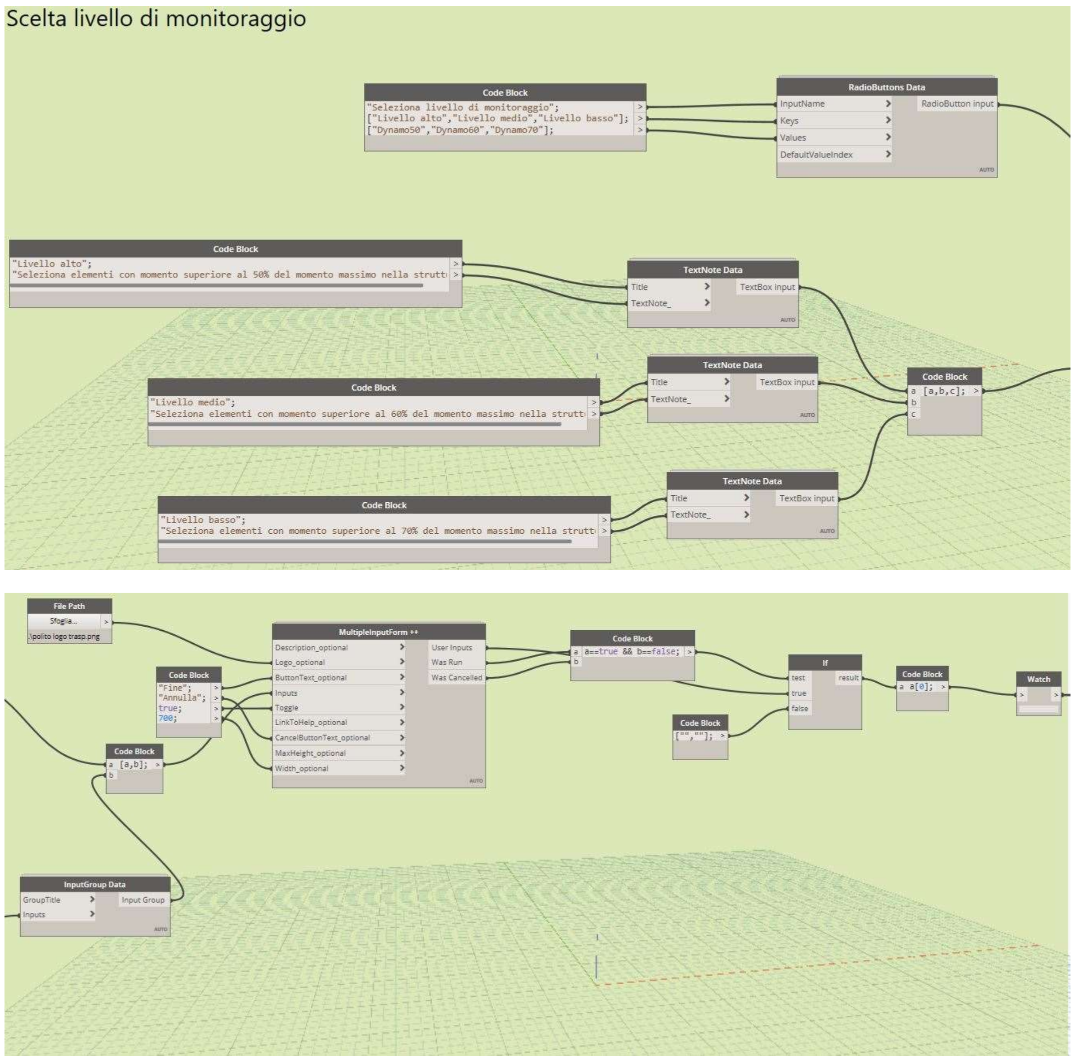


Figure 36. Part 1 and 2 of the portion of the script dedicated to the choice of the SHM level.

Dynamo allows the user to customize the created interface adding a picture and in this case the Politecnico di Torino logo has been chosen.

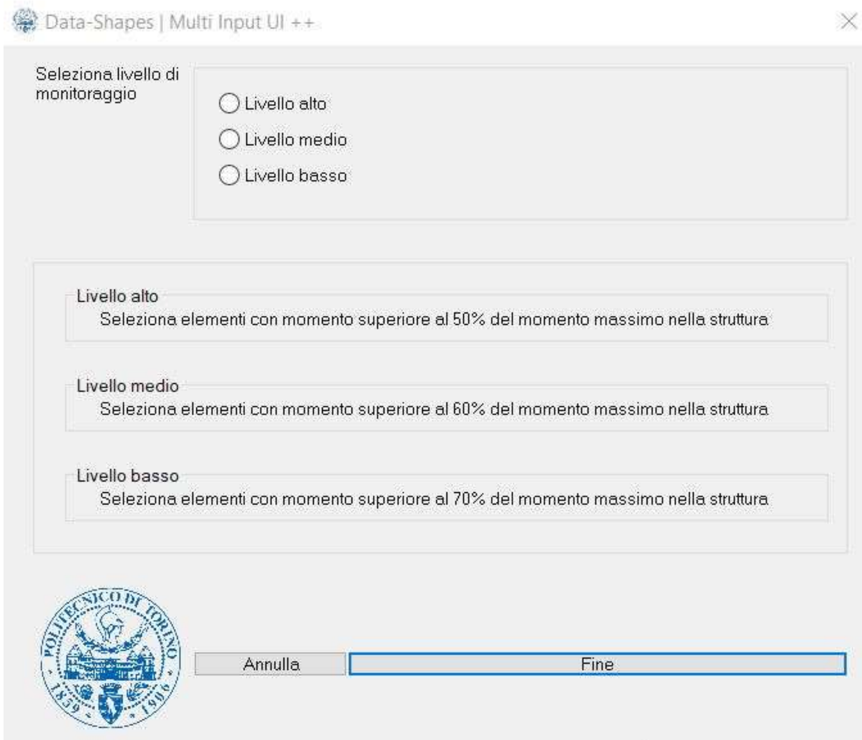
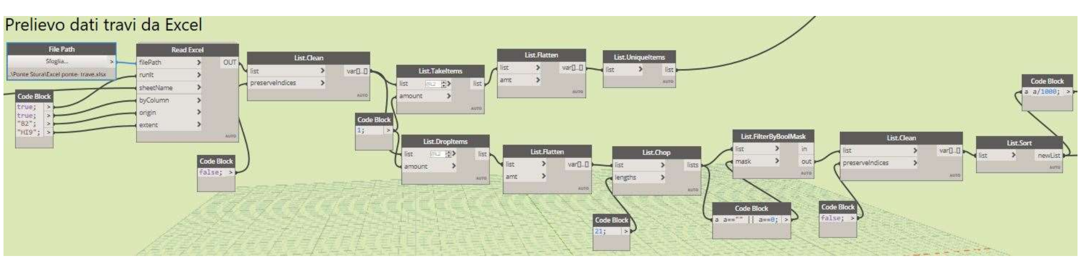


Figure 37. Monitoring level selecion interface.

2.7.2.2 Data management from Excel files

Starting from this point of the algorithm the script splits in to parts, one for the beam and the other one for the columns. The first two group of nodes are similar for both columns and beams and have the function to extract the values of the position of the sensors fro the Excel sheets related to the monitoring level selected in the previously described interface.

The main nodes used in this part of the script are *ReadExcel,* that is used to import data from Excel, and some nodes from the package *List* such as *List.Chop*, *List.Clean*, *List.Flatten* and *List.Sort*.



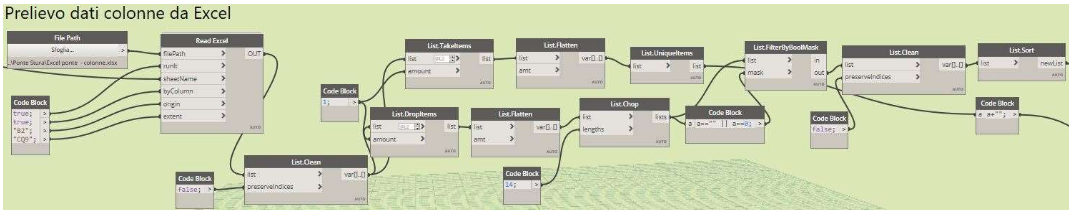


Figure 38. Data management from Excel for beams (above) and columns (below).

2.7.2.3 Sensors positioning for beams

Starting from the positions imported from the Excel file this group of nodes has the function to create and locate the sensors in the right position in the monitored beams of the Revit model.

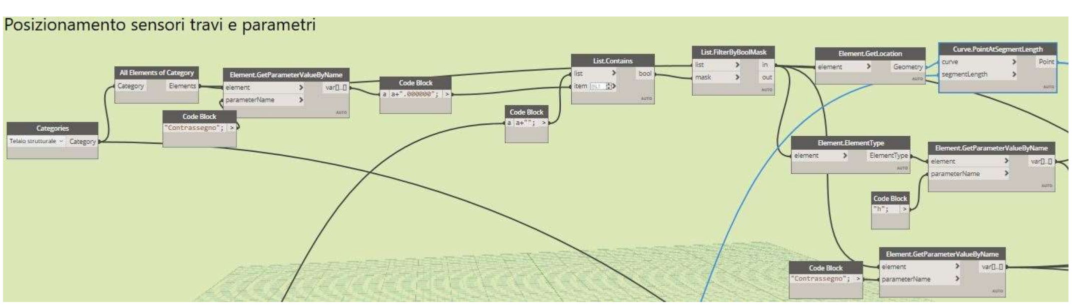
In particular, starting from the marks of the monitored elements, are obtained the location of the structural elements (with the node *Element.GetLocation*) and their starting point (with the node *Curve.PointAtSegmentLength*). Then the position data of the sensors are translated from the central axle fo the beams to the position of the rebars in the extrados and intrados with the node *Geometry.Translate.*

Once the positions are defined the sensor instances are created with the node *FamilyInstance.ByPoint.*

In the final part of this group the sensors parameters are setted. For this purpose the node Element.SetParameterByName has been used.

The setted parameters are :

- Elemento Host: defines the mark of structural element that hosts the sensors and is the same value for sensors in extrados and intrados,
- Allineamento: defines the position of the sensors in the cross section and could be setted to “Intradosso” or “Estradosso”,
- Posizione locale (m): defines the longitudinal position of the sensors inside the host beam.



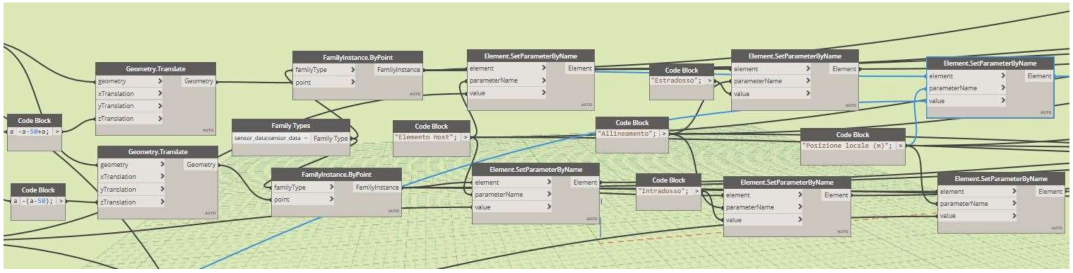


Figure 39. Sensors placing in monitored beams.

2.7.2.4 Beams identification code

Once the sensor instances are placed an identification code has been created putting together the sensor parameters. The aim of the code is to identify uniquely each sensor and will be used also for the bill of the sensors.

The identification code is composed by:

- Host element mark,
- Sensor position inside the cross section of the host element,
- Longitudinal position inside the host element.

An example of a sensor code is:

“108/Estradosso/1,5”

and identifies the sensor located at the extrados rebar level of the beam number 108 and at a distance of 1,5 m from the origin of the beam.

With the same procedure an identification code for the rebars that contains the sensors are created.

An example of a rebar code is:

“108/Estradosso”

and identifies the rebar located near the extrados of the beam number 108.

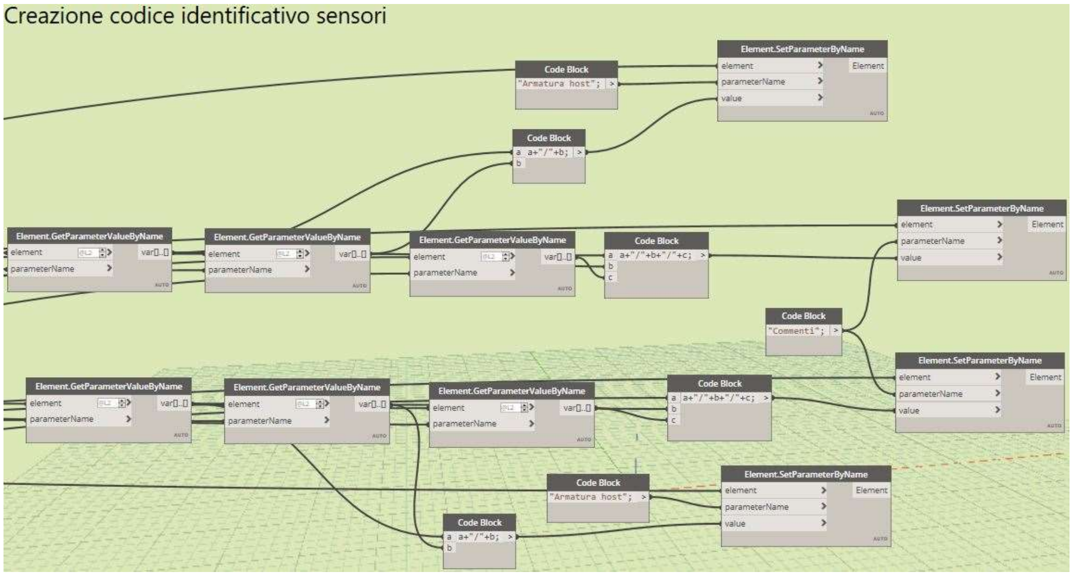


Figure 40. Identification code for beams.

2.7.2.5 Sensors positioning for columns

Starting from the positions imported from the Excel file this group of nodes has the function to create and locate the sensors in the right position in the monitored columns of the Revit model.

In particular, starting from the marks of the monitored elements, are obtained the location of the structural elements (with the node *Element.GetLocation*) and their starting point (with the node *Curve.PointAtSegmentLength*). Then the position data of the sensors are translated from the central axle of the columns to the position of the rebars in the 4 corners of the cross section with the node *Geometry.Translate.*

Once the positions are defined the sensor instances are created with the node *FamilyInstance.ByPoint.*

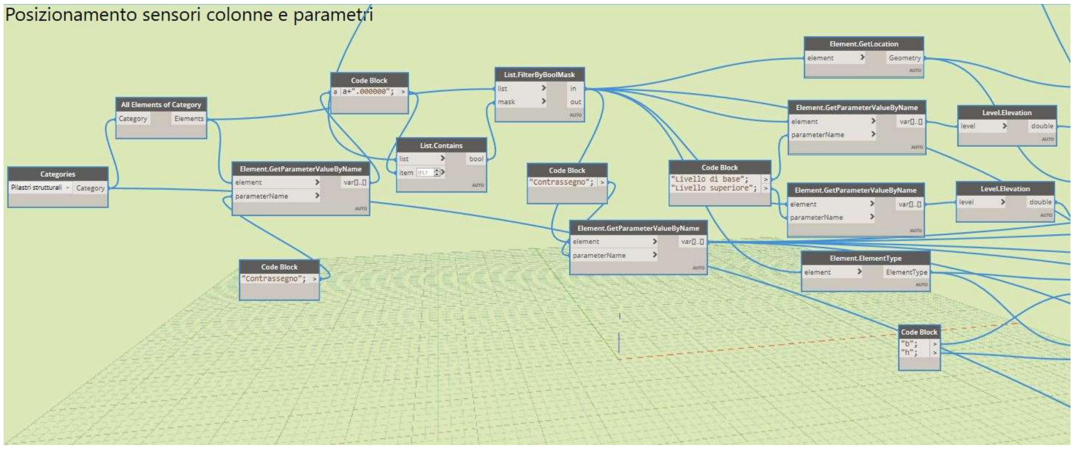
The script has been created in order to be compatible with beams characterized with generic inclinations in the space both in the horizontal and vertical planes.

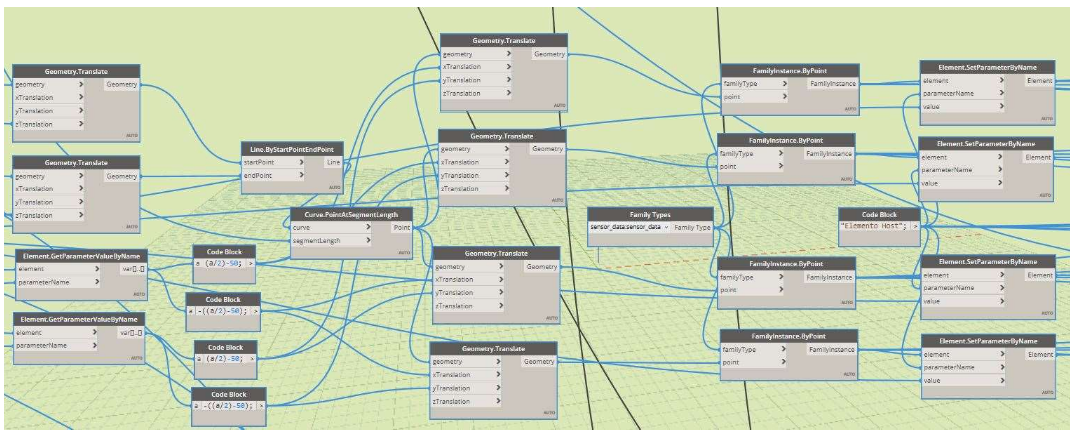
In the final part of this group the sensors parameters are setted. For this purpose the node Element.SetParameterByName has been used.

The setted parameters are :

- Elemento Host: defines the mark of structural element that hosts the sensors and is the same value for sensors in extrados and intrados,
- Allineamento: defines the position of the sensors in the cross section and could be setted to “pp”, “pn”, “np” or “nn” with “p” that stands for a positive displacement from the center of the cross section and “n” stands for a negative one,

- Posizione locale (m): defines the longitudinal position of the sensors inside the host column.





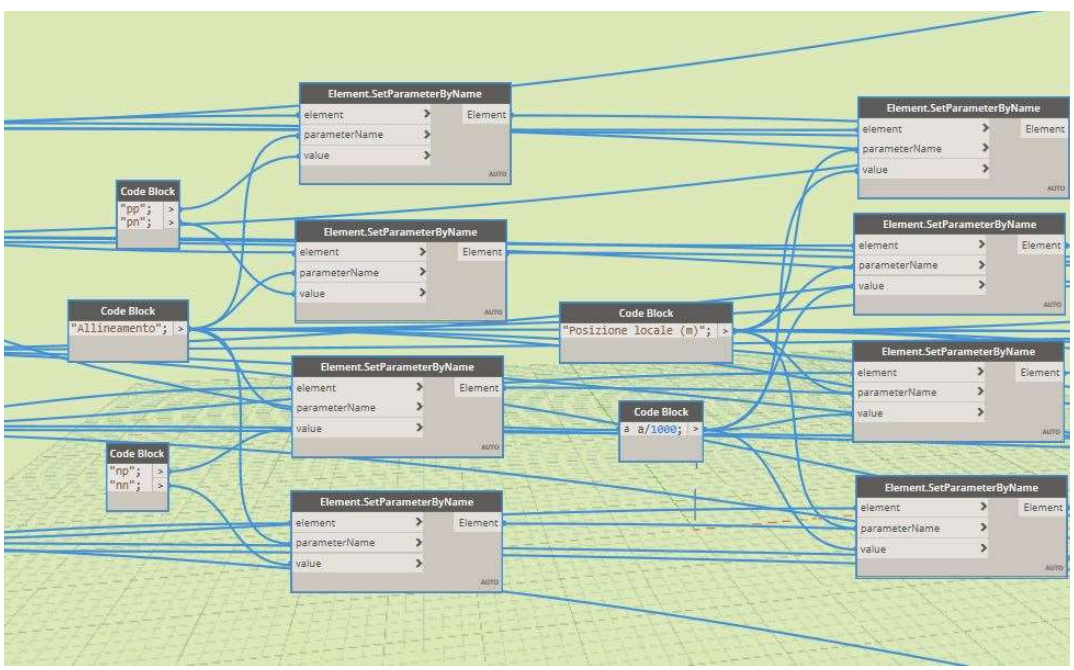


Figure 41. Sensors placing for monitored columns.

2.7.2.6 Columns identification code

Once the sensor instances are placed an identification code has been created putting together the sensor parameters. The aim of the code is to identify uniquely each sensor and will be used also for the bill of the sensors.

The identification code is composed by:

- Host element mark,
- Sensor position inside the cross section of the host element,
- Longitudinal position inside the host element.

An example of a sensor code is:

"24/pp/2,0"

and identifies the sensor located in the right top corner of the cross section of the column number 24 and at a distance of 2,0 m from the base of the column.

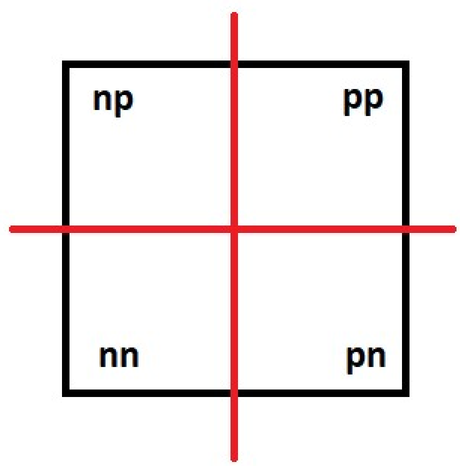


Figure 42. Column cross section positions.

With the same procedure an identification code for the rebars that contains the sensors are created.

An example of a rebar code is:

"24/pp"

and identifies the rebar located in right top corner of the column number 24.

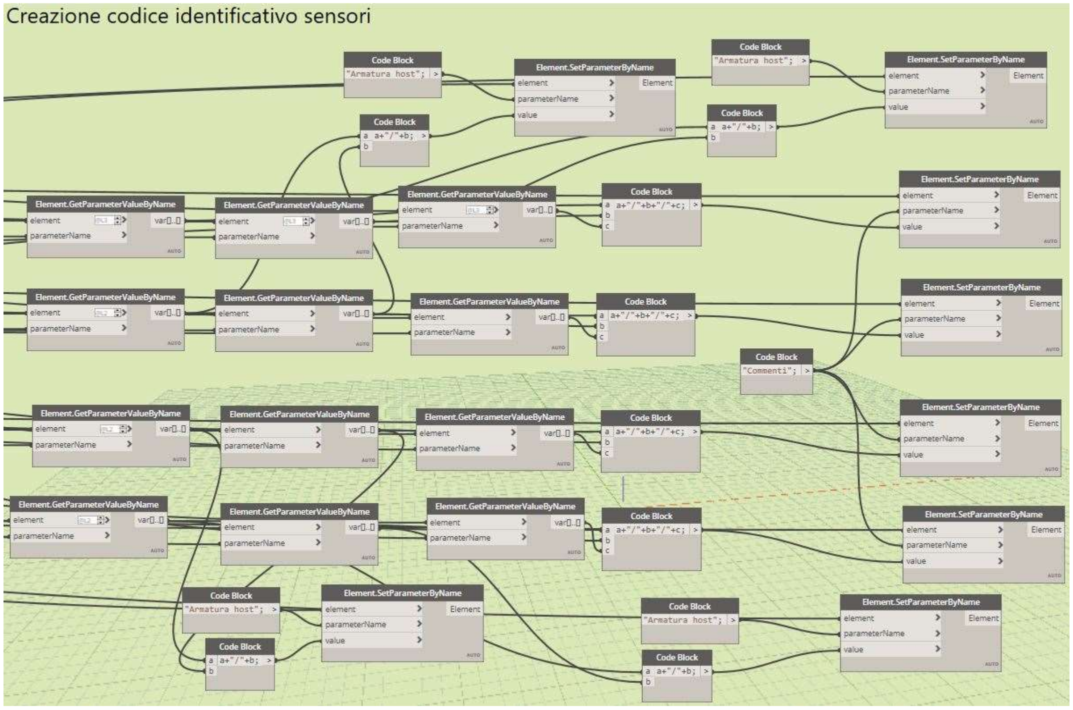


Figure 43. Identification code for columns.

2.7.2.7 Visualization of monitored elements

The sensors are represented with a cube with an edge of 10 mm and particulrly small compared to the structural elements of the building. For this reason could be a problem for the user to identify the monitored elements.

To solve the problem has been created a part of the script that generates a new 3D view called "Monitored" in which the structural elements that contains the sensors are coloured red.

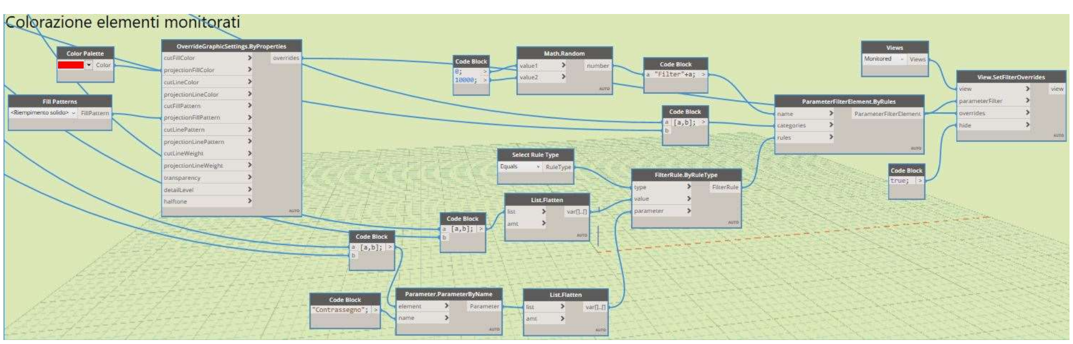


Figure 44. Group of nodes dedicated to the coloring of the monitored elements.

2.7.2.8 Automatic script results

In order to explain the functioning of the script some examples of application will be shown. In particular the following pictures represent the results for all the three monitoring levels.

- High Monitoring Level: in this configuration the monitorred beams are 21 and the monitored columns are 17. The total number of sensors in the building is 916 with a maximum of 36 sensors in one column and 40 sensors in one beam.

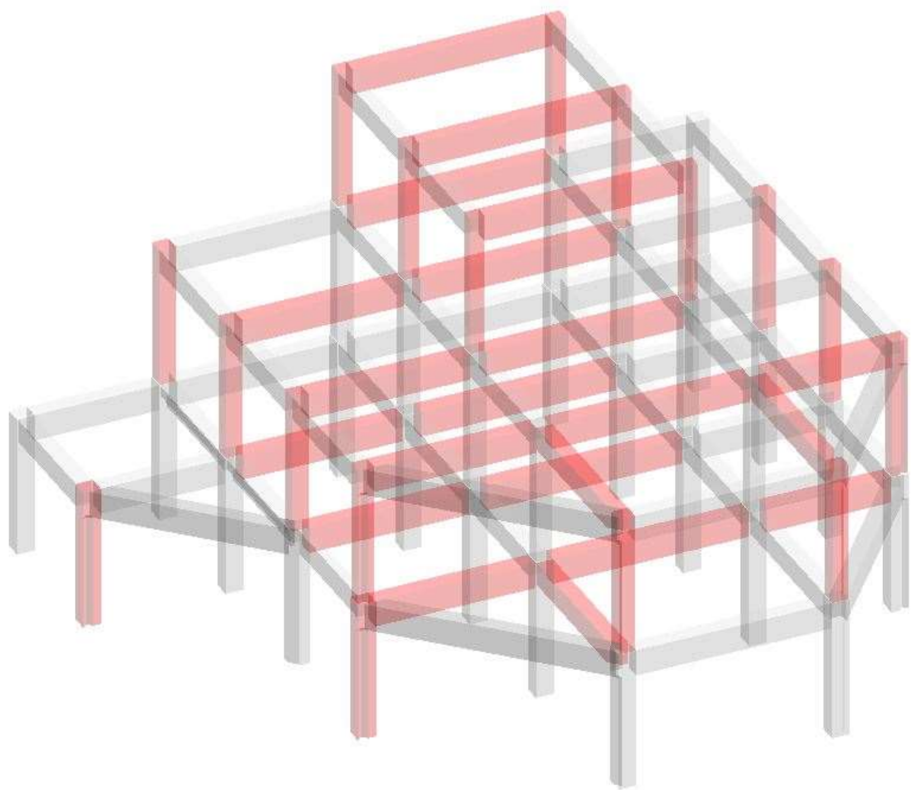


Figure 45. High level of Structural Health Monitoring.

In the following immages are represented the sensors in a monitored beam and column.

In particular the column is monitored with one sensor (for each corner) in the base sector, top sector and middle of the height.

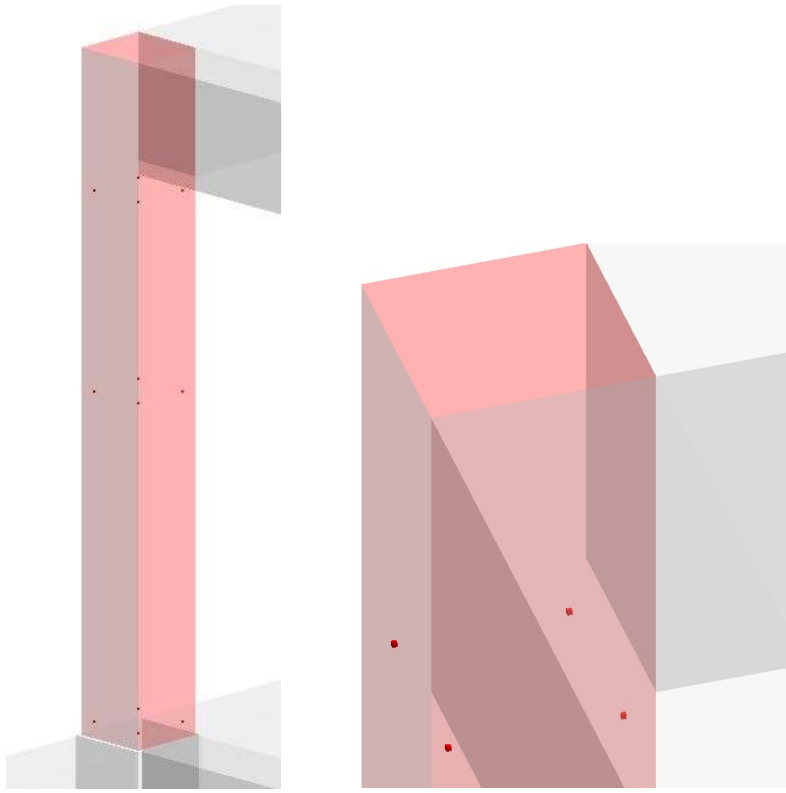


Figure 46. Monitored column.

As regards the monitored beam in the following picture contains 5 sensors (in the extrados and intrados) for each sector (left, center, right). The transition sector do not contains sensors because the length of the beam is not greater than 5 m.

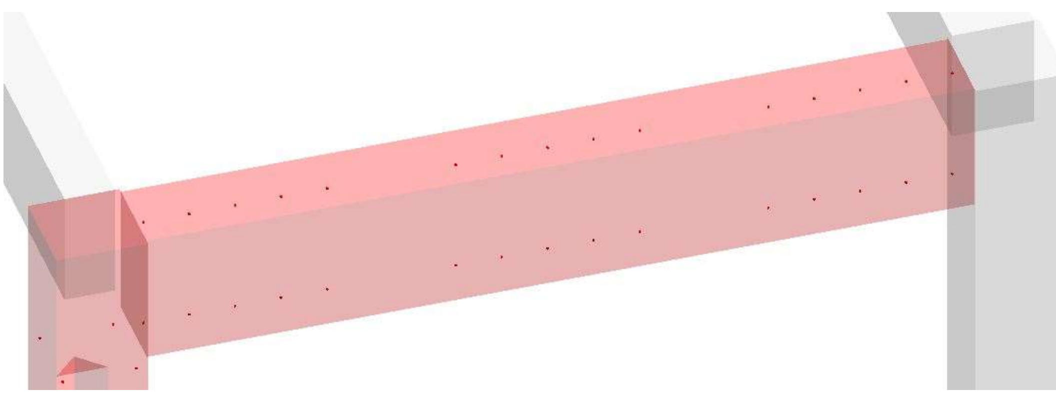


Figure 47. Monitored beam.

In the following picture are shown the parameters of a sensor located at the extrados of beam number 56 at a distance of 2,75 m from the start of the element. In the parameters is possible to read the code of the identification code of the sensor, the number of the host element and the code of the rebar that contains the sensor. Another important information that is contained in the sensor parameters, and that will be discussed more in depth later, is the value of deformations measured from the sensor in the real structure. At this point of the design process the values of deformations are not available yet and for this reason the parameters will appear with a null value.

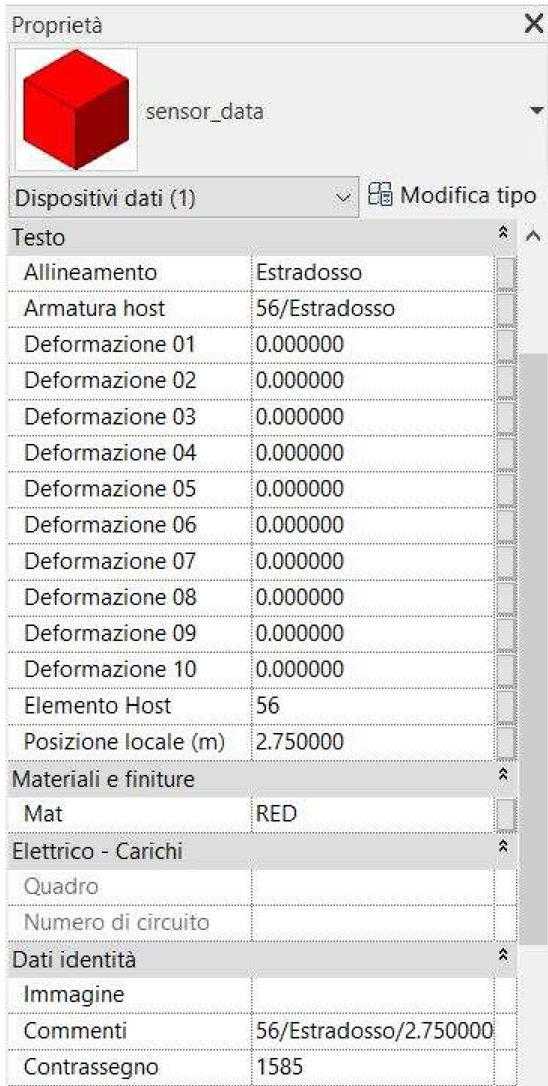


Figure 48. Sensor parameters.

- Medium Monitoring Level: in this configuration the monitorred beams are 15 and the monitored columns are 13. The total number of sensors in the building is 598 with a maximum of 36 sensors in one column and 40 sensors in one beam.

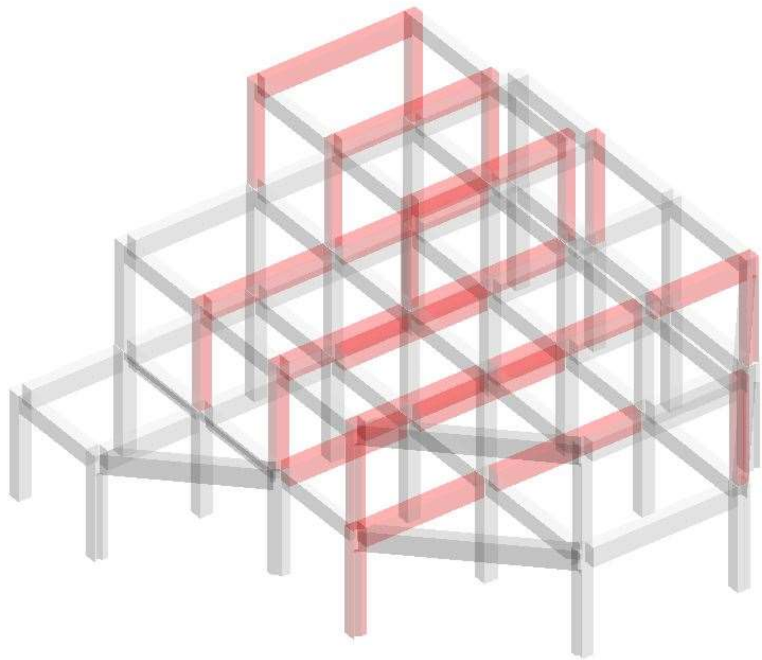


Figure 49. Medium level of Structural Health Monitoring.

- Low Monitoring Level: in this configuration the monitorred beams are 9 and the monitored columns are 8. The total number of sensors in the building is 334 with a maximum of 36 sensors in one column and 40 sensors in one beam.

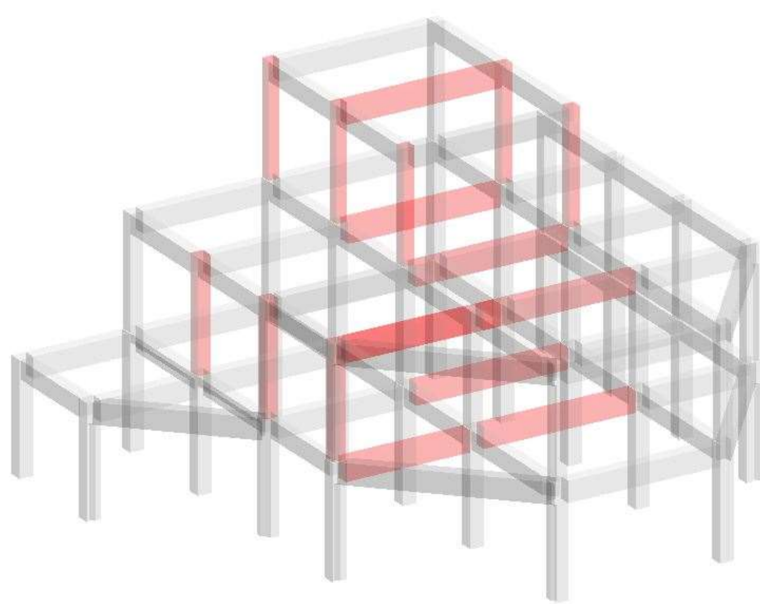


Figure 50. Low level of Structural Health Monitoring.

The comparison between the three different monitoring levels shows that the total amount of sensors used in the system may vary a lot. The choice of the most appropriate level depends on the importance of the structure and on the loads to whom is subjected as well as on the available budget for the design of the Structural Health Monitoring system.

The level has beeen setted to 50th, 60th and 70th percentil but can be personalized directly in the Excel sheets by a simple numerical change in the percetil cell in order to set the wanted levels. This possibility to adjust the system allows the user to meet the economical and structural needs without adding difficulties in the automathic process.

2.8 Manual sensors positioning in Revit model with Dynamo

The automatic algorithm is an extremely powerful instrument bacause allows the user to save time an create a Structual Health Monitoring system that controls all the elements of the building that are subjected to major bending moments.

On the other hand the control of the process should always be in the hands of the designer and could happens that some structural elements, that are crucial for health of the structure, wouldn’t be monitored by the system due to their low bending moments.

To avoid this problem and enable a more user controlled SHM system design a manual sensors positioning script has been designed with Dynamo.

2.8.1 Manual selection of the monitored elements and choice of the number of sensors

The script starts with a group of nodes dedicated to the choice of the input data that are:

- Monitored beams,
- Monitored columns,
- Number of sensors in the left sector of the monitored beams,
- Number of sensors in the central sector of the monitored beams,
- Number of sensors in the right sector of the monitored beams,
- Number of sensors in the base sector of the monitored columns,
- Number of sensors in the top sector of the monitored columns.

In particular the main nodes are from the package Data Shapes (TextBox Data, SelectModelElements Data, InputGroup Data and MultipleInputForm ++) in order to create an interface that allows the user to select the elements that need to be monotired and the number of sensors.

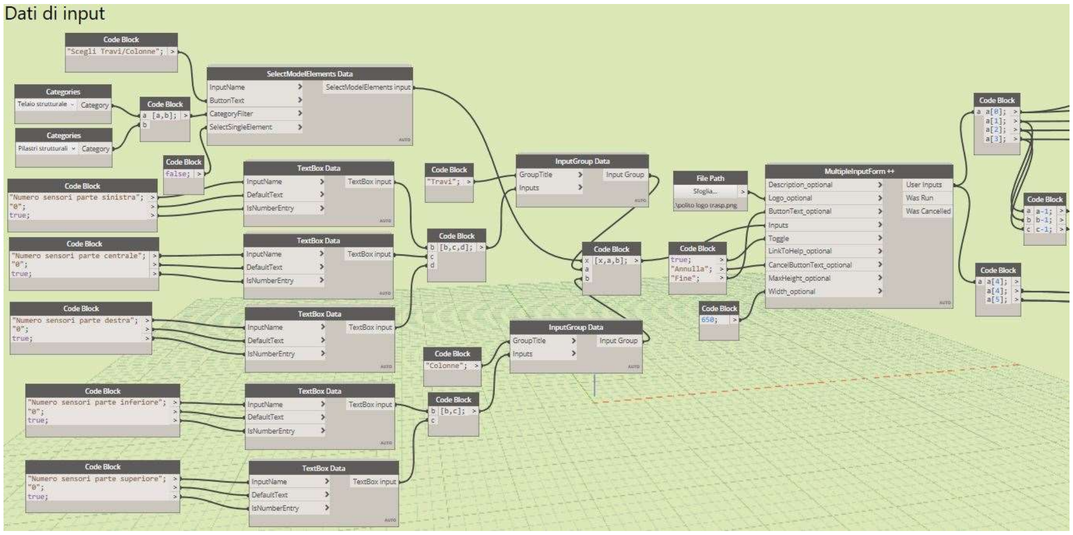


Figure 51. Group of nodes dedicated to the creation of the interface for input data insertion.

The interface that appears once the script has been ran shows an upper button "*Scegli Travi/Colonne"* that allows the user to select the structural elements by clicking on them in the 3D view of the Revit Model. After the selection is concluded theuser has to click on the button "*Termina*" and then has to fill the blank spaces in the interface created by Dynamo that corresponds to the number of sensors in the different sectors of the structural elements.

Figure 52. Input data interface.

It is possible to choose different number of sensors in the various portion of the elements or to maintain the same value.

2.8.2 Sector length calculation

Once the monitored elements has been choosen the length of the three monitored sections in the beams and two sections in the columns need to be calculated. This goal is reached with the use of the nodes *Element.GetParameterValueByName* that gives back the values of the length for each element and then dividing these values by 4 for the beams and by 3 for the columns.

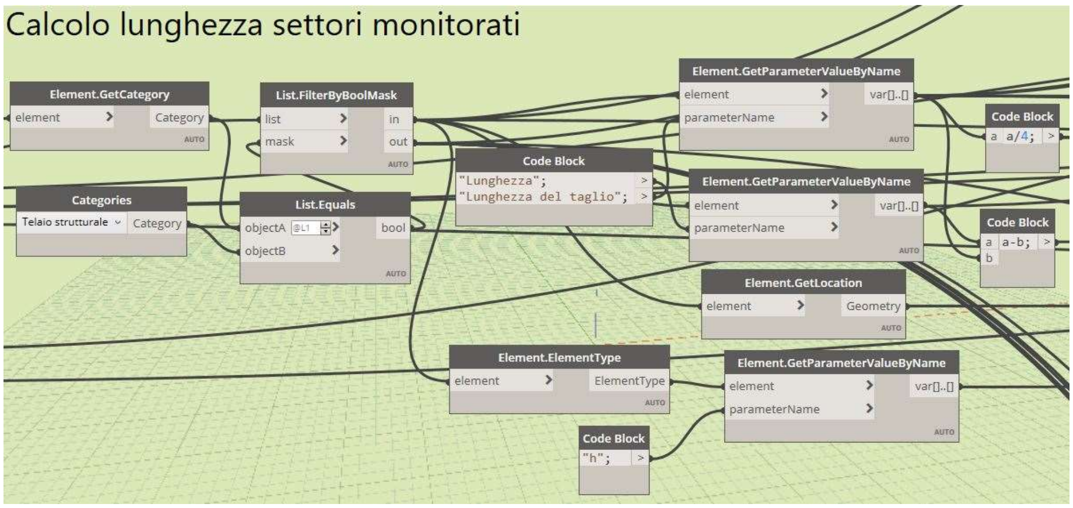


Figure 53. Sectors length calculation.

2.8.3 Beams length control

From this point on the script split in two main parts: one for the beams and the other for the columns.

The next operation is the control of the length of the beams in order to establish if it is necessary to place a single sensor (both at intrados and extrados) in the two intermediate sectors. The rule that has been chosen is the same adopted for the automatic script (only intermediate sectors of beams longer than 5 m will be monitored) and the control is performed with nodes from the List package (*List.Count, List.Cycle* and *List.Chop*).

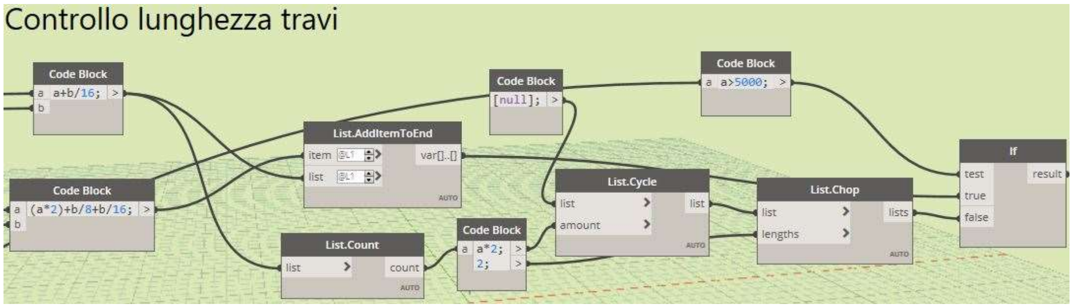


Figure 54. Length control of monitored beams.

2.8.4 Positions calculation for sensors in beams

The next step is the evaluation of the positions of the sensors starting from the numbers chosen by the user in the data input interface and the length of the section that will host them.

In particular three different calculation methodologies has been chosen for the three portion of the beam:

- Left portion: the position of the first sensor has been setted equal to the value of the concrete cover (50 mm) and the other ones has been calculated as an addition of the interaxis that is equal to the length of the sector divided by the number of sensors,
- Central portion: the position of the sensor has been calculated dividing the length of the sector by the number of devices and than to the values has been added the distance from the start of the beam,
- Right portion: the position of the last sensor has been setted equal to the value of the total length of the beam subtracted of the concrete cover. For the other ones the position has been obtained by simply subtracting the value of the interaxis that is obtained dividing the length of the portion by the number of sensors.

In order to solve this job many nodes from the List package has been used such as. *List.Count, List.Cycle, List.TakeItems, List.AddItemToFront, List.AddItemToEnd, List.Clean* and *List.Flatten.*

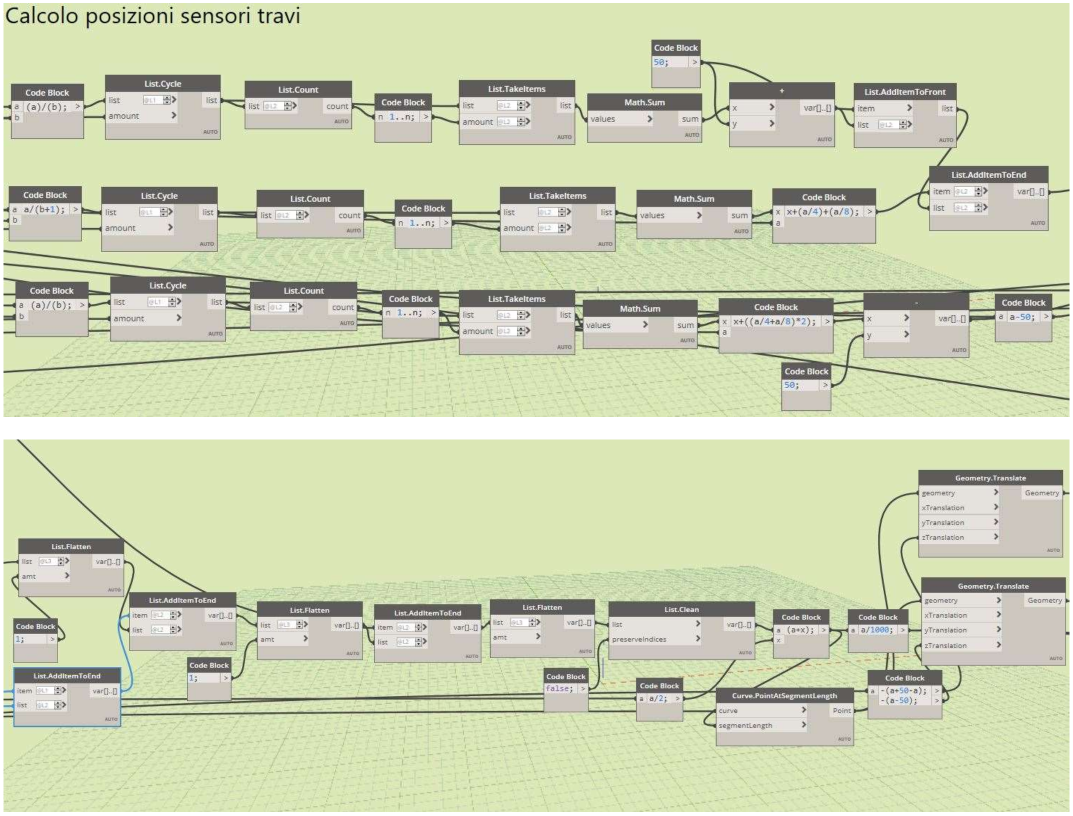


Figure 55. Sensors position calculation.

2.8.5 Sensors positioning for beams

Starting from the positions calculated in the previous step this group of nodes has the function to create and locate the sensors in the right position in the monitored beams of the Revit model. Once the positions are defined the sensor instances are created with the node *FamilyInstance.ByPoint.*

In the final part of this group the sensors parameters are setted. For this purpose the node Element.SetParameterByName has been used.

The setted parameters are :

- Elemento Host: defines the mark of structural element that hosts the sensors and is the same value for sensors in extrados and intrados,
- Allineamento: defines the position of the sensors in the cross section and could be setted to “Intradosso” or “Estradosso”,
- Posizione locale (m): defines the longitudinal position of the sensors inside the host beam.

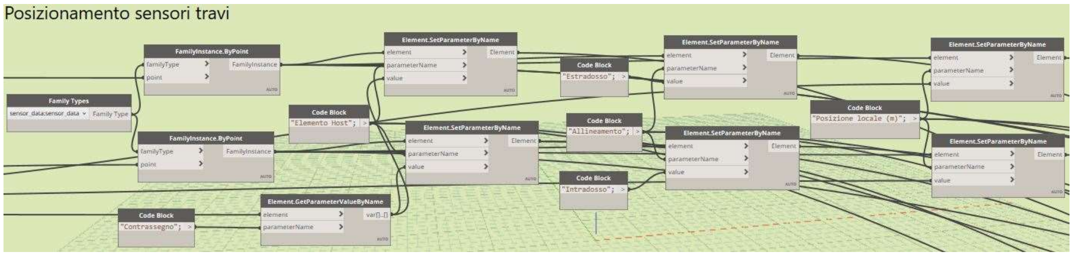


Figure 56. Sensors positioning for beams.

2.8.6 Beams identification code

Once the sensor instances are placed an identification code has been created putting together the sensor parameters. The aim of the code is to identify uniquely each sensor and will be used also for the bill of the sensors.

The identification code is composed by:

- Host element mark,
- Sensor position inside the cross section of the host element,
- Longitudinal position inside the host element.

An example of a sensor code is:

"75/Estradosso/1,5"

and identifies the sensor located at the extrados rebar level of the beam number 75 and at a distance of 1,5 m from the origin of the beam.

With the same procedure an identification code for the rebars that contains the sensors are created.

An example of a rebar code is:

"75/Estradosso"

and identifies the rebar located near the extrados of the beam number 75.

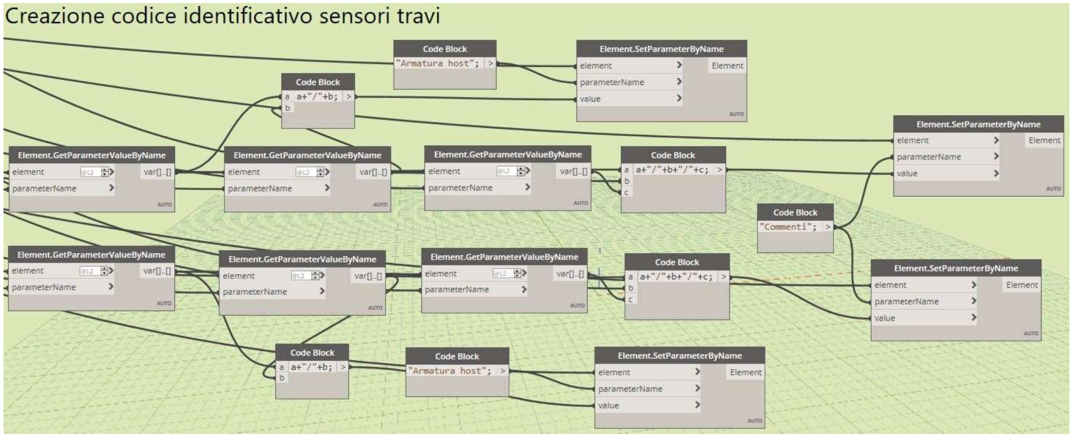


Figure 57. Creation of beams sensors identification code.

2.8.7 Positions calculation for sensors in columns

The evaluation of the positions of the sensors in the columns starts from the numbers chosen by the user in the data input interface and the length of the section that will host them.

In particular three different calculation methodologies has been chosen for the three portion of the beam:

- Base portion: the position of the first sensor has been setted equal to the value of the concrete cover (50 mm) and the other ones has been calculated as an addition of the interaxis that is equal to the length of the sector divided by the number of sensors,
- Central portion: the position of the single sensor is the middle of the height of the column reduced by the thickness of the beam located on top of it,
- Right portion: the position of the last sensor has been setted equal to the value of the total length of the beam subtracted of the concrete cover. For the other ones the position has been obtained by simply subtracting the value of the interaxis that is obtained dividing the length of the portion by the number of sensors.

In order to solve this job many nodes from the List package has been used such as. *List.Count, List.Cycle, List.TakeItems, List.AddItemToFront, List.AddItemToEnd, List.Clean* and *List.Flatten.*

Once the position of the sensors are calculated, with respect to axle of the column, 4 translations in the corners of the section has been performed thanks to the node *Geometry.Translate.*

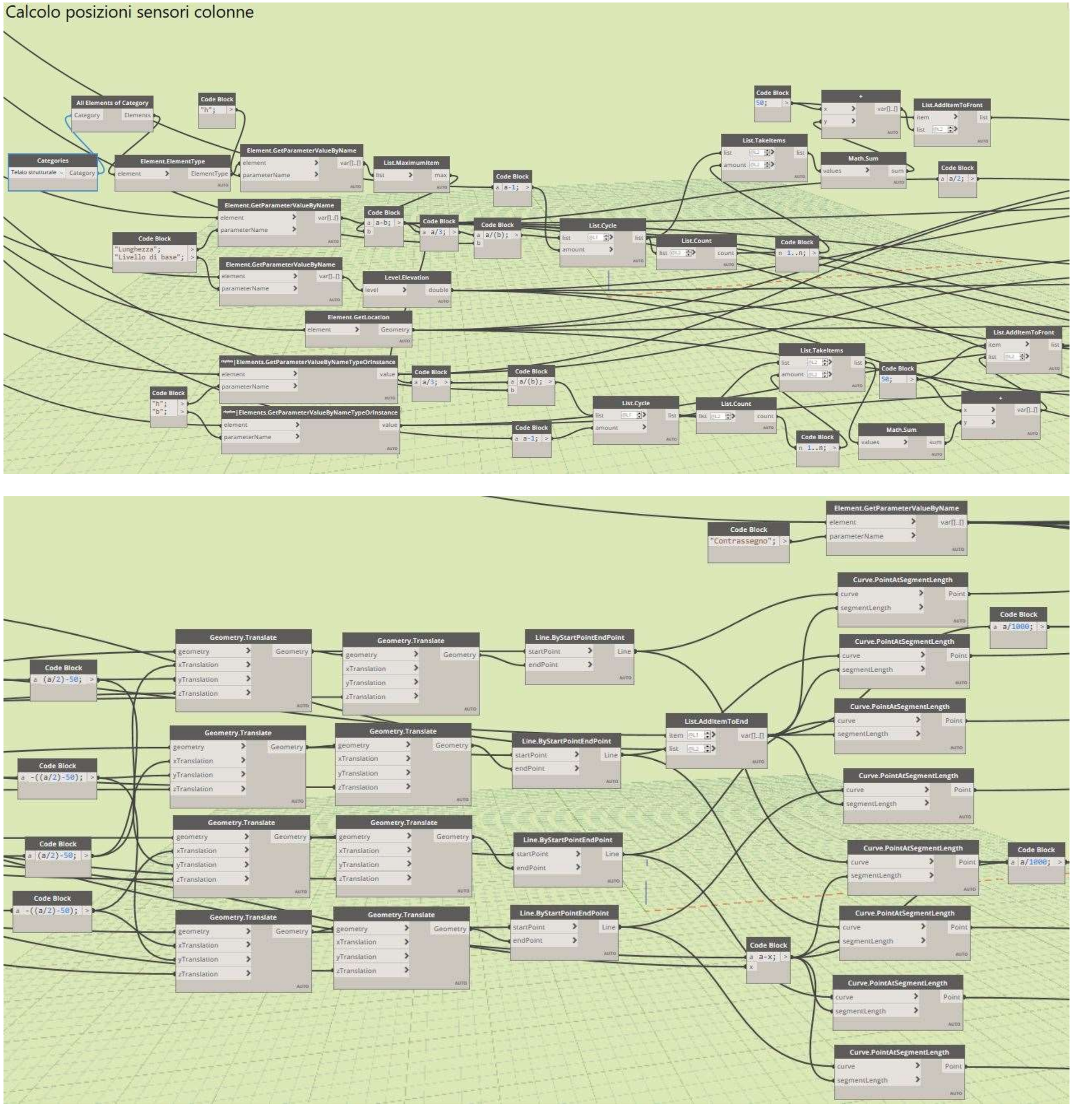


Figure 58. Calculation of the sensors positions for columns.

2.8.8 Sensors positioning for columns

Starting from the positions calculated in the previous step this group of nodes has the function to create and locate the sensors in the right position in the monitored columns of the Revit model. Once the positions are defined the sensor instances are created with the node *FamilyInstance.ByPoint.*

In the final part of this group the sensors parameters are setted. For this purpose the node Element.SetParameterByName has been used.

The setted parameters are :

- Elemento Host: defines the mark of structural element that hosts the sensors and is the same value for sensors in the 4 corners of the cross section,
- Allineamento: defines the position of the sensors in the cross section and could be setted to “pp”, “pn”, “np” or “nn”,
- Posizione locale (m): defines the longitudinal position of the sensors inside the host column.

For computational reasons this part or the script has been divided in two arms: one regarding the sensors of the top section of the columns and another one regarding the central e base section.

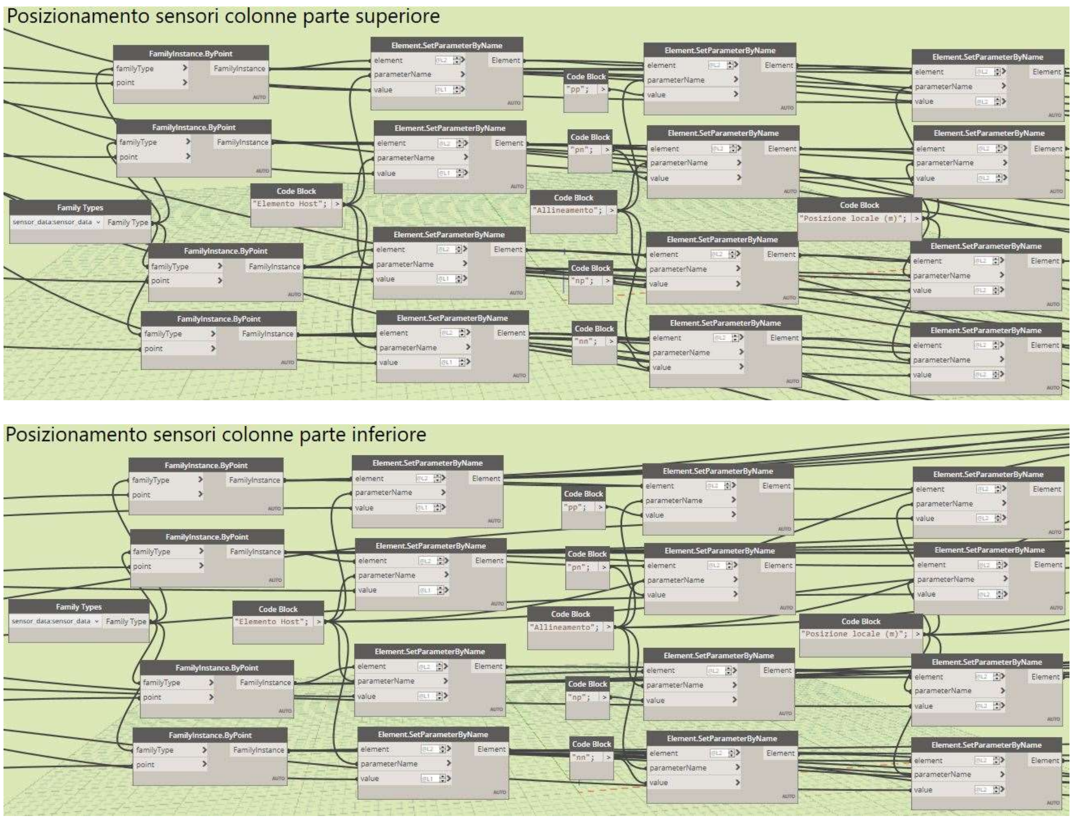


Figure 59. Sensors positioning in monitored columns.

2.8.9 Columns identification code

Once the sensor instances are placed an identification code has been created putting together the sensor parameters. The aim of the code is to identify uniquely each sensor and will be used also for the bill of the sensors.

The identification code is composed by:

- Host element mark,
- Sensor position inside the cross section of the host element,

- Longitudinal position inside the host element.

An example of a sensor code is:

"21/pp/2,0"

and identifies the sensor located in the right top corner of the cross section of the column number 21 and at a distance of 2,0 m from the base of the column.

With the same procedure an identification code for the rebars that contains the sensors are created.

An example of a rebar code is:

"21/pp"

and identifies the rebar located in right top corner of the column number 21.

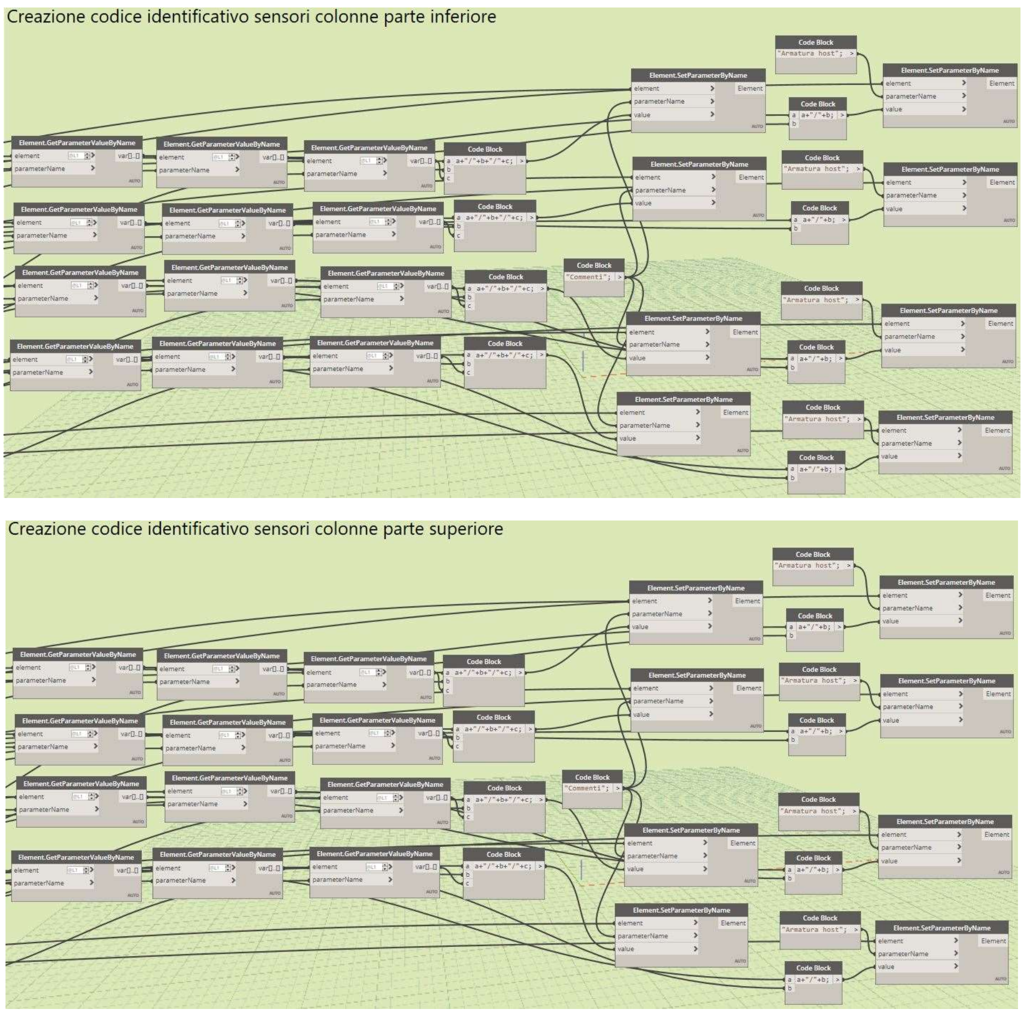


Figure 60. Parameter setting for sensors in moniotored columns.

2.8.10 Visualization of monitored elements

The sensors are represented with a cube with an edge of 10 mm and particulrly small compared to the structural elements of the building. For this reason could be a problem for the user to identify the monitored elements.

To solve the problem has been created a part of the script that change the colors of the monitored elements in order to make more visible to the user even if , at a certain distance, the sensors cannot be seen.

In this case, in order to distinguish the structural elements that has been selected manually from the one selected by the automatic script previously executed, the colo that has been chosen is blue.

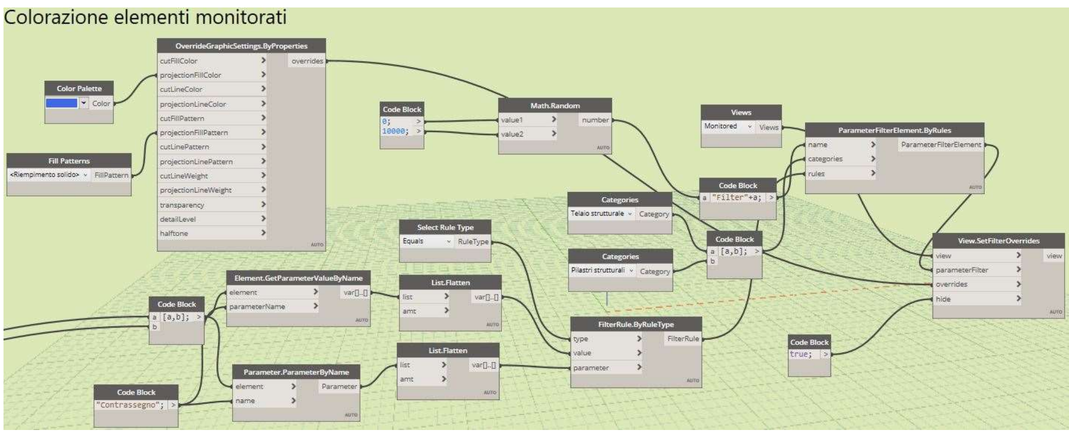


Figure 61. Group of nodes dedicated to the coloring of the monitored elements

2.8.11 Manual script results

In order to explain the functioning of the script an example of application will be shown. In particular the following pictures represent the result of the monitoring of three beams and two columns. With the purpose to test the efficiency of the script have been chosen beams with different orientation (two parallel to main directions of the building and the other one with a generic inclination in the horizontal plane).

As regards the columns two elements belonging to two different storeys as been chosen.

The total number of sensors in the monitored beams selected manually is 62 and the number of sensors in the columns is 40.

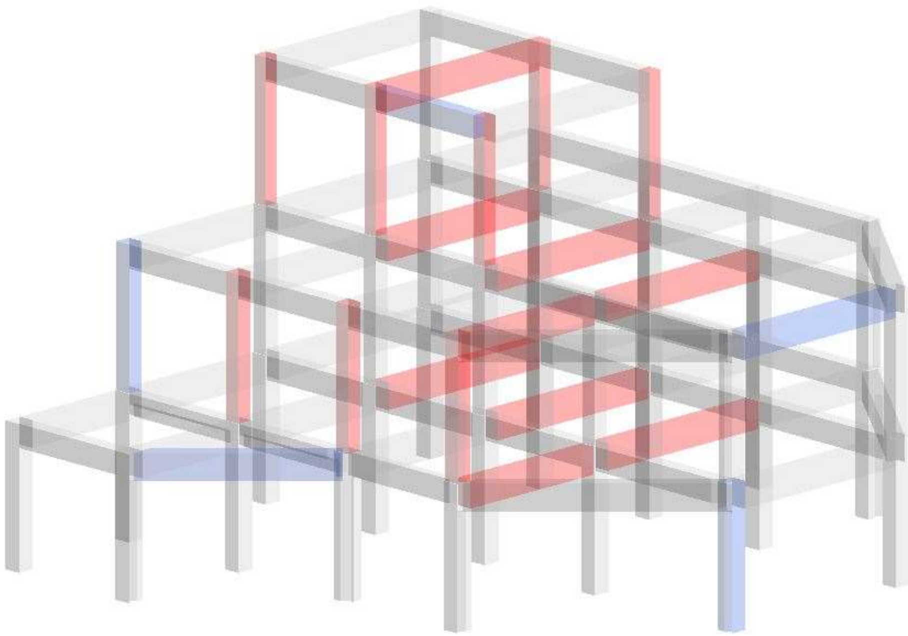


Figure 62. Monitored view after the manual script has been ran.

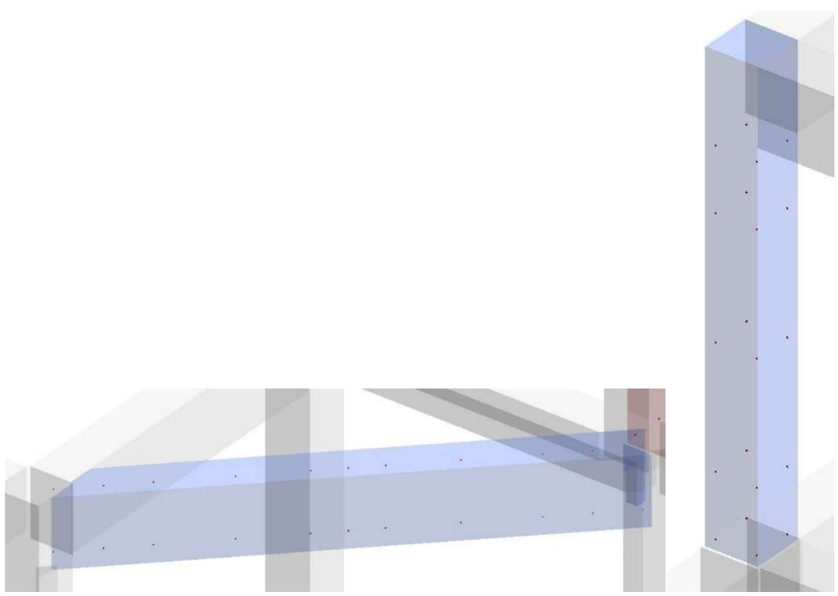


Figure 63. Monitored beam and column selected with the manual script.

In the following picture are shown the parameters of a sensor located at the extrados of beam number 75 at a distance of 2,49 m from the start of the element. In the parameters is possible to read the code of the identification code of the sensor, the number of the host element and the code of the rebar that contains the sensor. Another important information that is contained in the sensor parameters, and that will be discussed more in depth later, is the value of deformations measured from the sensor in the real structure. At this point of the design process the values of deformations are not available yet and for this reason the parameters will appear with a null value.

Figure 64. Sensor parameters.

2.9 Automatic rebar positioning in Revit model with Dynamo

According to the previous descrition of the S3 sensors, each one of them will be placed inside an hole in a dedicated rebar. For this reason it is fundamental to represent also the structural reinforcements in the Revit model in order to obtain an accurate representation of the Structural Health Monitoring System.

For this purpose a Dynamo script has been designed and the process of the smart rebars placement (the rebars that contains sensors) has been automated.

The main idea at the base of this algorithm is to recognize the structural elements that contains the sensors and place inside of them the rebars (two for the beams and 4 for the columns).

2.9.1 Monitored beams identification

The first section of the part of the script dedicated to the beams reinforcements has the function to individuate the monitored beams in the model and to identify their direction. Once the direction of each element is known a subdivision in three different categories is performed:

- Beams oriented parallel to x axis ,
- Beams oriented parallel to y axis,
- Beams oriented in a general direction.

From each of theese three group of beams a branch od the script will spread but the function of them will be the same. For this reason only the part of the script dedicated to the beams parallel to y axis will be explained in depth.

In order to realize the previously described task has been used Dynamo nodes such as *Element.GetParameterValueByName*, *All Elements of Category, Element.GetLocation* and *List.FilterByBoolMask.*

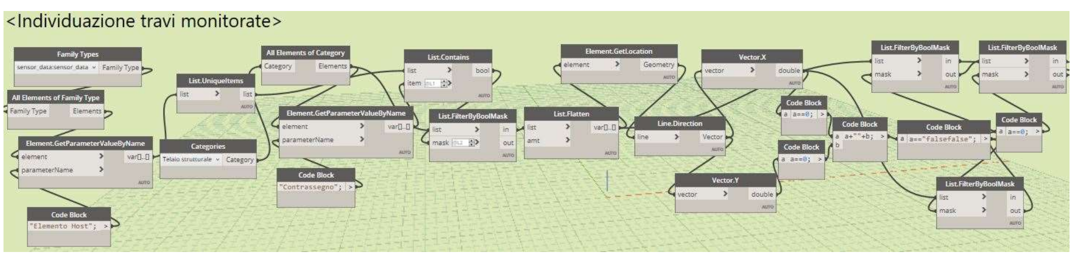


Figure 65. Individuation of monitored beams.

2.9.2 Calculation of the number of beams for each alignment

Once the beams has been divided in groups according to the orientation the algorithm proceeds with the calculation of the number of beams for each alignment. The goal is to understand if some of the monitored beams are adjacent in order to set a single reinforcement for them. The first step that has been done is the evaluation of the coordinate of the starting point of each beam. Then has been performed the subdivision in allignment with the nodes *List.GroupByFunction* and *List.SortByFunction.*

The functions that have been used are *Point.X, Point.Y* and *Point.Z* that give the values of the coordinate of the input point.

In the end a few lists containing the coordinates of the monitored beams grouped for the alignment has been obtained and the last step of this section is to count the number of beams in each list.

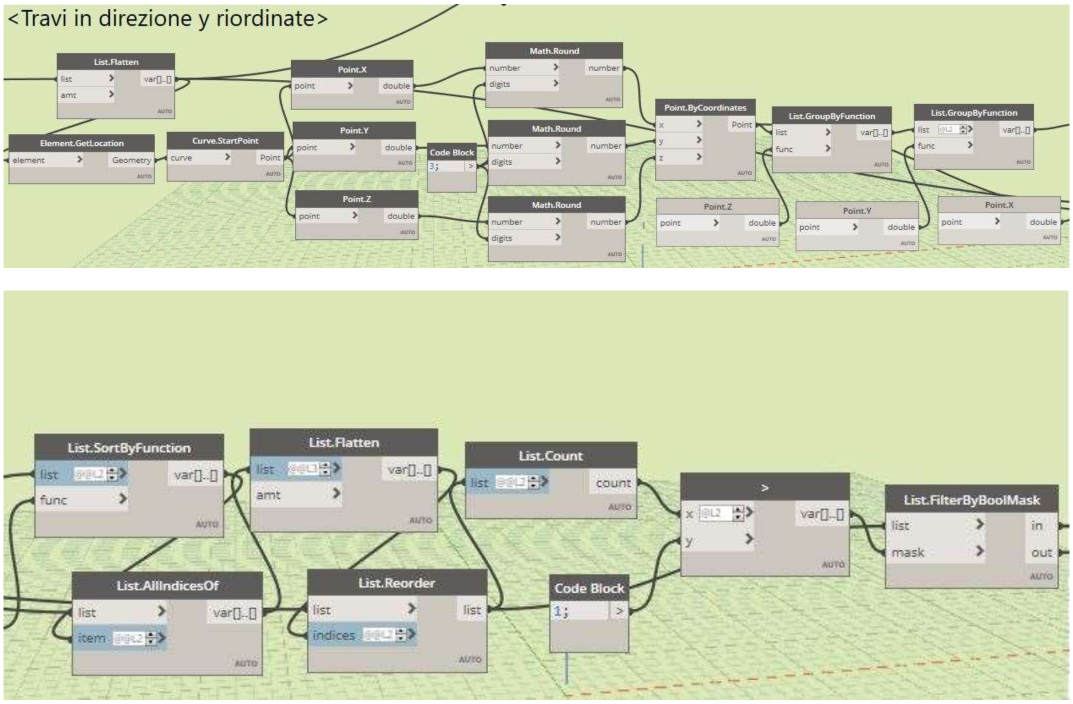


Figure 66. Subdivision of monitored beams according to the alignment.

2.9.3 Evaluation of positions of beams in the same alignment

The next step is the evaluation of the position for each beam of the alignment. In particular this part of the script has the function to control if the a beam is adjacent o the other beams of the same alignment. If not could be considered as a single beam and will be grouped with the other beams that are alone in their alignment.

For this typology of beam a simple single reinforcement, both at intrados and extrados, is placed.

This section has been created using several nodes from Dynamo such as *List.Flatten, Curve.StartPoint, Curve.EndPoint, List.DropItem* and *Geometry.IsAlmostEqualTo*.

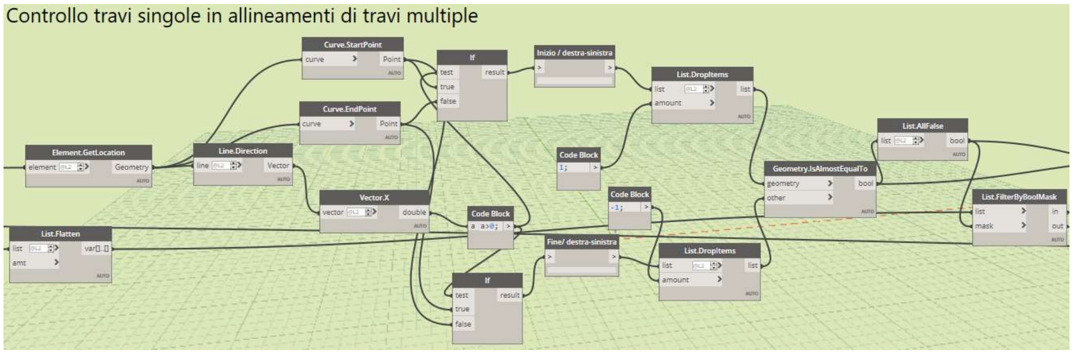


Figure 67. Imdividuation of single beams in alignments of multiple beams.

2.9.4 Control of the mutual position of beams belonging to the same alignment

In this sector of the script the lists are controlled in order to define if beams belonging to the same alignment are one consecutive to the other or separated by a non monitored beam. If the two elements are adjacent will be considered as a single beam with length equal to the summ of the two and a continuos rebar will be placed for both elements.

For this task many nodes from the List package has been used: *List.Count, List.AllIndicesOf, List.DropItem, List.GetItemAtIndex, List.Flatten and List.FilterByBoolMask.*

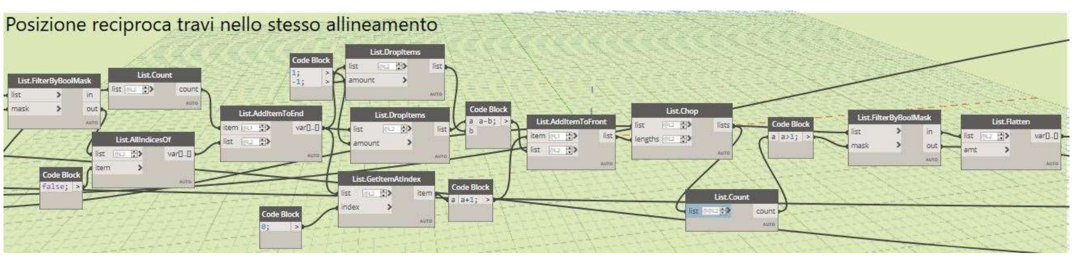


Figure 68. Control of the mutual position of the beams.

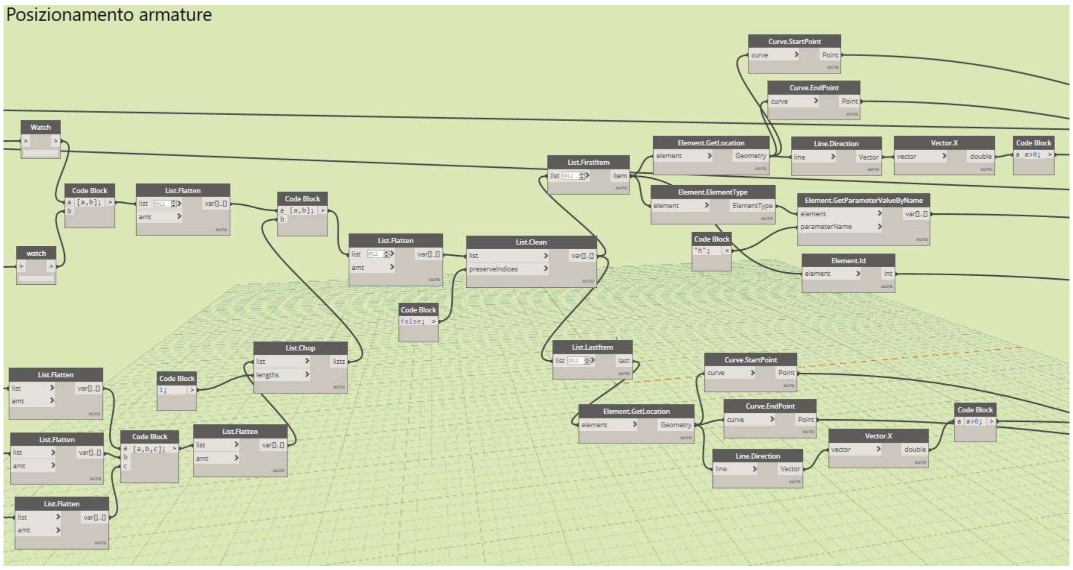
2.9.5 Rebars positioning in beams

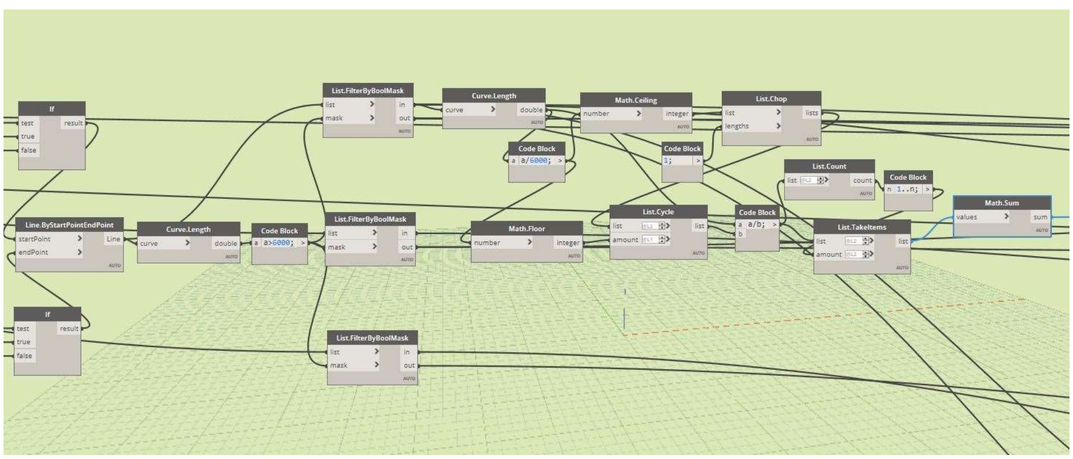
Once the monitored beams has been divided and classified according to the allignment and the mutual positions, the rebars has been positioned with the next section of the script. In particular the lenght of the monitored element has been is controlled:

- If the monitored beam is shorter than 6 m a simple reinforcement is placed,
- If the monitored beam, or the summ of two consecutive beams, is longer than 6 m two consecutive reinforcements are placed with a length for both equal to half the length of the element.

In the case of the second option a subsequent manual setting of the length of the rebars can be done in order to place the discontinuity (and the relative overlapping zone) in the more convenient location according to the bending moment diagram.

The main nodes used for this section are: *Element.GetParameterValueByName, Curve.Endpoint, Curve.StartPoint, Curve.Length, Curve.PointAtSegmentLength, Vector.ByCordinates* and *Geometry.Translate.* Fundamental for this application are the nodes from the Dynamo package *DynamoRebar* that is dedicated to the structural reinforcements.





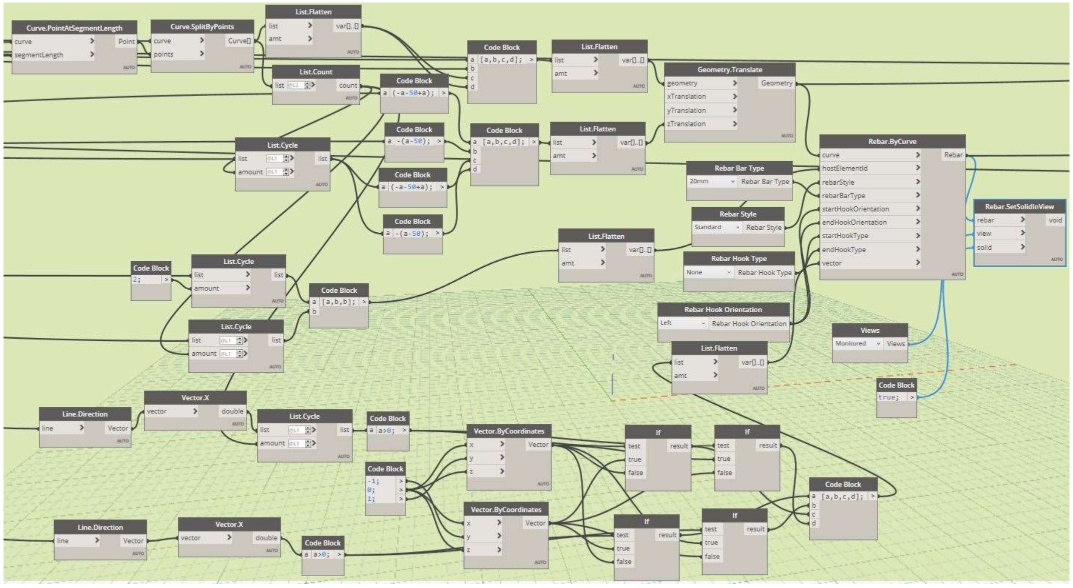


Figure 69. Rebar positioning script.

2.9.6 Parameter setting for beams rebars

The last part of the script dedicated to the beams reinforcements ha the function to set the parameters. In particular the setted parameter is the identification code of the rebar that is created with the following structure:

"Elemento host/Allineamento"

The value of the first part depends on the number of the beam in which the rebar is placed.

The second part depends on the position of the rebar inside the cross section of the monitored beam and the value could be "Intradosso" or "Estradosso".

An example of the parameter could be *"108/Intradosso"* and defines the rebar located at the intrados of the beam number 108.

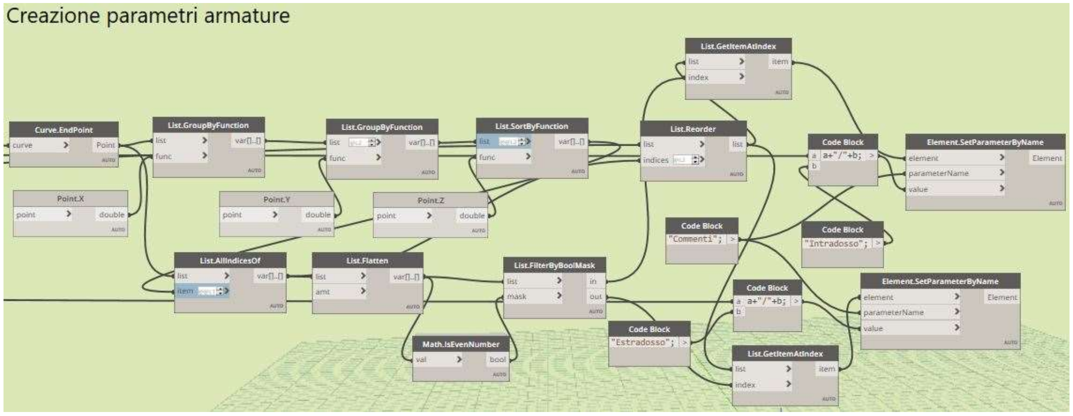


Figure 70. Parameter setting for beams rebars.

2.9.7 Identification of monitored columns

As well as for the beams, the branch of the script dedicated to the columns starts with the identification of the monitored elements. Unlike to the previous case, columns do not need to be classified according to the direction.

This part of the algorithm identifies all the columns that contain sensors and group them in a list.

In order to realize the previously described task have been used Dynamo nodes such as *Element.GetParameterValueByName*, *All Elements of Fmily Type, List.AllIndicesOf, List.Reorder* and *List.Flatten.*

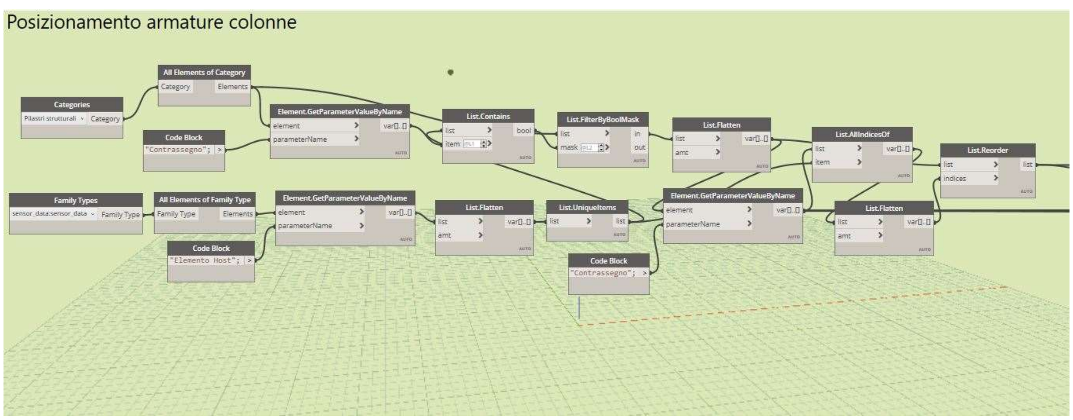


Figure 71. Monitored columns identification.

2.9.8 Evaluation of monitored columns positions

The following step is the evaluation of the position of each monitored element in order to calculate the positions of the rebars.

The nodes used in this section are *Element.GetLocation, Element.GetParameterValueByName, Level.Elevation* and some nodes from the Dynamo *List* package such as *List.GetItemAtIndex, List.AllIndicesOf* and *List.CountOccurences.*

The result of this section is a list of coordinates of start point and end point for each monitored column.

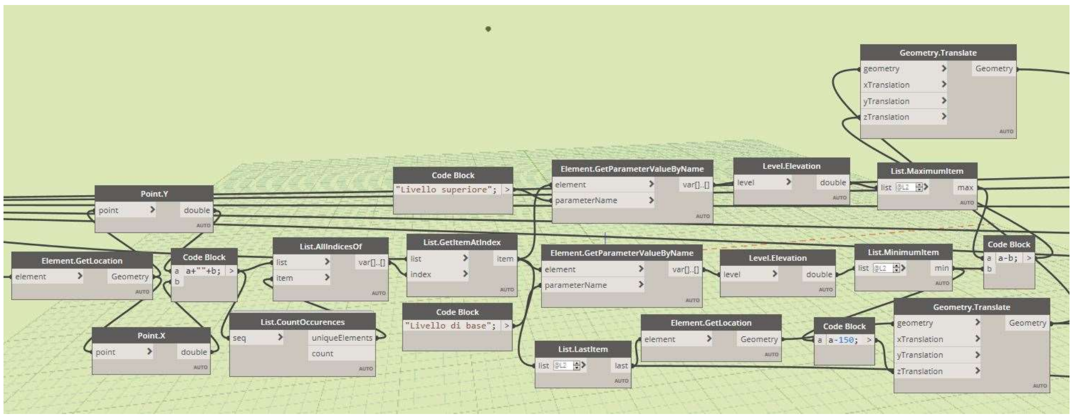


Figure 72. Position of the monitored columns in the model.

2.9.9 Translation from the axle of the column to the real position of the rebars

Once the positions of the axles of the columns in the Revit model have been defined the calculation of the real positions of the rebars inside the cross section of the element need to be calculated.

In particular from the center of the cross section are performed four different translations in the direction of the corners. Each corner is reached with a double translation of a quantity equal to the half width of the column decreased of the thickness of the concrete cover in the two main directions of the element.

This goal is reached by using the following Dynamo nodes: *Curve.PointAtSegmentLength, Curve.SplitByPoints, List.Count, List.Flatten, List.AddItemToEnd* and *Geometry.Translate.*

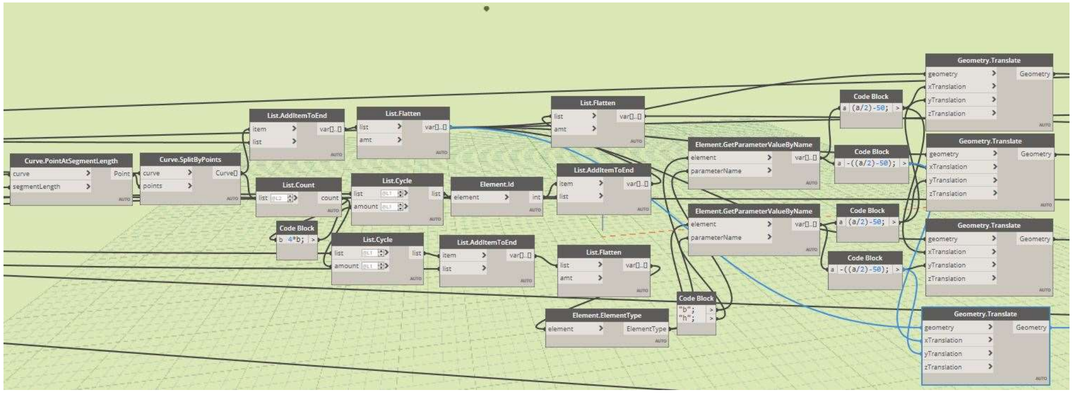


Figure 73. Translation of the rebars positions.

2.9.10 Rebar istances creation

Once the correct positions of the rebars has been calculated the next step is the creation and positioning of the rebars in the Revit model.

The main nodes used for this section are: *Element.GetParameterValueByName, Curve.Endpoint, Curve.StartPoint, Curve.Length, Curve.PointAtSegmentLength, Vector.ByCordinates* and *Geometry.Translate.* Fundamental for this application are the nodes from the Dynamo package *DynamoRebar* that is dedicated to the structural reinforcements. This packages allows the user to select the typology of rebar that will be placed in the model, th e value of the rebar's diameter and the hook's typology both at the start and at the end of the structural reinforcements.

This settings could also be changed later directly in the parameters menu of each rebar in the Revit model.

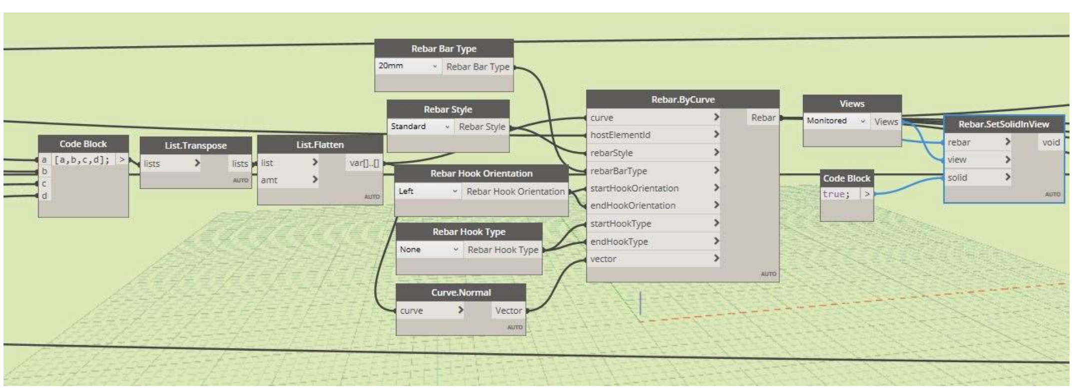


Figure 74. Rebars placing in columns.

2.9.11 Parameter setting for columns rebars

The last part of the script dedicated to the columns reinforcements has the function to set the parameters. In particular the setted parameter is the identification code of the rebar that is created with the following structure:

"Elemento host/Allineamento"

The value of the first part depends on the number of the column in which the rebar is placed.

The second part depends on the position of the rebar inside the cross section of the monitored column and the value could be "pp", "pn", "np" or "nn" according to the corner in which the rebar is located.

An example of the parameter could be *"23/pp"* and defines the rebar located at the right top corner of the cross section of the column number 23.

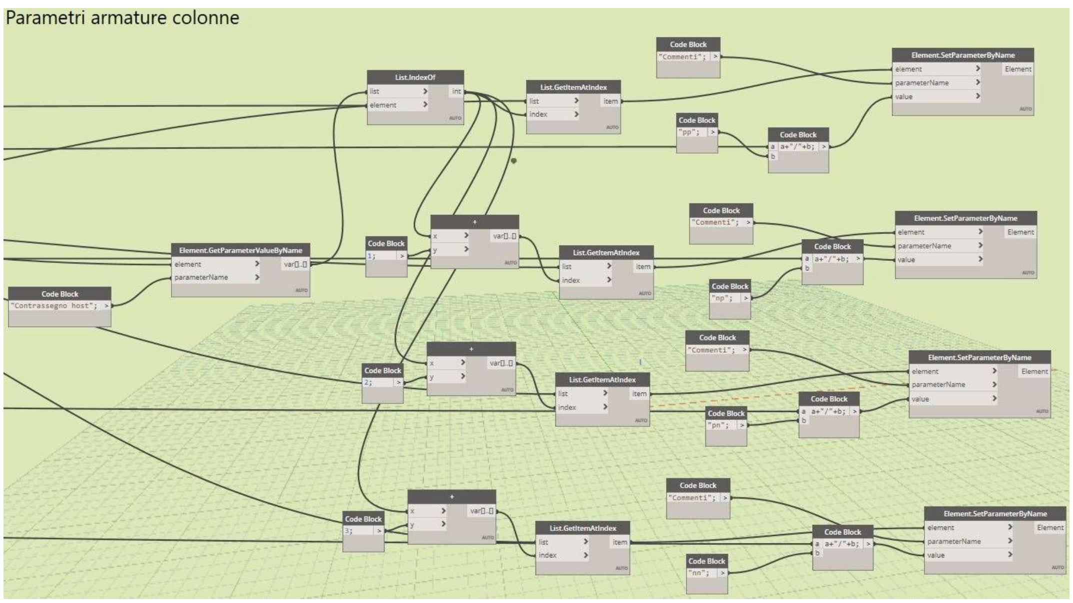


Figure 75. Parameter setting for columns rebars.

2.9.12 Results of the rebar placement script

After the placement of the script the model is complete and contains all the needed sensors and the correspondent rebars. In the following images is shown the result of a low automatic monitoring level completed with a few structural elements selected with the manual script and completed with the rebars.

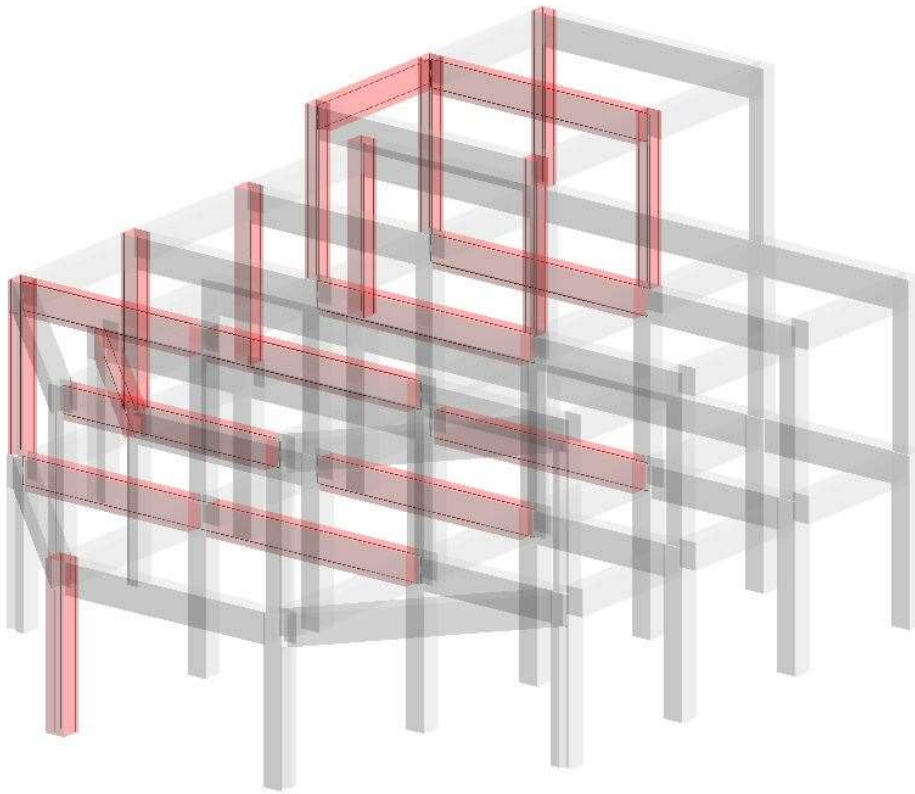


Figure 76. Complete Revit model with sensors and rebars.

The advantages of this digital twin of the structure including the Structural Health Monitoring System is the possibility to visualize easily the monitored structural elements and the position of the sensors.

In addition, with the possibility to insert in the parameters of the sensors the measured values is possible to create a sort of "black box" of the building containing the history of deformations and the state of health of the structure.

The next images show examples of rebars containing sensors in a column and a beam.

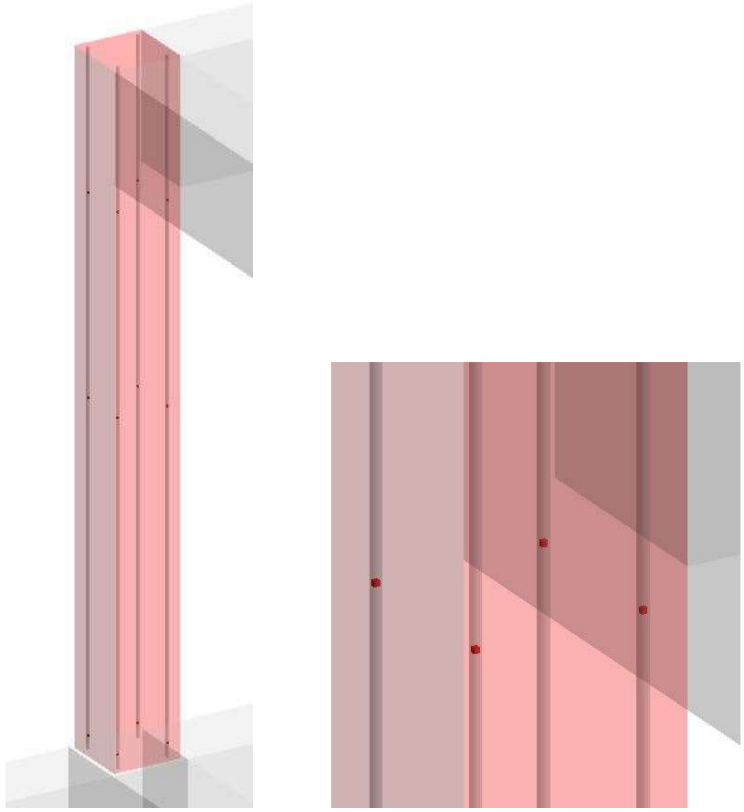


Figure 77. Monitored column and relative sensors.

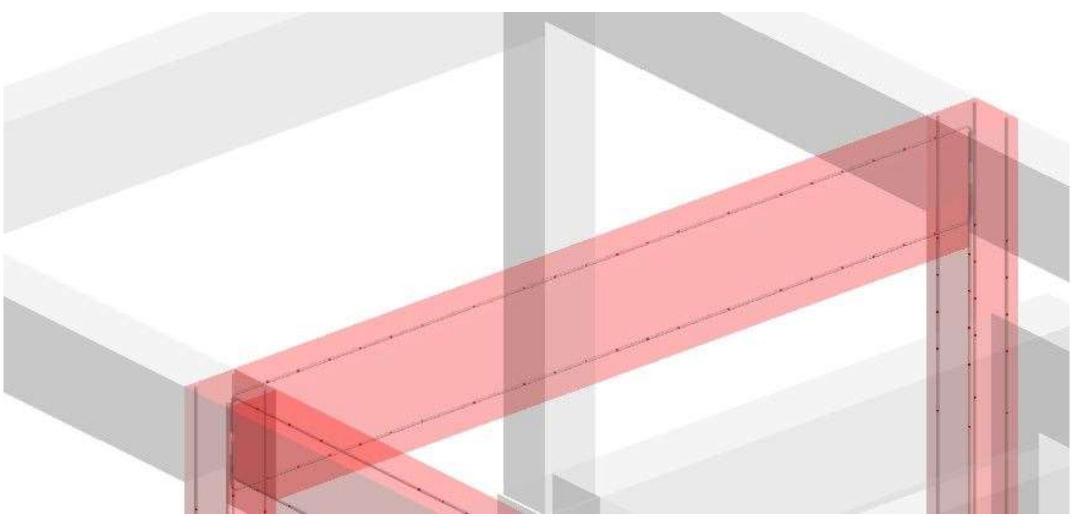


Figure 78. Monitored beam.

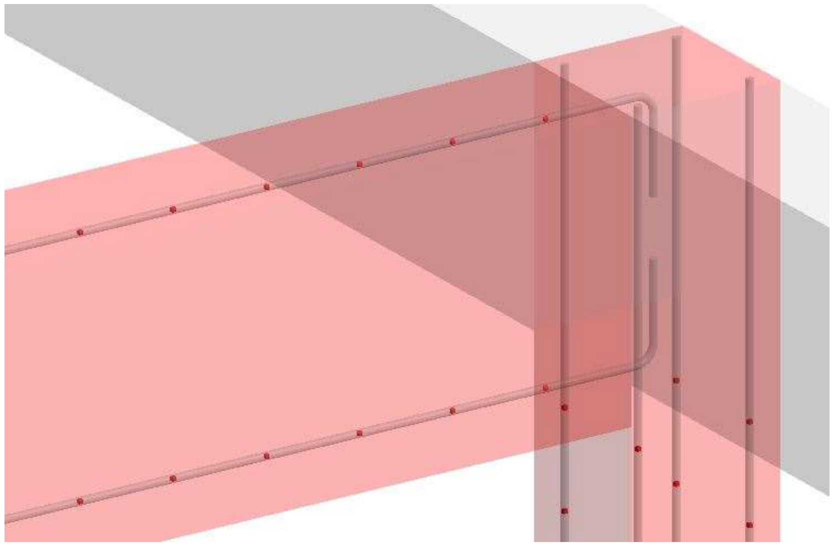


Figure 79. Sensors and reinforcements in a monitored beam.

Chapter 3: Sensors data simulation

In order to create a more realistic model a set of deformations data has been created in order to fill the parameters of the sensors in Revit. To solve this task has been ued the structural model exported in Robot that has been shown previously but a new group of load cases has been created.

3.1 Load cases

To simulate a brief history of the building's deformations a set of incremental loads has been used based on 10 step. In particular only the 10 load cases has been created considering only the dead load of the structure and the variable load (2 kN/m^2) that has been multiplied by 10 different coefficients.

The coefficients that have been used are:

- Step 1: 0,1
- Step 2: 0,2
- Step 3: 0,3
- Step 4: 0,4
- Step 5: 0,5
- Step 6: 0,6
- Step 7: 0,7
- Step 8: 0,8
- Step 9: 0,9
- Step 10: 1,0

With this coefficients a set of 10 different variable loads (from 0,2 kN/m^2 to 2,0 kN/m^2) have been obtained.

In the following images some load cases are show. In particular the first image is related to step 1 (0,2 kN/m^2), the second to step 5 (1,0 kN/m^2), the third to step 7 (1,4 kN/m^2) and the fourth to step 10 (2,0 kN/m^2).

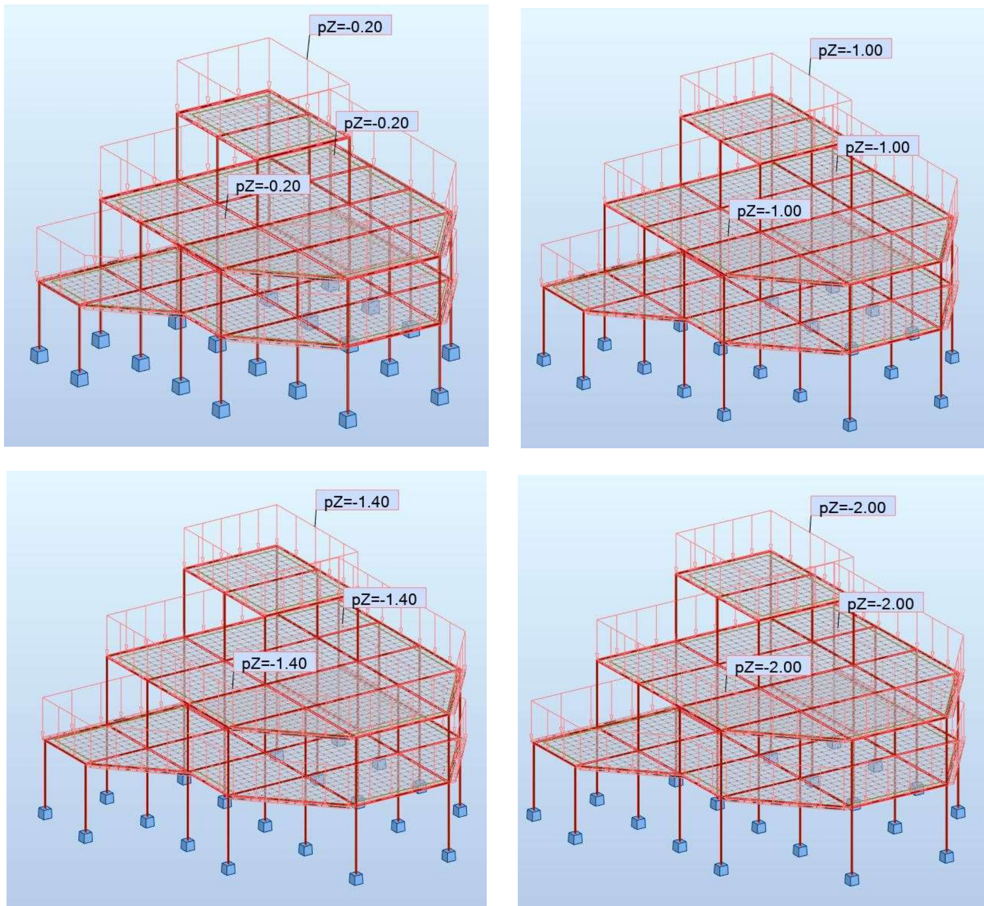


Figure 79. Some examples of the load cases used for the simulation of the deformations.

Once the load have been defined the analysis has been executed and the data have been organized in a table. In particular the table has been organized in order to contain values of the bending moment for each monitored structural element in the needed sections. For this reason the sections have been setted equal to the positions of the sensors whom values are known from the automatic sensor placement Excel file.

As regards the positions of the monitored elements that have been selected with the manual script, tha values need to be added manually.

3.2 Data management on Excel

Once the data form the Robot analysis are available the next step is the exportation to Excel.
The exported data are organized in 4 columns:

- Identification data code: has the following structure *"Element number/sensor position/load case number"*,
- Structural Element identification number,
- Length of the structural element (m),
- Bending moment (kN/m).

The data are divided in two different sheets, one for the beams and the other one for the columns. In both files the the values fo the bending moments are used to calculate the stresses at the level of the sensors and then the correspondent deformations.

In order to calculate the values of the stresses and deformations the neutral axis needs to be calculated. For this purpose two dedicated Excel sheets have been created (one for the beams and one for the columns). Once the value of the neutral axis is known the moment of inertia of each section has been calculated and has been used to obtain the stresses at the level of the sensors near estrados and intrados for the beams and in the four corners of the columns.

From the values of the stresses the deformations have been calculated.

In the following images are shown the Excel files used for the calculation of the deformations.

Elemento/Punto (m)/Condiz.	Nome	Lunghezza (m)	MY (kNm)	x (mm)	J (mm^4)	σ arm,intr (Mpa)	σ arm,estra (Mpa)	Ɛarm,intr	Ɛarm,estra
12/ utente x=0,29/ 15 (C)	51	6	-38,75	53,0	8417843120	-46,05	1,59	-0,00146	5,05E-05
12/ utente x=0,29/ 16 (C)	51	6	-39,9	53,0	8417843120	-47,42	1,64	-0,00151	5,2E-05
12/ utente x=0,29/ 17 (C)	51	6	-41,06	53,0	8417843120	-48,80	1,68	-0,00155	5,36E-05
12/ utente x=0,29/ 18 (C)	51	6	-42,21	53,0	8417843120	-50,17	1,73	-0,0016	5,51E-05
12/ utente x=0,29/ 19 (C)	51	6	-43,36	53,0	8417843120	-51,53	1,78	-0,00164	5,66E-05
12/ utente x=0,29/ 20 (C)	51	6	-44,51	53,0	8417843120	-52,90	1,83	-0,00168	5,81E-05
12/ utente x=0,29/ 21 (C)	51	6	-45,67	53,0	8417843120	-54,28	1,87	-0,00173	5,96E-05
12/ utente x=0,29/ 22 (C)	51	6	-46,82	53,0	8417843120	-55,65	1,92	-0,00177	6,11E-05
12/ utente x=0,29/ 23 (C)	51	6	-47,97	53,0	8417843120	-57,01	1,97	-0,00181	6,26E-05
12/ utente x=0,29/ 24 (C)	51	6	-49,12	53,0	8417843120	-58,38	2,01	-0,00186	6,41E-05
12/ utente x=1,97/ 15 (C)	51	6	30,97	53,0	8417843120	36,81	-1,27	0,00117	-4,04E-05
12/ utente x=1,97/ 16 (C)	51	6	31,89	53,0	8417843120	37,90	-1,31	0,001205	-4,16E-05
12/ utente x=1,97/ 17 (C)	51	6	32,82	53,0	8417843120	39,01	-1,35	0,00124	-4,28E-05
12/ utente x=1,97/ 18 (C)	51	6	33,75	53,0	8417843120	40,11	-1,38	0,001276	-4,4E-05
12/ utente x=1,97/ 19 (C)	51	6	34,68	53,0	8417843120	41,22	-1,42	0,001311	-4,52E-05
12/ utente x=1,97/ 20 (C)	51	6	35,6	53,0	8417843120	42,31	-1,46	0,001345	-4,64E-05
12/ utente x=1,97/ 21 (C)	51	6	36,53	53,0	8417843120	43,42	-1,50	0,001381	-4,76E-05
12/ utente x=1,97/ 22 (C)	51	6	37,46	53,0	8417843120	44,52	-1,54	0,001416	-4,89E-05
12/ utente x=1,97/ 23 (C)	51	6	38,39	53,0	8417843120	45,63	-1,57	0,001451	-5,01E-05
12/ utente x=1,97/ 24 (C)	51	6	39,31	53,0	8417843120	46,72	-1,61	0,001486	-5,13E-05

Figure 80. Excel file for beam deformations.

caratteristiche sez		*copriferro*			*ARMATURA TESA*								
B	**H**	**h-d**	εcu	εyd	**Φ1**ipotesi	**Φ2**ipotesi	**Φ3**ipotesi	**Φ4**ipotesi	**Φ5**ipotesi	**Φ6**ipotesi	**Φ7**ipotesi	**Φ8**ipotesi	**Φ9**ipotesi
[m]	**[m]**	**[m]**	**[-]**	**[-]**	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**
0,45	0,75	0,03	0,35	0,19	0,02	0,02	0,02	0,02	0	0	0	0	0
0,45	0,75	0,03	0,35	0,19	0,02	0,02	0,02	0,02	0	0	0	0	0
0,45	0,75	0,03	0,35	0,19	0,02	0,02	0,02	0,02	0	0	0	0	0
0,45	0,75	0,03	0,35	0,19	0,02	0,02	0,02	0,02	0	0	0	0	0
0,45	0,75	0,03	0,35	0,19	0,02	0,02	0,02	0,02	0	0	0	0	0
0,45	0,75	0,03	0,35	0,19	0,02	0,02	0,02	0,02	0	0	0	0	0
0,45	0,75	0,03	0,35	0,19	0,02	0,02	0,02	0,02	0	0	0	0	0

ARMATURA COMPRESSA																
Φ'1ipotesi	Φ'2ipotesi	Φ'3ipotesi	Φ'4ipotesi	Φ'5ipotesi	Φ'6ipotesi	Φ'7ipotesi	Φ'8ipotesi	Φ'9ipotesi	Φ'10ipote:	Φ'11ipote:	Φ'12ipote:	Φ armatura	d	d'	fcd	mRD
[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[N/mm^2]	[-]
0,02	0,02	0,02	0,02	0	0	0	0	0	0	0	0	0,008	0,71	0,04	14,11	0,012106
0,02	0,02	0,02	0,02	0	0	0	0	0	0	0	0	0,008	0,71	0,04	14,11	0,012466
0,02	0,02	0,02	0,02	0	0	0	0	0	0	0	0	0,008	0,71	0,04	14,11	0,012828
0,02	0,02	0,02	0,02	0	0	0	0	0	0	0	0	0,008	0,71	0,04	14,11	0,013187
0,02	0,02	0,02	0,02	0	0	0	0	0	0	0	0	0,008	0,71	0,04	14,11	0,013547
0,02	0,02	0,02	0,02	0	0	0	0	0	0	0	0	0,008	0,71	0,04	14,11	0,013906
0,02	0,02	0,02	0,02	0	0	0	0	0	0	0	0	0,008	0,71	0,04	14,11	0,014268

% meccanica di armatura			pi greca								asse neutro
ws	fyd	As,min	π	As	A's	AsTOT	Ax^2	Bx	C	Δ	x
[-]	[N/mm^2]	[mm^2]	[-]	[mm^2]	[mm^2]	[mm^2]	[-]	[-]	[-]	[-]	[mm]
0,012181	391,3043	140,3304	3,141593	1256,637	1256,637	2513,274	5079,6	414086,4	-36232556	9,08E+11	53,0
0,012544	391,3043	144,5215	3,141593	1256,637	1256,637	2513,274	5079,6	414086,4	-36232556	9,08E+11	53,0
0,012911	391,3043	148,7506	3,141593	1256,637	1256,637	2513,274	5079,6	414086,4	-36232556	9,08E+11	53,0
0,013276	391,3043	152,9448	3,141593	1256,637	1256,637	2513,274	5079,6	414086,4	-36232556	9,08E+11	53,0
0,01364	391,3043	157,1405	3,141593	1256,637	1256,637	2513,274	5079,6	414086,4	-36232556	9,08E+11	53,0
0,014004	391,3043	161,3378	3,141593	1256,637	1256,637	2513,274	5079,6	414086,4	-36232556	9,08E+11	53,0
0,014372	391,3043	165,5732	3,141593	1256,637	1256,637	2513,274	5079,6	414086,4	-36232556	9,08E+11	53,0

Figure 81. Excel file for beam's neutral axis calculation.

3.3 Sensors deformations setting in Revit with Dynamo

Once the deformations have been calculated a Dynamo script has been created in order to fill in the sensor's parameters dedicated to the measured values.

The algorithm is divided in two main parts, one for the beams and the other for the columns.

As regards the beams, the first part of the script is dedicated to the exportation of the deformations from the Excel sheet to the Dynamo environment. The nodes that have been used are: *File.Path, Read.Excel, List.CountOccurrences, List.Clean* and *String.Split.*

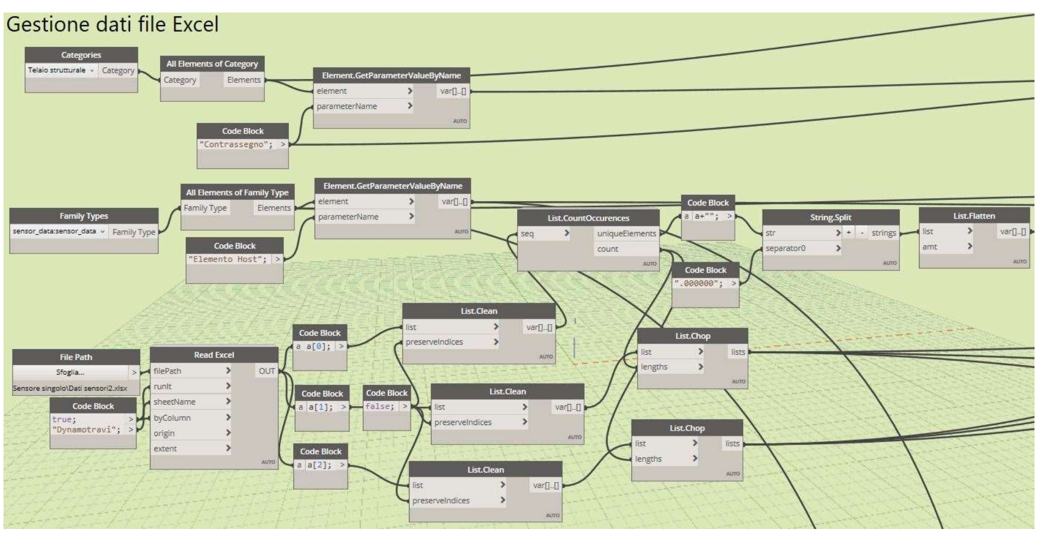


Figure 82. Beams deformations exported from Excel file.

Then the deformations data are divided according to the directions of the beams using nodes such as *List.FilterByBoolMask, List.AllIndicesOf, List.Reorder, List.GroupByFunction, List.Contains* and *List.GetItemAtIndex.*

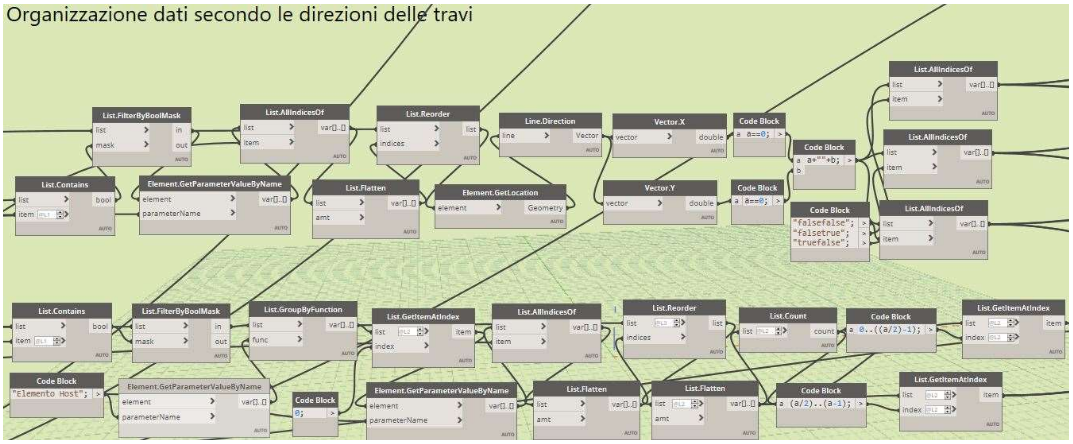


Figure 83. Deformations grouped by beams direction.

The last step of the script is the filling of the parameters in Revit for each sensor of the monitored beams. For this purpose have been created 6 branches of the script for beams in X direction, Y direction and inclined direction both for intrados and extrados and all with the same structure. The Dynamo nodes that have been used are: *Element.SetParameterByName, Element.GetLocation, List.SortByFunction, List.Flatten, List.AllIndicesOf* and *List.Chop.*

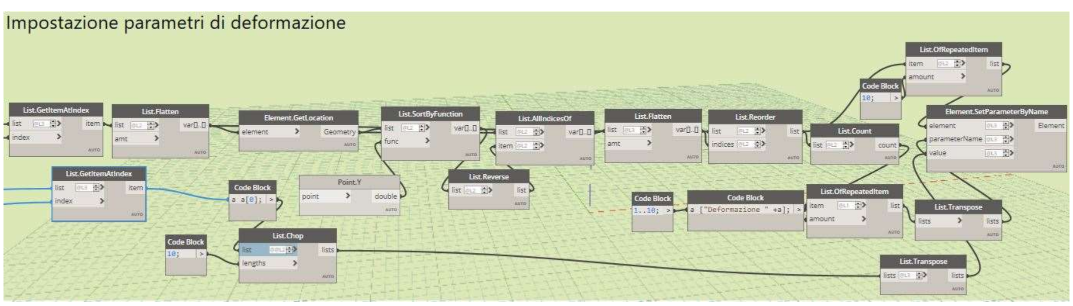


Figure 84. Parameters filling with deformations for beams.

As concerns the columns the initial part of the script has the same function of exportation of the data. The nodes that have been used are: *File.Path, Read.Excel, List.CountOccurrences, List.Clean, List.Chop* and *String.Split.*

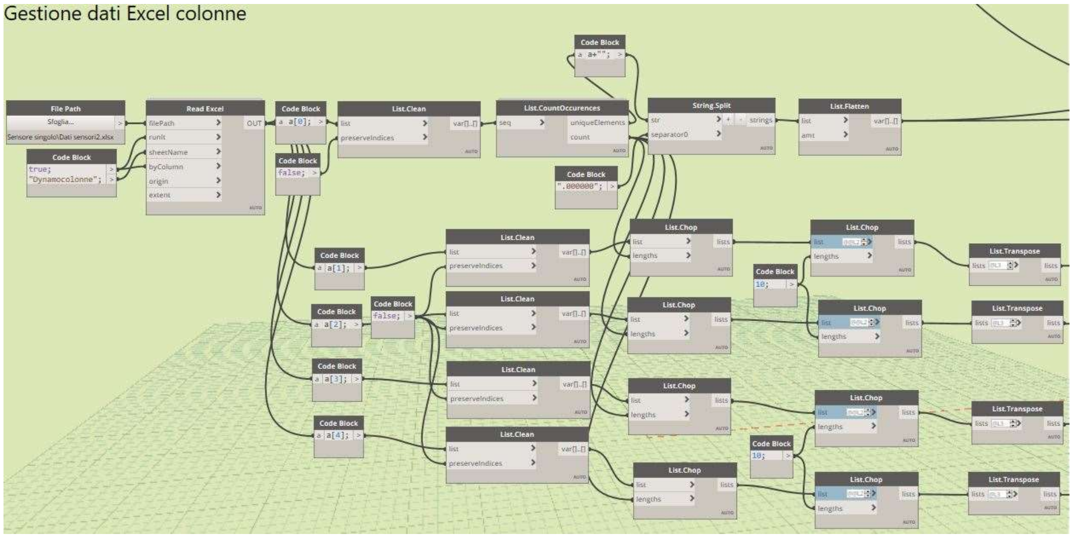


Figure 85. Data management for monitored columns.

Once the deformations has been imported the next step is the organization according to the different columns and for each corner allignment. In order to group the data the following nodes has been used: *List.FilterByBoolMask, Element.GetParameterValueByName, List.GetItemAtIndex, List.GroupByFunction* and *List.AllIndicesOf*.

Figure 86. Deformations grouped by corners.

The last step is the setting of the 10 parameters from each sensor using the previously organized data. For this purpose have been created 6 branches of the script for beams in X direction, Y direction and inclined direction both for intrados and extrados and all with the same structure. The nodes that have been used are: *List.GetItemAtIndex, List.Count, List.SortByFunction* and *Element.SetParameterValueByName.*

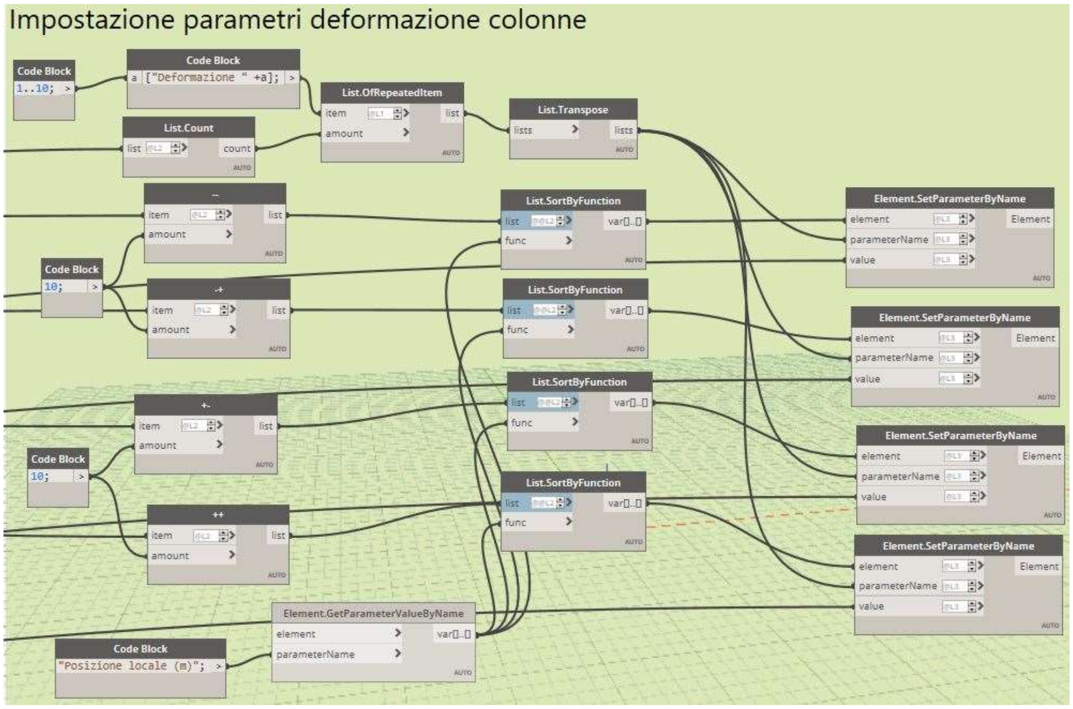


Figure 87. Parameters filling for monitored columns.

3.4 Script results

After the execution of the script all the 10 deformations parameters are filled with the values calculated with the structural model on Robot.

An example of the values of deformations is shown in the following image related to a sensors located in the right top corner (pp) of the cross section of the column number 24 at a distance from the base equal to 0,58 m.

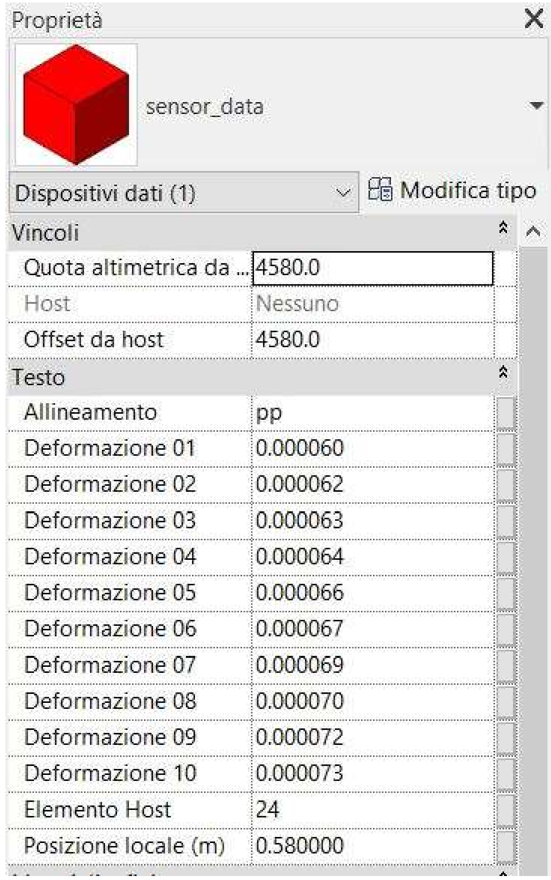


Figure 88. Sensor parameters filled with deformation values.

Chapter 4: SHM system design for bridges

4.1 Modification process

Once the Structural Health Monitoring System automatic design algorithm has been created and tested on the previous structure, the following step is the adaptation process in order to obtain an automatic routine that is able to deal with bridge structures.
The adjustments that need to be done are both related to different characteristics of a bridge compared to a building (that is the case study that has been used to develop the Dynamo codes described in the previous chapters) and to particularities strictly related to the Revit categories used to realize the model of the bridge.
For these reasons each of the previously created Dynamo scripts needs to be adapted with little change in order to work properly and these operations will be described in this chapter.

4.2 Case study: Stura bridge

In order to settle the algorithm to a structure with the characteristics of a bridge a case study has been used. In particular the bridge that has been studied is the Stura bridge that is a wokpiece belonging to the RA10 motorway connection that connects the city of Turin with the Caselle airport.

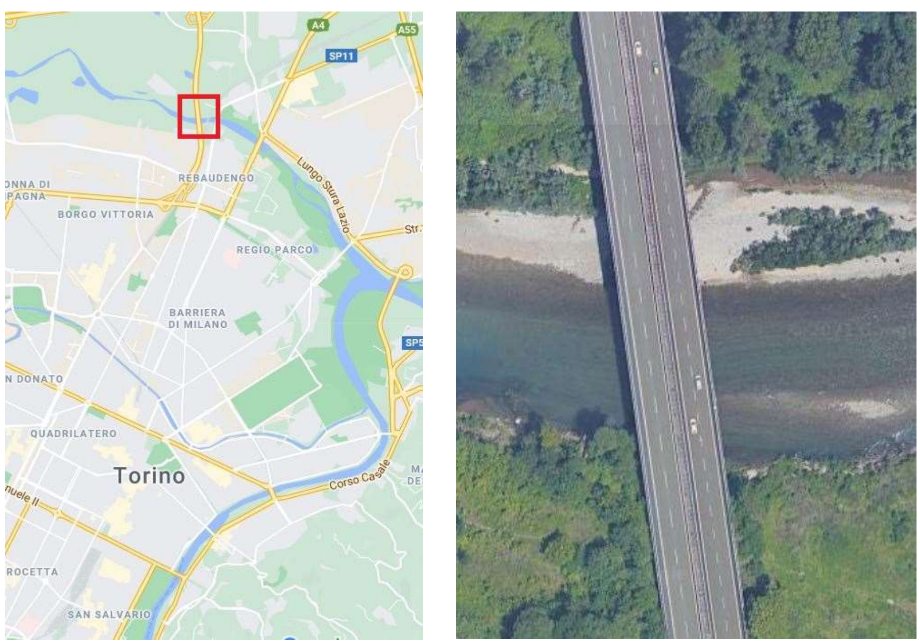


Figure 89. Location and aerial view of the Stura Bridge. Source. Google Maps.

The bridge has been built to overpass the Stura di Lanzo river and is located approximately on the progressive K2+ 800 m from the start of the road in the direction from Turin to Caselle airport.
The structure is composed by a 150 m length double bridge with two adjacent decks; each one of them corresponds to a different travel direction and contains two lanes.
Each one of the two parallel bridge is composed by 5 spans of equal length. Each span is composed by a concrete slab supported by three main pre-stressed concrete girders and by rectangular-shaped transversal concrete beams.

The spans are supported by a pier caps that are placed on top of three circular piers each one.

Figure 90. Photo of the Stura Bridge taken during an inspection on site.

The Stura bridge was the case study of previuosly realized thesis works and in particular a Revit model of the structure has been already made by Luis Miguel Hernández Ramos in his thesis "*Structural Health Monitoring through the Building Information Modelling.* Luis Miguel Hernández Ramos, Francesco Tondolo, Anna Osello. 2019".
I take this opportunity of thanking him for the work he has done.

The Revit model is shown in the following pictures:

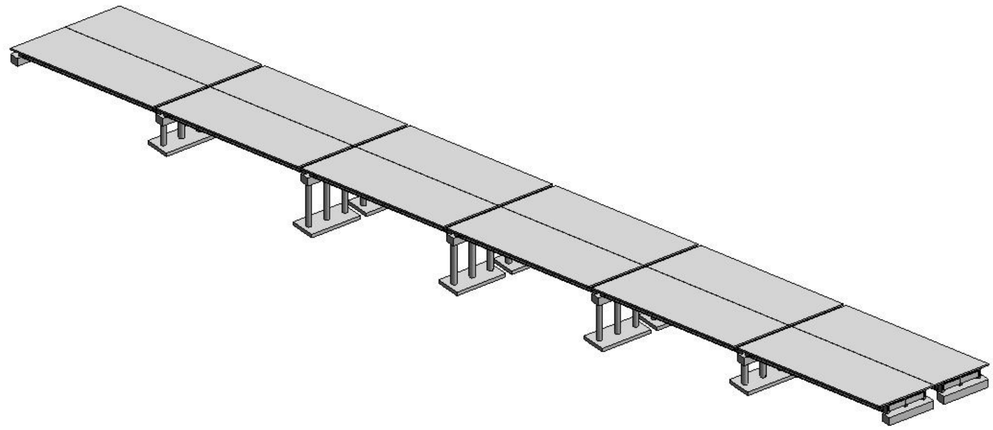


Figure 91. 3D view of Stura bridge model.

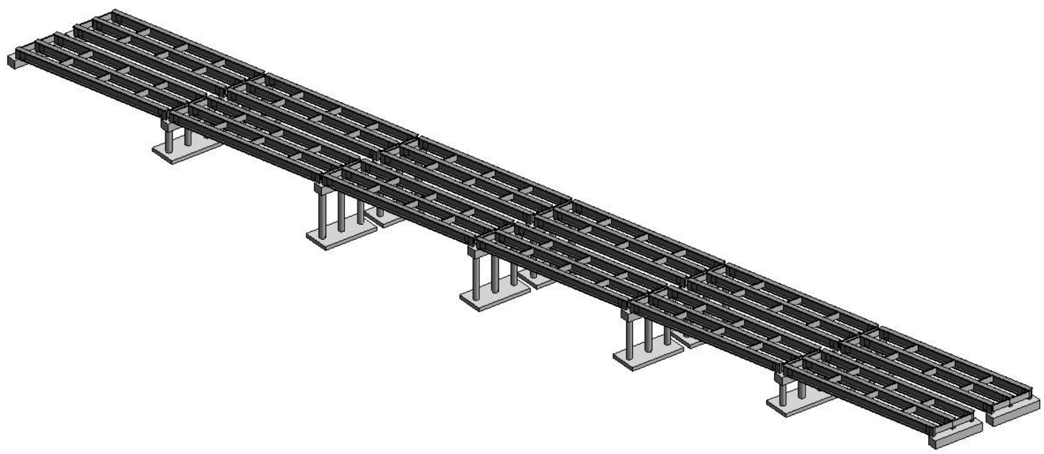


Figure 92. Revit model without the concrete slab.

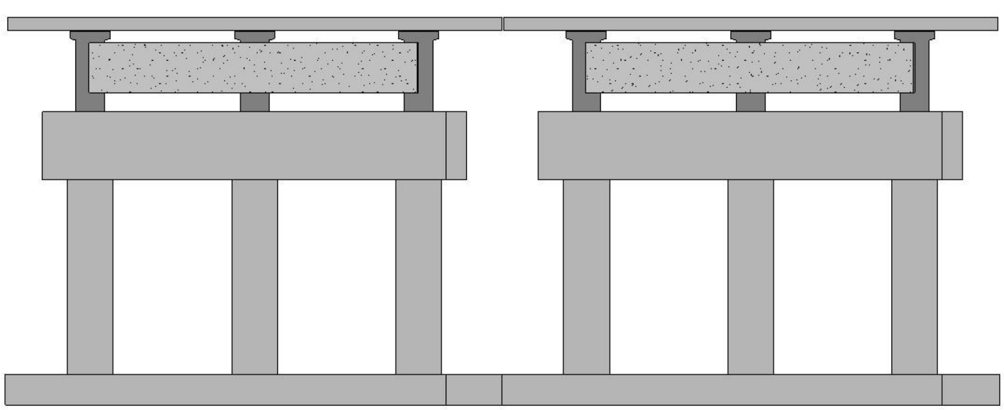


Figure 93. Transversal profile of the bridge.

In the following image is shown the Revit family created to represent the pre-stressed concrete beams that has a variable cross section along the length of the element.

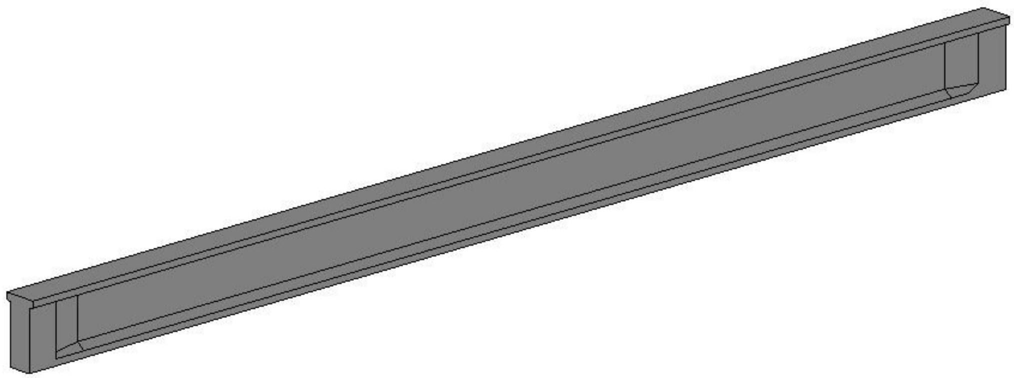


Figure 94. Revit family of the pre-stressed concrete beam.

4.3 Structural analysis on Robot

Once the Revit model of the bridge is available the nest step is the structural analysis that will gives the values of bending moment that will be used to set the Structural Health Monitoring system.
The structural model was obtained using the direct link in Revit that allows the user to export the model in Robot and convert it in a structural one.
This function is very simple and fast but has shows also many problems due to unrecognized connections between the structural elements. This problem creates some errors in the final results and needed to be fixed manually.
But despite this, the use of the Revit-Robot link still remains a better solution compard to creating by zero a new structural model.

For the analysis have been considered 6 different load combinations composed with the following structure:

1,35 x (Dead load) + 1,50 x (Notional lanes load) + 1,50 x (Tandem systems load)

The combinations have been created in order to maximize the positive bending moment in midspan of the external longitudinal beams. Each combination maximize the bending moment of the external beams of the same span in the two bridges.

As regard the notional lanes the values of the Load Model 1 have been considered. In particular, starting from the most loaded extremity of the transversal section and moving towards the centerline of the deck has been placed the following notional lanes:

- First 1,5 m : unloaded,
- Notional lane 1 (3m): uniformly distributed load of 9,0 kN/m^2 and two axle loads of 300 kN,

- Notional lane 2 (3m): uniformly distributed load of 2,5 kN/m^2 and two axle loads of 200 kN,
- Notional lane 3 (2,1m): uniformly distributed load of 2,5 kN/m^2 and one axle load of 100 kN,
- Remaining area: unloaded.

The third notional lane is tighter than the other ones and contains only one axle load because, according to the transverse distribution of Courbon in the case of maximum load on the external beam, considering a wider length would have decreased the value of the bending moment.

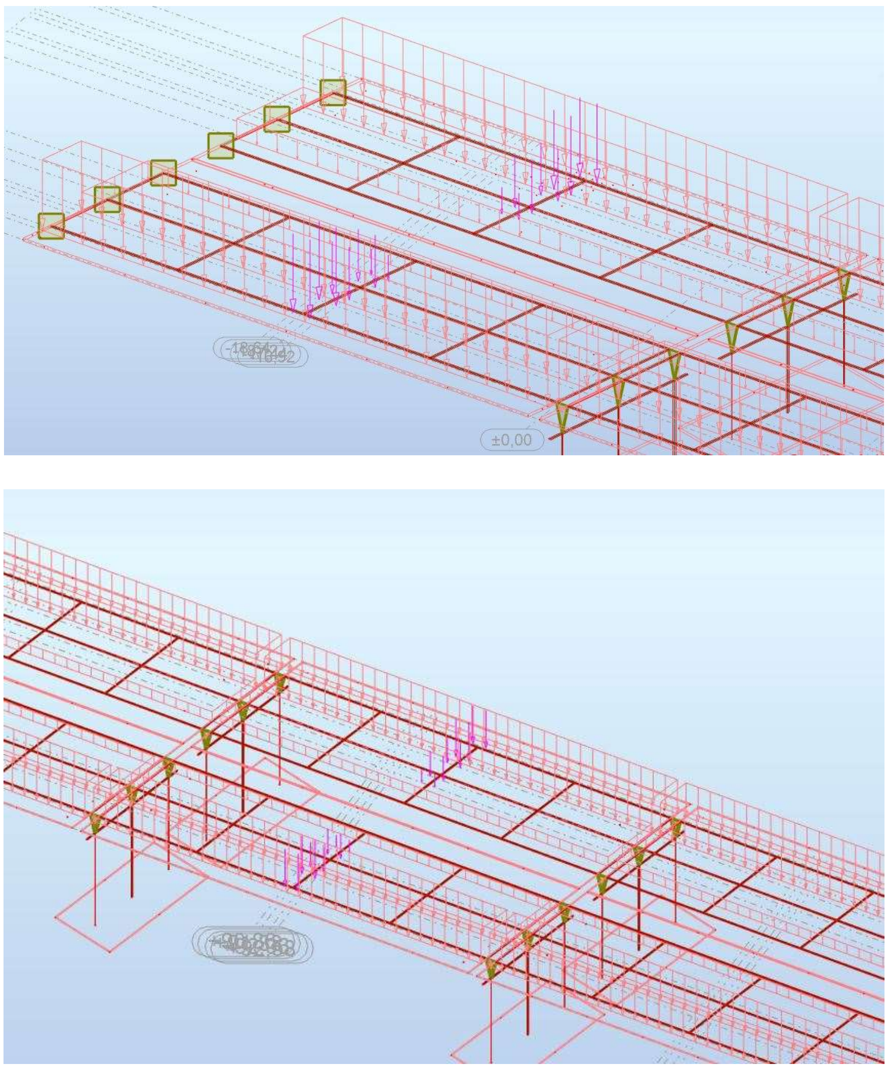


Figure 95. Load combinations for maximizing bending moment in span 1 and 4.

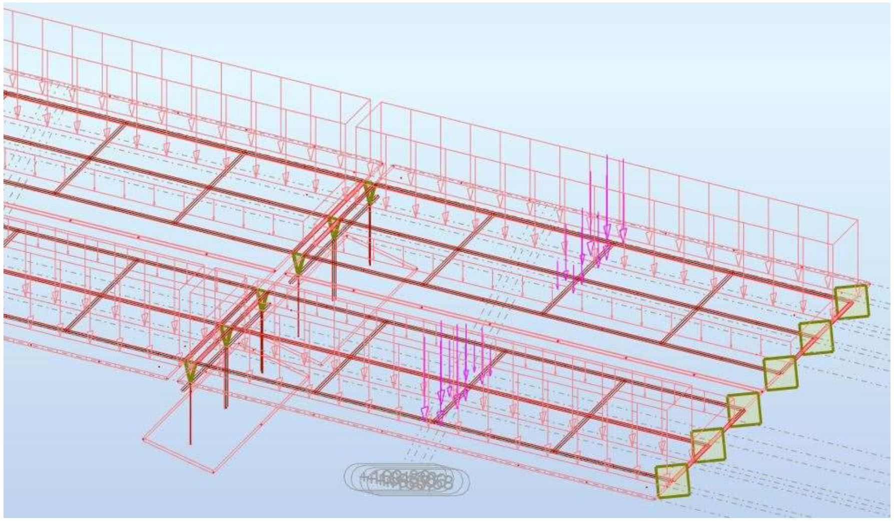


Figure 96. Load combinations for maximizing bending moment in span 6.

A more accurate structural analysis would have required more load combinations in order to maximize also the extremal beams on the internal side of the two bridges but for the aim of this thesis work a lower number of combinations is sufficient.

In addition, once the automatic script has been executed is simple, thanks to the symmetry, to understand the beams on the inner side of the deck that need to be monitored and the SHM system can be completed with the manual script.

The following step is the management of the analysis results. The values of the bending moment have been organized in a table that has been exported to Excel.

4.4 Data management on Excel

The Excel file used for the mangement of the bending moment values has the same structure of the one used for the first study case but with some differences.

The data were divided in two different Excel files, one for the columns and one for the beams due to the different location of the stress concetration zones. In fact for the beams the monitored sectors are three (the two extremities and the midspan zone) and for the columns the zones subjected to major bending moment are only the top and the bottom.

4.4 Beams and columns Excel files

As concerns the sheets related to calculation of the envelope of the bending moment no modifications occured compared to the file created for the first case study.

The following sheets are still structured on three different monitoring levels (High, Medium and Low) and the structure of each sheet is the same and for this reason only one of them will be described. The percentils chosen could vary from

Considering the sheet “90”, all the bending moment data are collected in a column with the number of the element and the length and filtered with respect to a percentile (50%) of the maximum bending moment of the beams. If the maximum bending moment in a beam is lower than the fixed threshold the correspondent lines are setted as empty.

Once obtained the information on the monitored beams, a further subdivision has been made in three different levels of Structural Health Monitoring:

- Level 1: beams with bending moment higher than 90% and lower than 92.5% of the maximum,
- Level 2: beams with bending moment higher than 92.5% and lower than 95% of the maximum,
- Level 3: beams with bending moment higher than 95%.

For each level a different spacing of the sensors is considered in order to have an higher density of sensors in the zones of the beam subjected to higher bending moments.

In particular for Level 1 hase been chosen an interaxis of 2,5 m, for Level 2 of 2,0 m and for Level 3 of 1,5 m.

The interaxis used for the sensors are higher, in comparison to the ones used for the first case study, because of the higher length of the monitored beams.

Then the length of each beam was divided in 5 parts:

- two external sectors of length equal to 1/4 of the length of the beam,
- a central sector with a length equal to 1/4 of the length of the beam,
- two transition sectors with a length of 1/8 of the length of the beam.

After the calculation of the length of each portion the number of sensors contained is obtained by simple multiplicaion of the length by the interaxis correspondent to the monitoring level.

An important difference from the previous case is that for the pre-stressed longitudinal beams the most important values of the bending moment are in the mid span area and for this reason a different number of sensors has been used for the external parts and for the central one.

In particular the number of sensor in external sectors has been calculated as the number in the central part subtracted by 2.

Smart Bar Parameters			
Length left section (m)	8,8	N. sensors left	4
Length central section (m)	8,8	N. sensors center	6
Length right section (m)	8,8	N. sensors right	4

Figure 97. Number of sensors in a monitored beam of the bridge.

The final part of the Excel sheet is related to the calculation of sensors positions and is the same of the previous case study.

The position depends on the thickness of the concrete cover, half the width of the column adjacent to the monitored beam and the value of the interaxis that depends on the level of monitoring defined previously.

		Posizione sensori (mm)							
1	2	3	4	5	6	7	8	9	sensori intermedi
100	1600	3100	4600						11156
21600	20100	18600	17100	15600	14100				24544
35600	34100	32600	31100						

Figure 98. Sensors positions in a monitored beam.

As concerns the Excel file dedicated to columns it took no modifications to adapt the files to the different structural typology and the composition remained the same.

4.5 Automatic sensors positioning in Revit model with Dynamo

4.5.1 SHM level selection

The first part of the script designed for the case study of the three storey building works properly also for the bridge and for this reason has not been modified. It starts with a group of nodes dedicated to the selection of the monitoring level. In particular are used three nodes from the package Data Shapes (TextNote Data, RadioButtons Data and

MultipleInputForm ++) in order to create an interface that allows the user to select between three different monitoring levels:

- High monitoring level: each structural element with bending moment higher than 80% of the maximum bending moment in the structure will be monitored,
- Medium monitoring level: each structural element with bending moment higher than 85% of the maximum bending moment in the structure will be monitored,

- Low monitoring level: each structural element with bending moment higher than 90% of the maximum bending moment in the structure will be monitored.

Dynamo allows the user to customize the created interface adding a picture and in this case the Politecnico di Torino logo has been chosen.

The values of the percentils used to define the three different monitoring levels have been changed with respect to the values used in the first case study. In particular, due to a greater homogeneity of the structure the bending moments are similar between the structural elements and for this reason the percentils have been increased.

In general the values of the percentils can be setted manually without any problems in order to meet the user's needs.

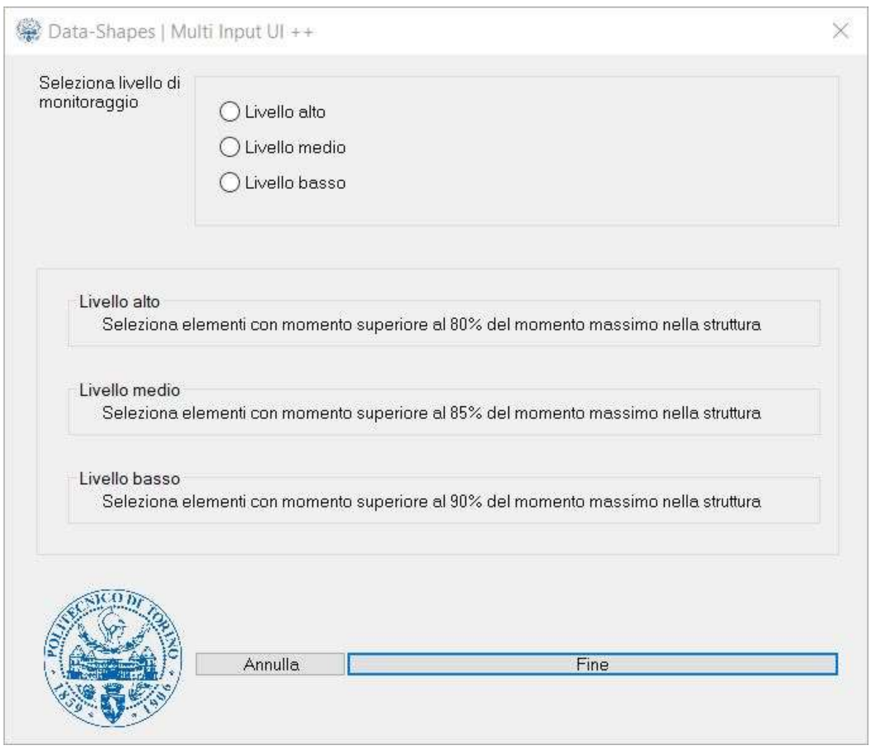


Figure 99. User interface for SHM level interface.

4.5.2 Data management from Excel files

This section is divided in two different branches both with the function to export the data from the Excel files and to reorder them in the most convenient way to place in the further step the sensors in the Revit model. In comparison to the script of the previous case study no modifications have been applied.

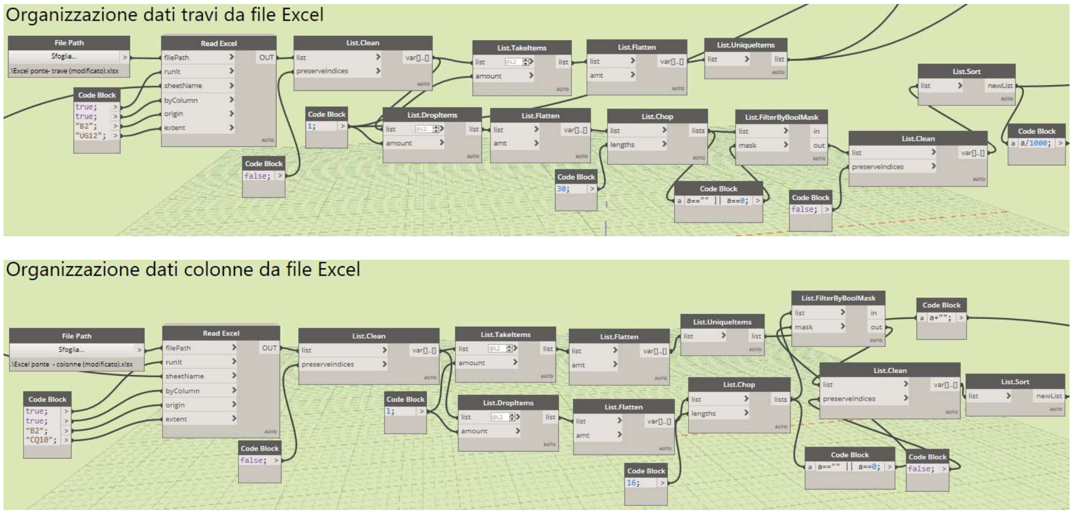


Figure 100. Part of the script dedicated to the selection of the data from the Excel files of beams (up) and columns (down).

4.5.3 Sensors positioning for monitored beams

The next step is the control of the list of monitored elements and the comparison with the list of all the values of the beam elements in the model in order to obtain their locations. This part of the script has been changed from the one developed in the first case study.

In order to solve this task the Dynamo nodes that has been used are: *Element.GetParameterValueByName, List.Contains, List.FilterByBoolMask, Element.GetLocation, List.Reorder* and *Element.GetParameterValueByNameTypeOrIstance.*

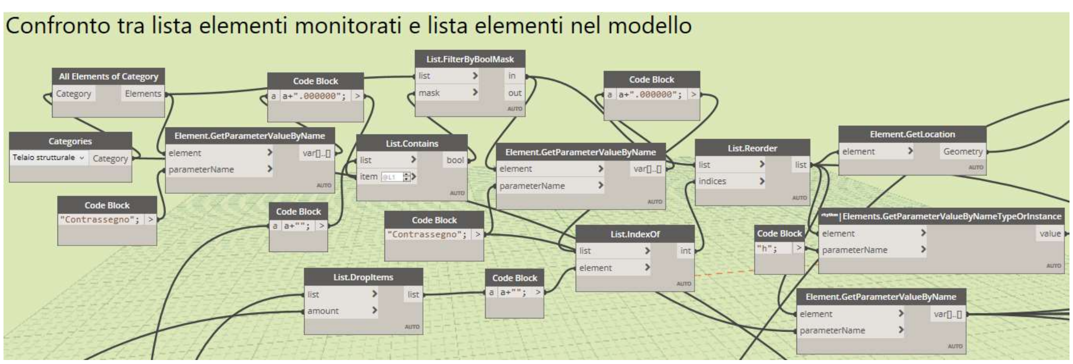


Figure 101. Management of the list of the monitored beams.

In particular the last node has been used because the node *Element.GetParameterValueByName* cannot be used with the Revit family of the beams.

Then the values of the sensors positions have been combined with the position data of the monitored elements in order to place the sensors in the Revit model. The nodes that has been used are: *Curve.PointAtSegmentLength, Geometry Translate, FamilyInstance.ByPoints* and *Element.SetParameteByName.*

The last node has been used to set the parameters of the sensors (Elemento Host, Allineamento, Posizione locale) that have the same characteristics as the one setted in the previous model.

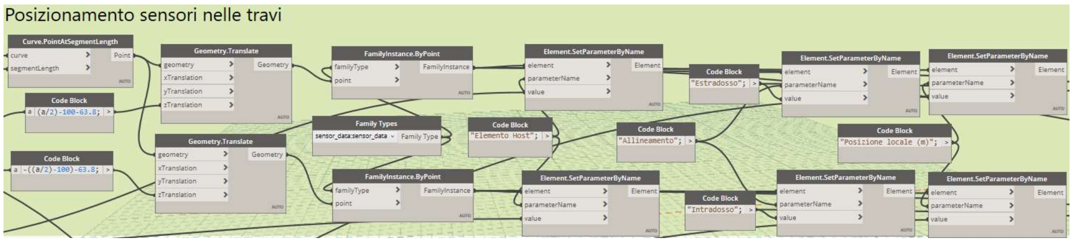


Figure 102. Sensors placement and parameters setting.

The last part of the script is dedicated to the setting of the main parameter that is the identification code of the sensors that have the same structure of the previous case study.

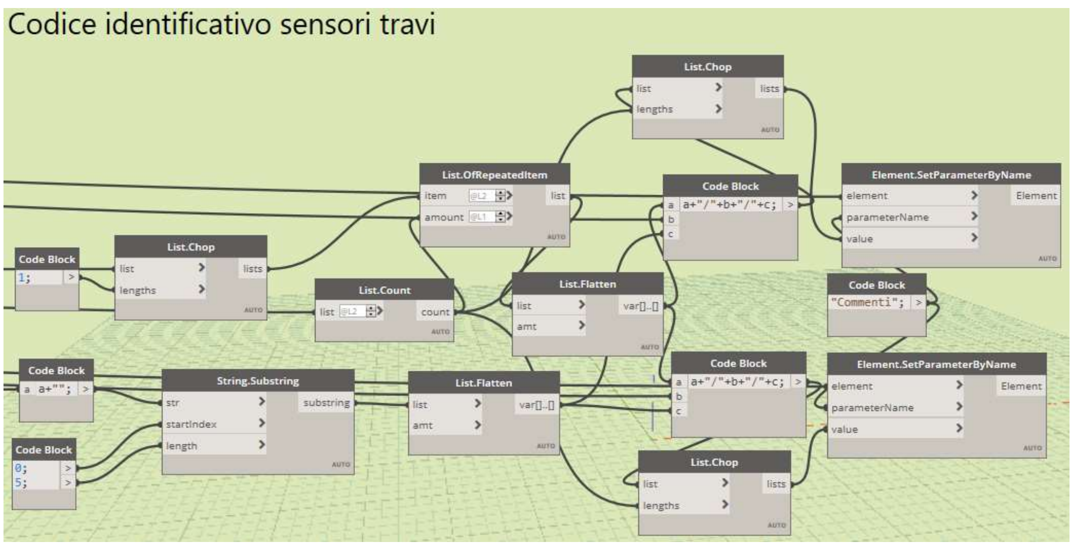


Figure 103. Identification code parameter setting.

4.5.4 Part of the script dedicated to the piers

As concerns the sensors positioning in the piers the structure is the same of the beams one with a section dedicated to the comparison of the list of the monitored elements and the evaluation of the position of the columns in the Revit model. Then the values of the columns positions are combined with the sensors positions and the sensors are placed in the model. The last part of the script is dedicated to the parameters setting of the sensors.

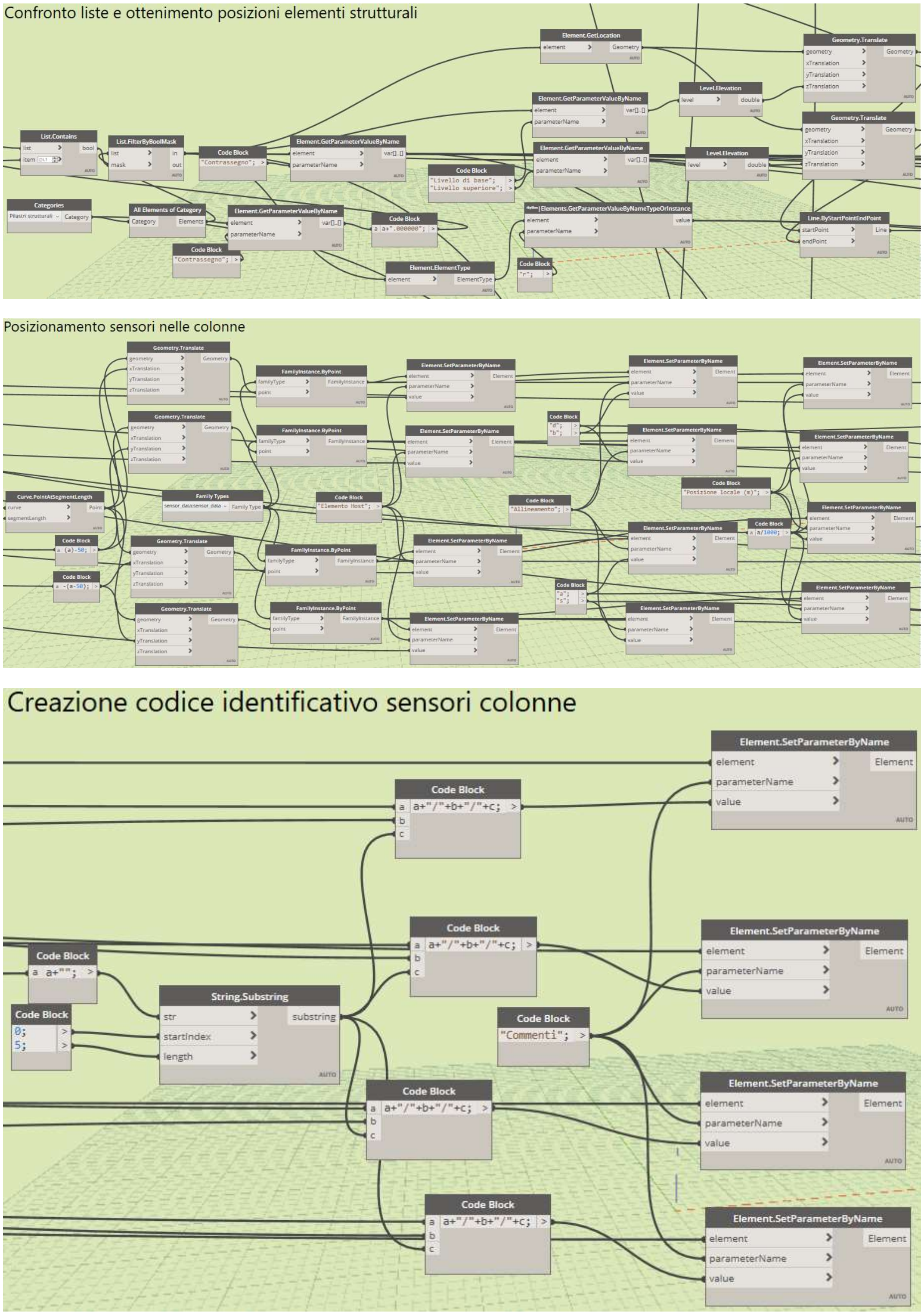


Figure 104. Script part dedicated to sensors in columns.

The only change in this part of the script are the values used for the parameter "Allineamento" that depends on the position of the sensors inside the cross section of the pier. The rule used for thi parameter is shown in the following image.

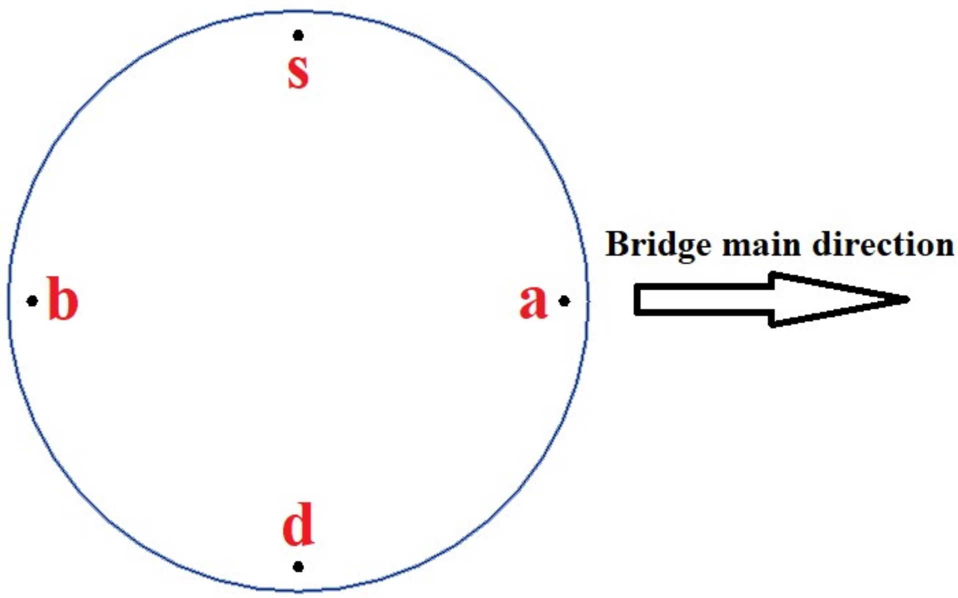


Figure 105. Values of the "Allineamento" parameter for columns sensors.

Referring to the previous image the possible values for the parameter are:

- "a" : comes from "alto" and is related to the top position of the cross section considering the main direction of the bridge,
- "b" : comes from "basso" and is related to the bottom position of the cross section considering the main direction of the bridge,
- "d" : comes from "destra" and is related to the right position of the cross section considering the main direction of the bridge,
- "s" : comes from "destra" and is related to the left position of the cross section considering the main direction of the bridge.

4.5.5 Script results

The following image shows the result of a medium monitoring level. The external beams of each span and the external piers will be monitored. As was previously described the used load combination are related to maximizing the bending moment only in the mid span of the external beams located on the outer part of the decks. And for this reason the ones located in the inner extremity were not selected.

This is the result of the decision to work with a low number of load combinations and the monitored elements can be considered as scheme to follow and the other external beams will be selected with the manual script that will be described in the following section.

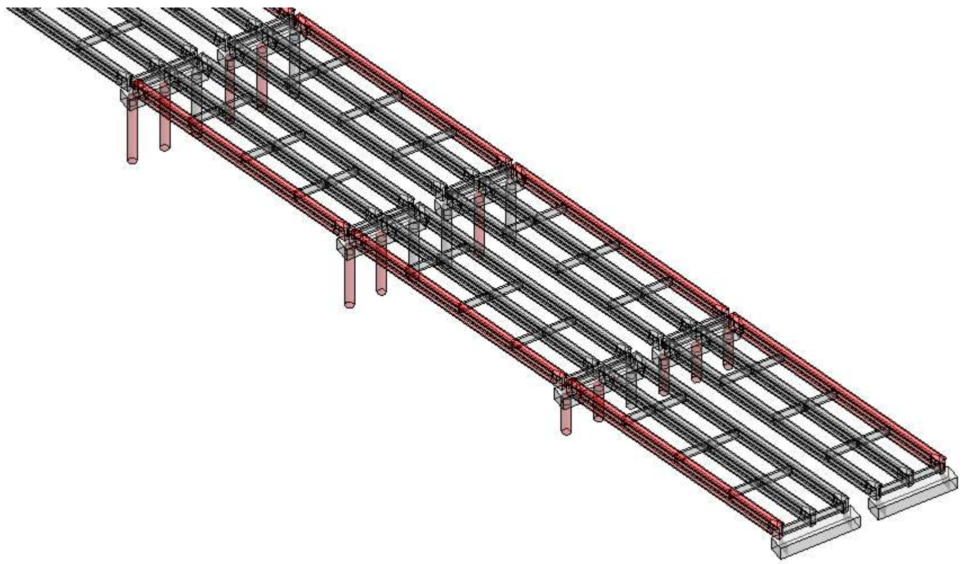


Figure 106. Monitored view of the Stura bridge.

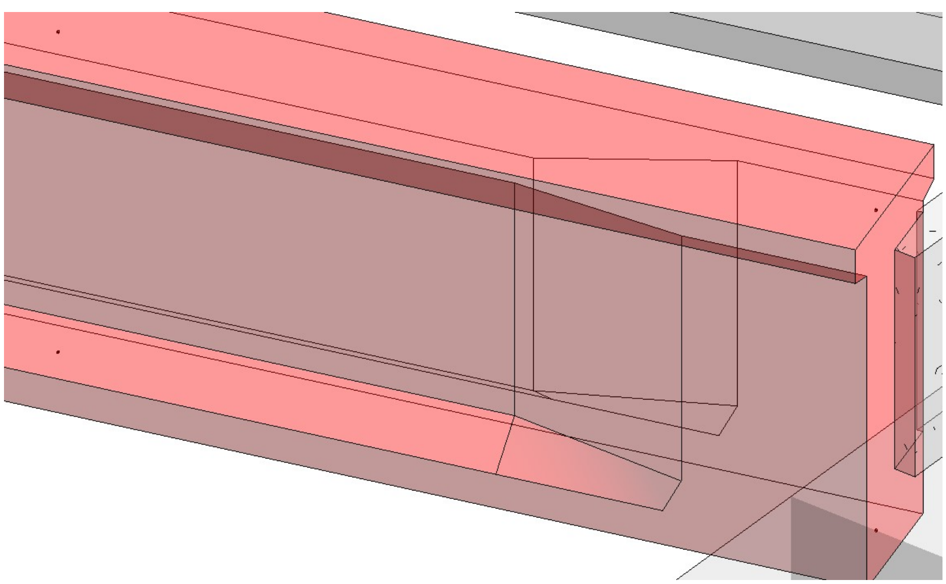


Figure 107. View of a monitored longitudinal beam.

In the previous image is shown a longitudinal beam monitored in the first sector with two sensors both at intrados and extrados.

4.6 Manual sensors positioning and smart bars positioning in Revit model with Dynamo

As regards the script related to the manual selection of the monitored elements the same modifications described for the previous script needed to be performed. This changes are related to different characteristics of the bridge and to issues related to the order of the values in some lists but do not change the main strucuture of the algorithm.

Corncerning the script created for the rebars positioning according to the sensors positions no changes were needed. The reason is the particular structure of the algorithm that places rebars in relation to the presence of sensors and is not dependent on the type of structure and on the way the sensors has been placed.

The easy of the adaptation process from the first to the second case study is a prove of the quality of the work that has been done during the creation of the first script in order to obtain an efficient system that is capable to deal with different type of structures.

4.7 Scripts results

In the following images are shown the results of a low monitoring level in which only the first span and an intermediate one are monitored. This selection is related to the different characteristic due the presence of the abutment in the first one. For each of the two spans and of the two adjacent decks have been monitored the external beams and piers.

The beams have been monitored with two sensors in the external sectors (both at intrados and extrados), four sensors in the central sector and one sensor in the intermediate zone.

As regards the piers, the four alignments are composed by three sensors in the top and bottom sectors and one sensor in the intermediate zone.

In particular the SHM system has been obtained by means of the automatic script that highlighted the elements that needed to be controlled for each span and then with the help of the manual script only two spans have been selected in order to reduce the number of sensors.

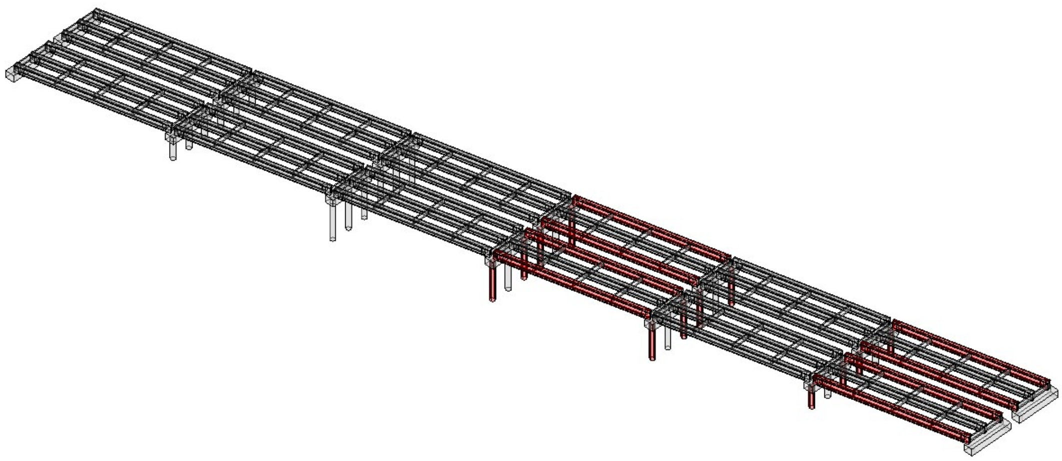


Figure 108. View of a Strura bridge under a low monitoring level.

The rebars has been placed with the dedicated script, a diameter of 20 mm has been chosen and the hook at the end of the rebars have been inserted with an inclination of 90° both for the beams and the piers.

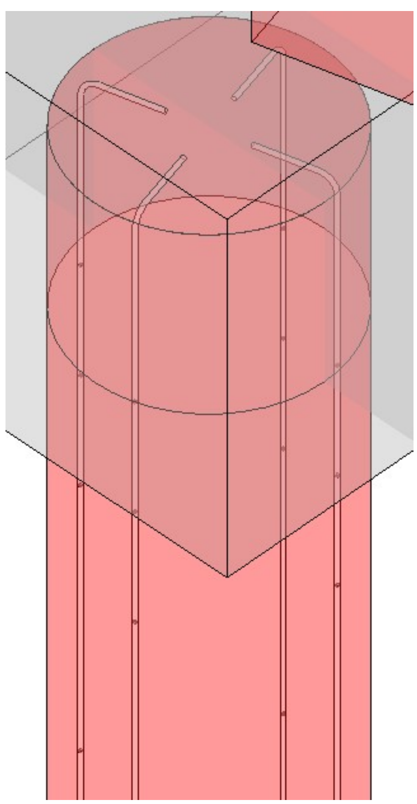


Figure 109. View of a monitored pier with rebars.

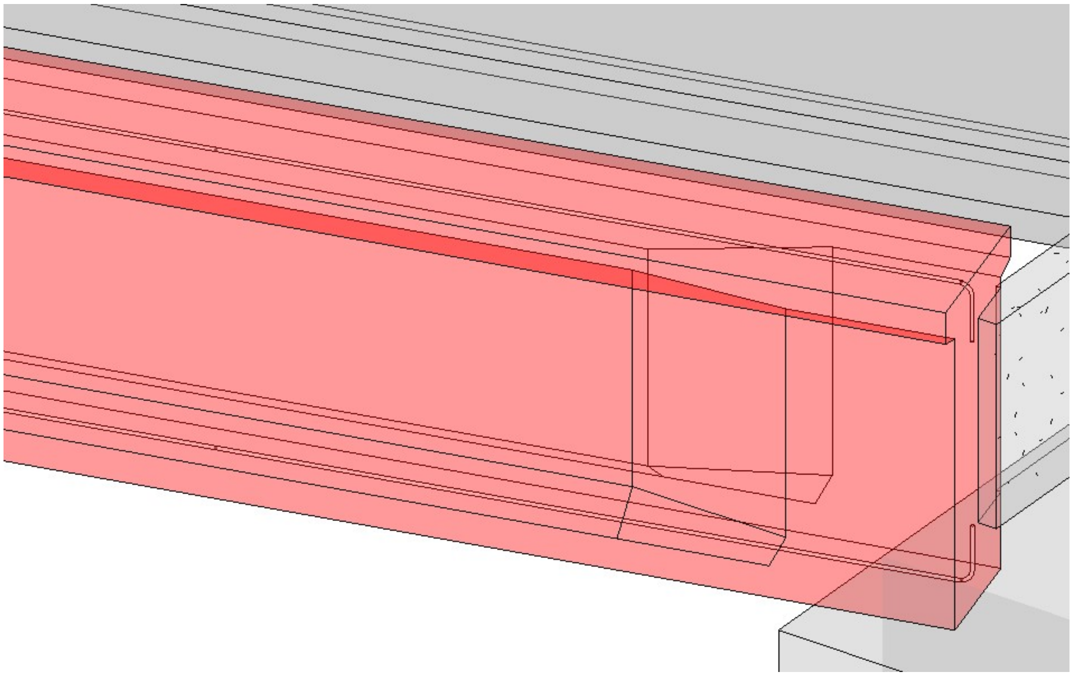


Figure 110. View of a monitored beam with rebars.

4.8 Electrical circuits creation

Once the sensors has been placed the following step is the representation of the electrical circuits that connect each sensor to the correspondent data logger that is the device that collect the sensor's data in order to send them to the gateway that is connected to the main server.

The data logger has been represented in Revit with a family belonging to the category "Attrezzatura elettrica" that allows the connection with the sensors. A smart positioning of the device has been thinked in order to protect it from the sun and the bad weather and at the same time to allow the shortest path for the wires.

In particular, regarding the low monitoring level configuration, has been decided to place 4 data logger located on the vertical wall of the external longitudinal beams near the pier caps. Each one is connected with two beams and the ones located in the first span are connected to two piers. The ones located in the middle spans are connected to four piers each one. This position is optimal because is located under the slab of the deck and is protected buta at the same time is accessible from the level of the road with a by-bridge.

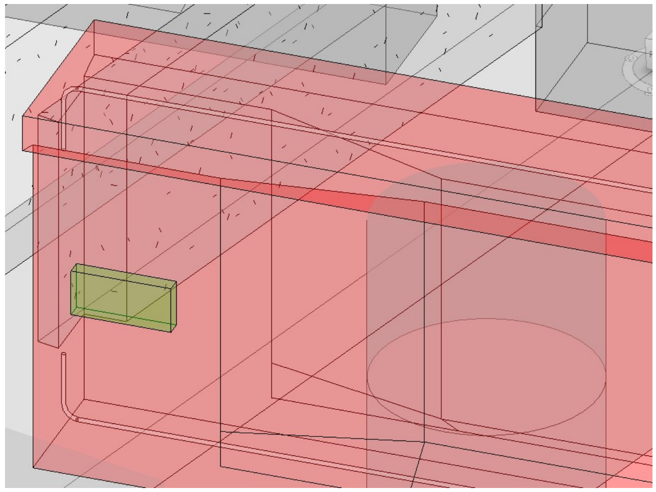


Figure 111. Data logger located on the longitudinal beam near the pier cap.

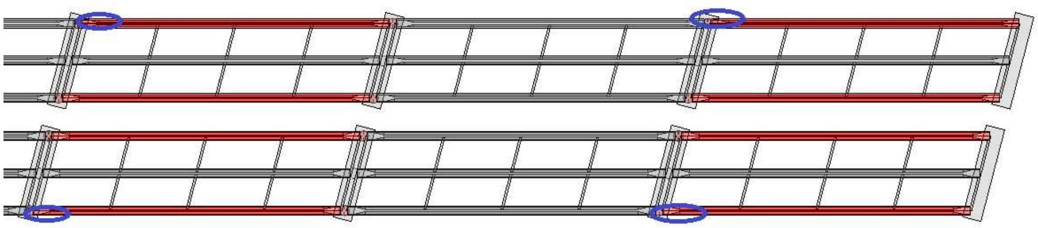


Figure 112. Data logger layuot.

In order to create the circuits the first step is the selection of the sensors that belong to the same circuit and then by clicking on the button "Dati" the circuit is automatically creted by Revit and then can be edited manually in order to choose the shortest path.

In the following images are shown some of the circuits that has been designed. In particular the path that has been chosen for the rebars is the following one:

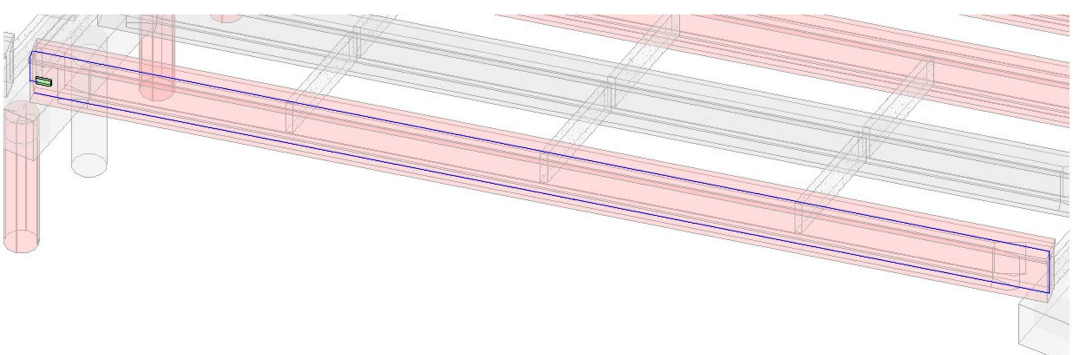


Figure 113. Beam sensors circuit.

Regarding to the piers two different circuits have been designed both containing the sensors of two allignments as we can see in the following images.

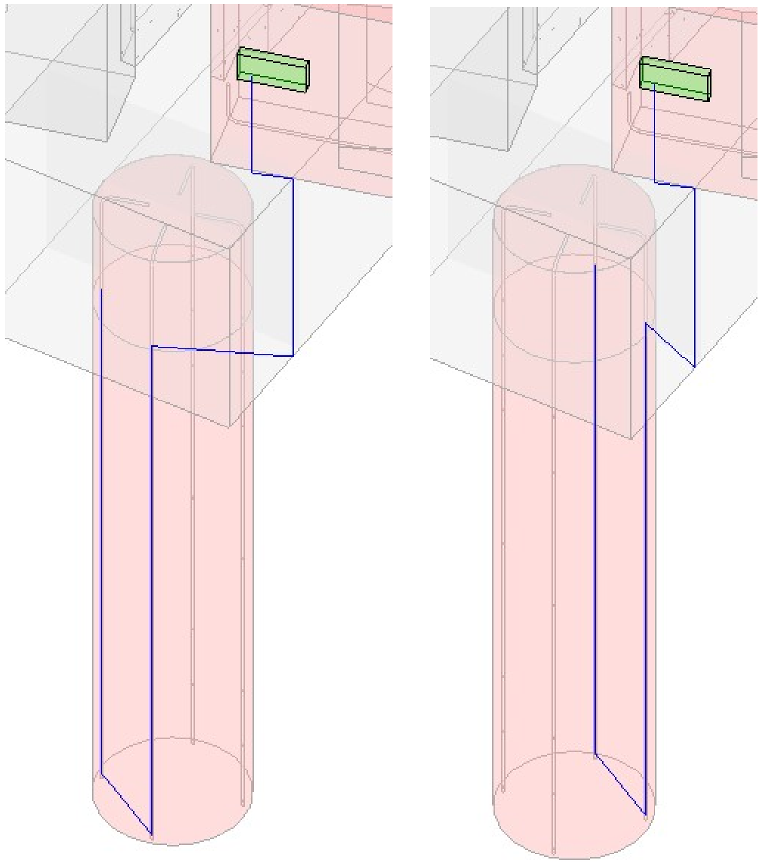


Figure 114. Column sensors circuits.

As concerns the circuits of the structural element located on the opposite side of the deck with respect to the data logger the path is longer and the wire goes along the pier cap o reach the device.

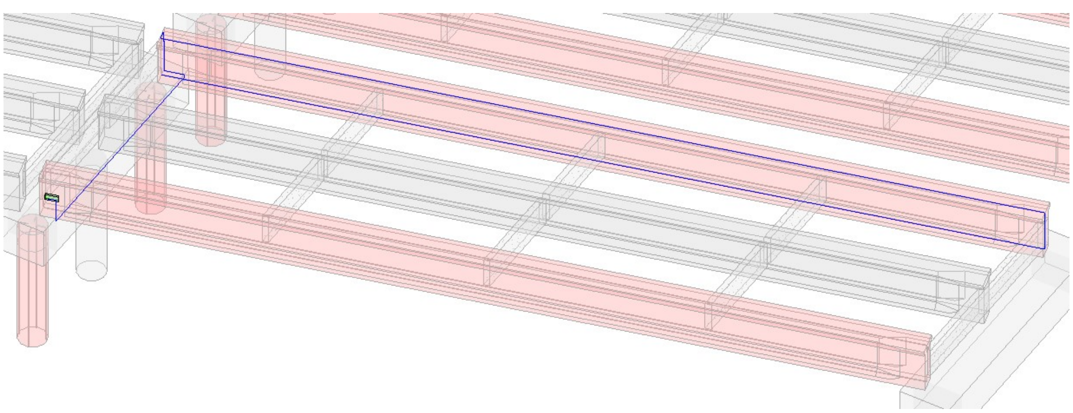


Figure 115. Circuit for a beam located on the opposite side of the deck.

4.9 Bills of the sensors and rebars creation

In order to create a more complete model, taking advantage of the many features contained in Revit, two tables representing the bills of the sensors and smart reinforcements contained in the model.

The bill of the sensors is composed by 7 different columns:

- Sensors identification code,
- Alignment in which the sensors is placed,
- Host structural element identification number,
- Local position of the sensor along the structural element,
- Name of data logger to which the sensor is connected,
- Identification code of the rebar that hosts the sensor,
- Name of the circuit that connect the sensor to the data logger.

<Distinta dei sensori>

A	B	C	D	E	F	G
Codice identificativo	Allineamento	Elemento Host	Posizione locale (m	Quadro	Armatura host	Nome circuito
13/s/9,489	s	13	9.4892	data logger 1	13/s	data logger 1/3
13/s/8,429	s	13	8.429289	data logger 1	13/s	data logger 1/3
13/s/7,369	s	13	7.369378	data logger 1	13/s	data logger 1/3
15/s/8,429	s	15	9.4892	data logger 1	15/s	data logger 1/6
15/s/7,369	s	15	8.429289	data logger 1	15/s	data logger 1/6
16/s/9,489	s	15	7.369378	data logger 1	15/s	data logger 1/6
16/s/7,369	s	16	9.4892	data logger 2	16/s	data logger 2/6
18/s/9,489	s	16	8.429289	data logger 2	16/s	data logger 2/6
18/s/8,429	s	16	7.369378	data logger 2	16/s	data logger 2/6
7/s/8,637	s	18	9.4892	data logger 2	18/s	data logger 2/3
7/s/7,671	s	18	8.429289	data logger 2	18/s	data logger 2/3
7/s/6,706	s	18	7.369378	data logger 2	18/s	data logger 2/3
9/s/7,671	s	7	8.6372	data logger 1	7/s	data logger 1/4
9/s/6,706	s	7	7.671956	data logger 1	7/s	data logger 1/4
10/s/8,637	s	7	6.706711	data logger 1	7/s	data logger 1/4
10/s/6,706	s	9	8.6372	data logger 1	9/s	data logger 1/9
12/s/8,637	s	9	7.671956	data logger 1	9/s	data logger 1/9
12/s/7,671	s	9	6.706711	data logger 1	9/s	data logger 1/9
1/s/4,925	s	10	8.6372	data logger 2	10/s	data logger 2/9
1/s/4,372	s	10	7.671956	data logger 2	10/s	data logger 2/9
1/s/3,819	s	10	6.706711	data logger 2	10/s	data logger 2/9
3/s/4,372	s	12	8.6372	data logger 2	12/s	data logger 2/4
3/s/3,819	s	12	7.671956	data logger 2	12/s	data logger 2/4
4/s/4,925	s	12	6.706711	data logger 2	12/s	data logger 2/4
4/s/3,819	s	1	4.9252	data logger 4	1/s	data logger 4/1
6/s/4,925	s	1	4.3724	data logger 4	1/s	data logger 4/1
6/s/4,372	s	1	3.8196	data logger 4	1/s	data logger 4/1
3/s/4.9252	s	3	4.9252	data logger 4	3/s	data logger 4/4
3/s/4.3724	s	3	4.3724	data logger 4	3/s	data logger 4/4
3/s/3.8196	s	3	3.8196	data logger 4	3/s	data logger 4/4
4/s/4.9252	s	4	4.9252	data logger 3	4/s	data logger 3/5
4/s/4.3724	s	4	4.3724	data logger 3	4/s	data logger 3/5

Figure 116. Extract from the sensors bill.

The bill of the rebars is composed by 6 columns:

- Rebars identification code,
- Host structural element identification number,
- Length of the rebar,
- Hook typology at the start of the rebar,
- Hook typology at the end of the rebar,
- Rebar's diameter.

<Distinta delle armature>

A	B	C	D	E	F
Codice identificativo	Contrassegno host	Lunghezza barra	Gancio all'inizio	Gancio alla fine	Diametro barra
1/b/1	1	6190 mm	Nessuno	Standard - 90 deg.	22 mm
1/d/1	1	6190 mm	Nessuno	Standard - 90 deg.	22 mm
1/a/1	1	6190 mm	Nessuno	Standard - 90 deg.	22 mm
1/s/1	1	6190 mm	Nessuno	Standard - 90 deg.	22 mm
3/b/1	3	6190 mm	Nessuno	Standard - 90 deg.	22 mm
3/d/1	3	6190 mm	Nessuno	Standard - 90 deg.	22 mm
3/a/1	3	6190 mm	Nessuno	Standard - 90 deg.	22 mm
3/s/1	3	6190 mm	Nessuno	Standard - 90 deg.	22 mm
4/b/1	4	6190 mm	Nessuno	Standard - 90 deg.	22 mm
4/d/1	4	6190 mm	Nessuno	Standard - 90 deg.	22 mm
4/a/1	4	6190 mm	Nessuno	Standard - 90 deg.	22 mm
4/s/1	4	6190 mm	Nessuno	Standard - 90 deg.	22 mm
6/b/1	6	6190 mm	Nessuno	Standard - 90 deg.	22 mm
6/d/1	6	6190 mm	Nessuno	Standard - 90 deg.	22 mm
6/a/1	6	6190 mm	Nessuno	Standard - 90 deg.	22 mm
6/s/1	6	6190 mm	Nessuno	Standard - 90 deg.	22 mm
7/b/1	7	4790 mm	Nessuno	Nessuno	22 mm
7/d/1	7	4790 mm	Nessuno	Nessuno	22 mm
7/a/1	7	4790 mm	Nessuno	Nessuno	22 mm
7/s/1	7	4790 mm	Nessuno	Nessuno	22 mm
7/b/2	7	5110 mm	Nessuno	Standard - 90 deg.	22 mm
7/d/2	7	5110 mm	Nessuno	Standard - 90 deg.	22 mm
7/a/2	7	5110 mm	Nessuno	Standard - 90 deg.	22 mm
7/s/2	7	5110 mm	Nessuno	Standard - 90 deg.	22 mm
9/b/1	9	4790 mm	Nessuno	Nessuno	22 mm
9/d/1	9	4790 mm	Nessuno	Nessuno	22 mm
9/a/1	9	4790 mm	Nessuno	Nessuno	22 mm
9/s/1	9	4790 mm	Nessuno	Nessuno	22 mm
9/b/2	9	5110 mm	Nessuno	Standard - 90 deg.	22 mm
9/d/2	9	5110 mm	Nessuno	Standard - 90 deg.	22 mm
9/a/2	9	5110 mm	Nessuno	Standard - 90 deg.	22 mm
9/s/2	9	5110 mm	Nessuno	Standard - 90 deg.	22 mm

Figure 117. Extract from the rebars bill.

The previuosly described tables can be used for the costs calculation, for the material orders and as scheme for the installation of the components of the Structural Health Monitoring System.

Chapter 5: Structural Health Monitoring real applications

In this chapter will be described three different examples of application a Structural Health Monitoring system in a real project. The first one is a classic SHM system with external sensors applied on an already builded structure. The other two are examples of a smart innovative application of the S3 sensors in new constructions.

For the three case studies have been realized three different Revit model in order to visualize the composition of the system and could be also used as storage of the monitored data by filling the sensors parameters.

5.1 Bologna bridge model

The Bologna bridge is a three span bridge over the Dora Riparia river located in the north-eastern area of Turin. The structure has been constructed in 1911 and have a total length of 53 m and a width of 15,4 m.

The bridge was instrumented with a set of accelerometers in order to create a monitoring system for the evaluation of the seismic behaviour as part of a previously realized project by the Politecnico of Turin.

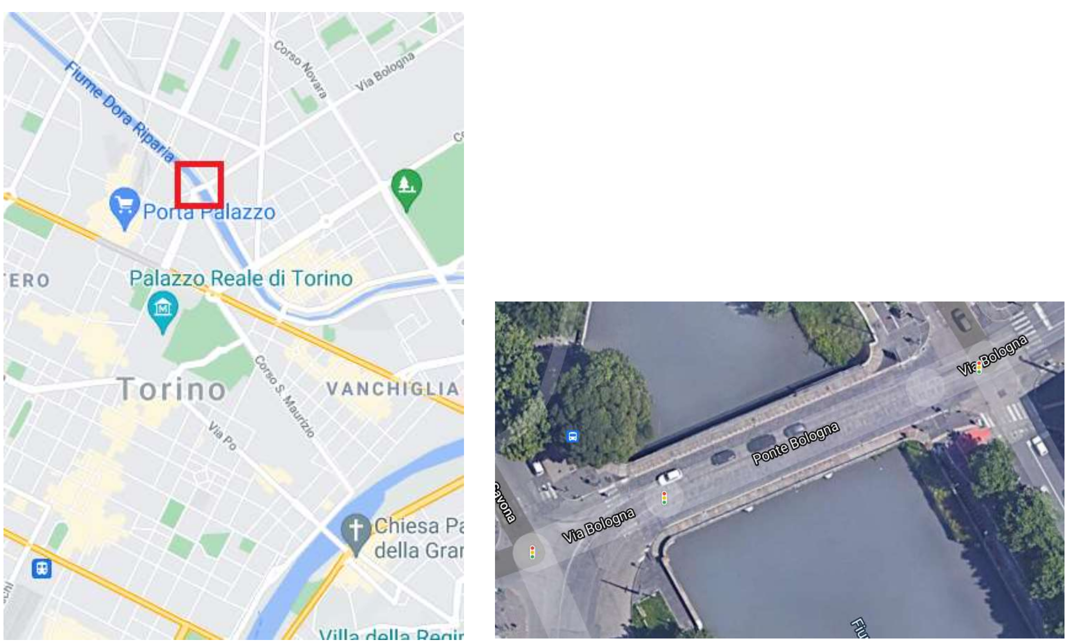


Figure 118. Location and aerial view of the Bologna Bridge. Source. Google Maps.

In this thesis work a Revit model of the structure containing also the Structural Health Monitoring system has been created.

The main element of the bridge are the piers, the abutments and the girder grill.

The piers has been created by the composition of three elements:

- Pier cap: has been obtained as extrusion and belongs to the category “Telaio strutturale”,
- Pier: has been obtained as extrusion and belongs to the category “Telaio strutturale”,
- Foundation: belongs to the category “Fondazioni strutturali”.

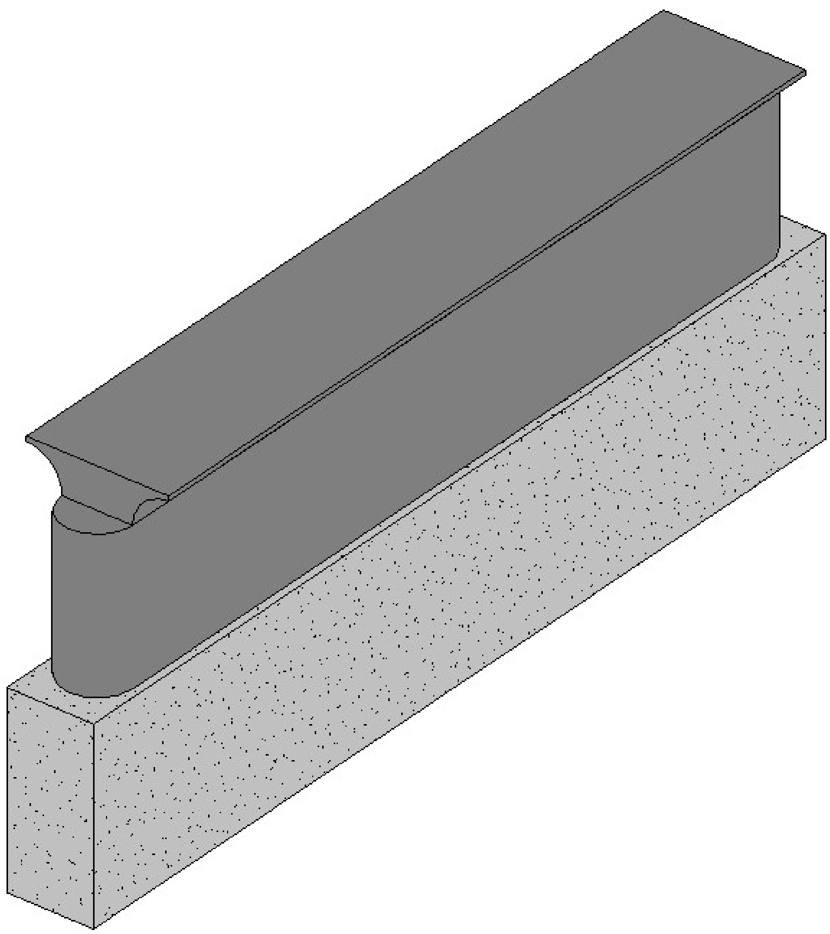


Figure 118. 3D view of the pier.

As regards the abutments they are composed by 5 different parts:

- Front wall: has been created as an extrusion and belongs to the category “Telaio strutturale”,
- 2 Wing walls: has been reated as an extrusioon and belongs to the category “Telaio strutturale”,
- Foundation: belongs to the category “Fondazioni strutturali”,
- Pavement: belongs to the category “Pavimenti”.

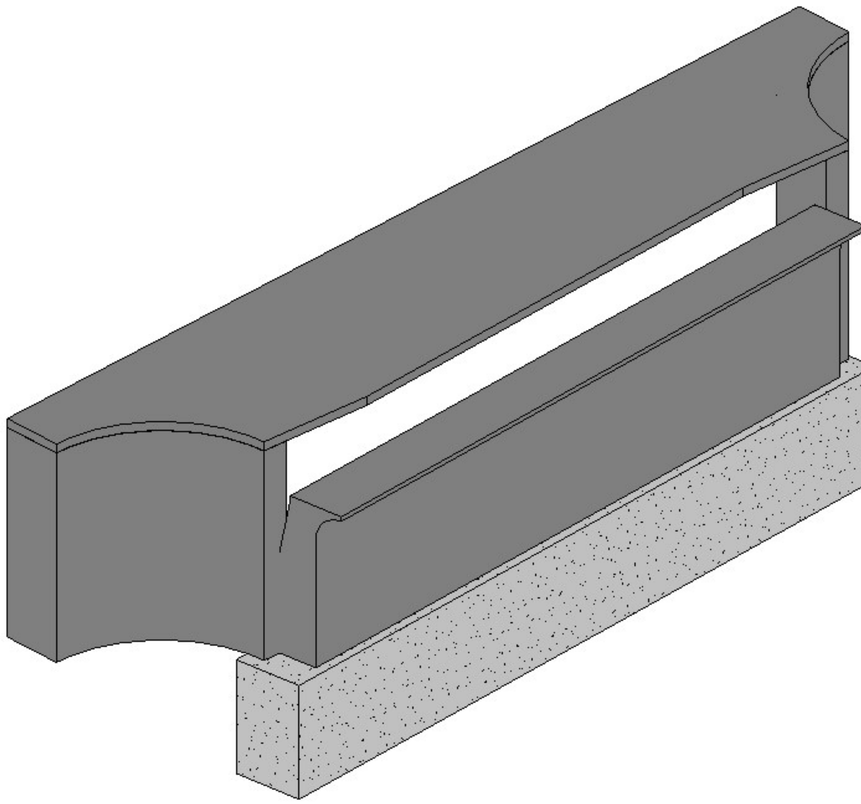


Figure 119. 3D view of the abutment.

In the following image is shown the beams grill and a transversal section from whom can be seen the variable thickness of the slab.

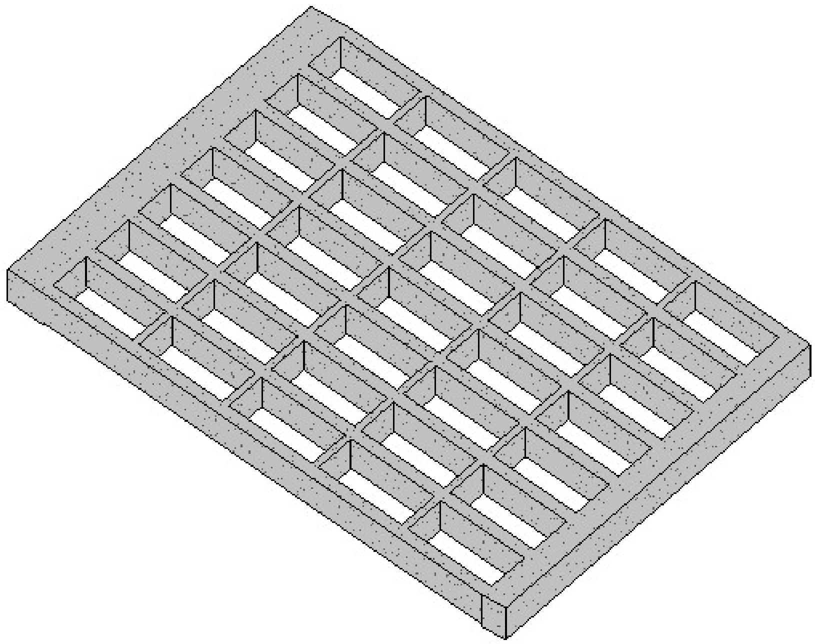


Figure 120. 3D view of the beams grill.

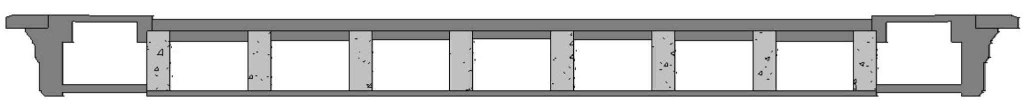


Figure 121. Transversal section of the deck.

In particular the slab have a variable thickness that decreases both from the pier to the midspan and from the side to the centerline of the deck.
A complete view of the 3D model of the bridge is shown in the following picture.

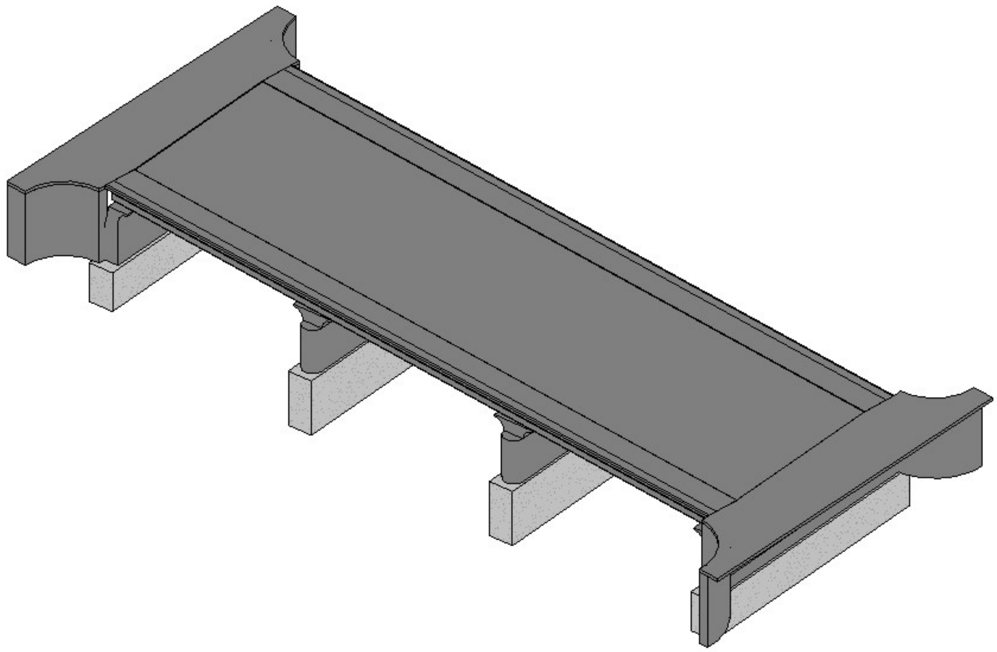


Figure 121. 3D view of the Bologna bridge.

Once the model has been created the following step is the positioning of the sensors according to the real scheme used for the monitoring study.

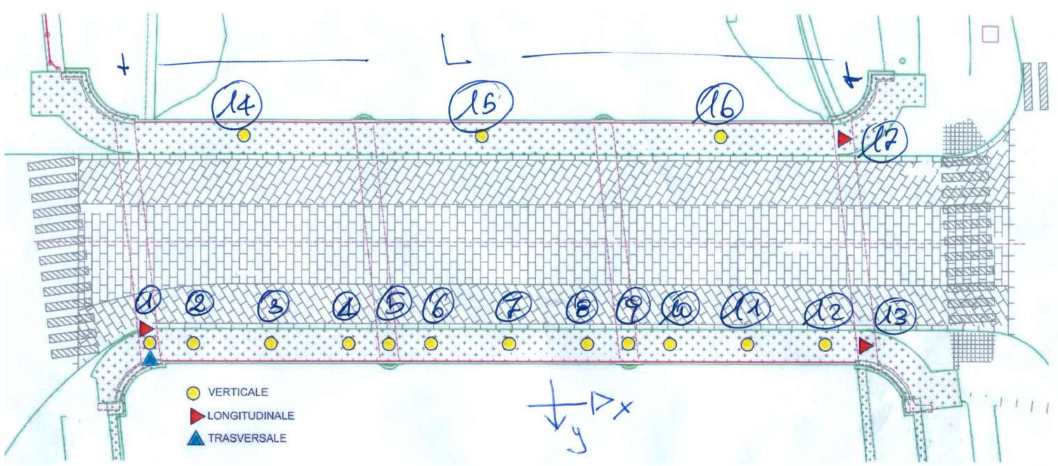


Figure 122. Accelerometers disposition on the Bologna bridge.

The sensors that have been used are:

- 1 accelerometer that monitors the transversal direction of the bridge,
- 3 accelerometers that monitor the longitudinal direction of the bridge,
- 15 accelerometers that monitor the vertical direction.

All the sensors are connected to a data center that is located near the left abutment of the bridge.

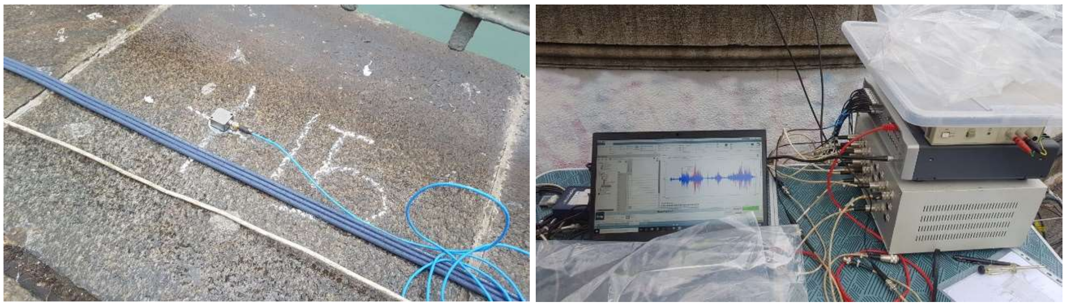


Figure 123. Accelerometers placed on site and data center.

In order to represent the accelerometers three different Revit family have been created with different colours (yellow, red and blue) and different shape that highlght the direction that is monitored by the sensor.

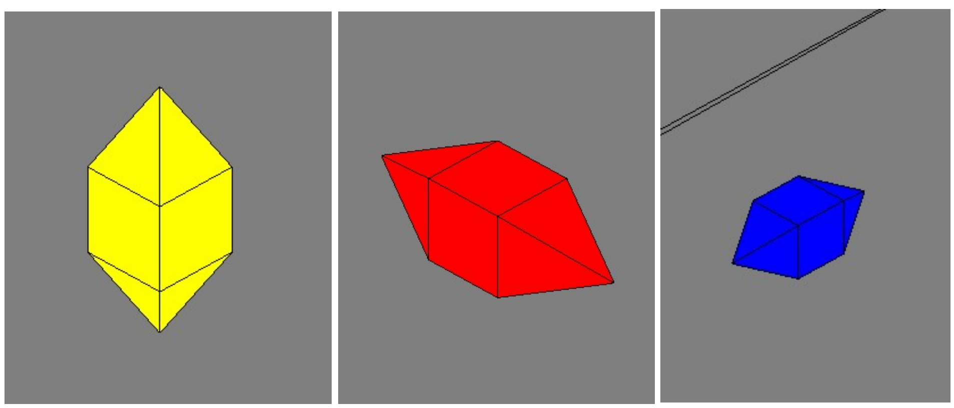


Figure 124. Vertical accelerometer, longitudinal accelerometer and transversal accelerometer.

For the data center has been created another family that is capable to connect with the sensors and create circuits.

The connection have been created in the same way as previously described for the Stura bridge model but with a main difference: in this SHM system have been used classical sensors that need to be connected to the data logger with their own circuit causing a high number of wires on the deck.

In the following images are shown the connections of two sensors located on the two sides of the deck.

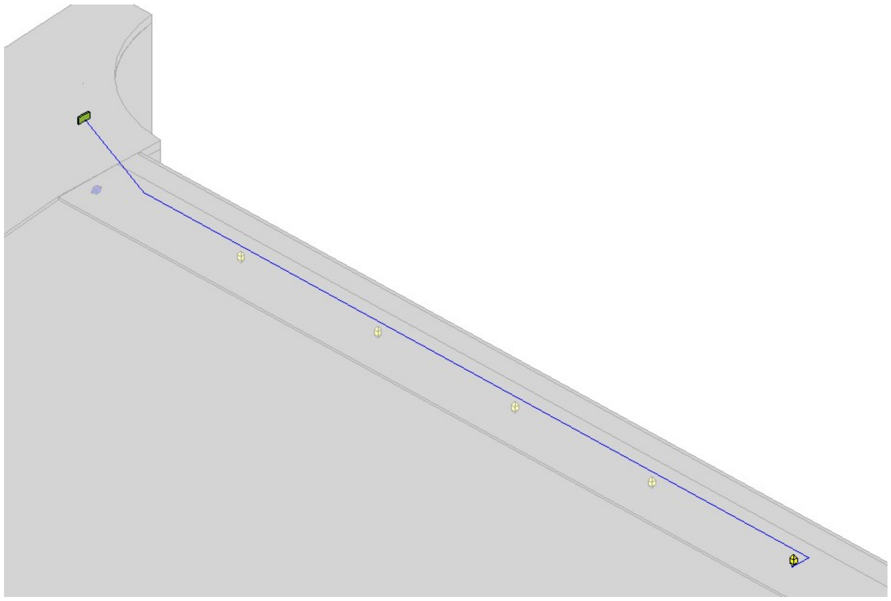


Figure 125. Circuit for a sensor located on the same side of the data receiver.

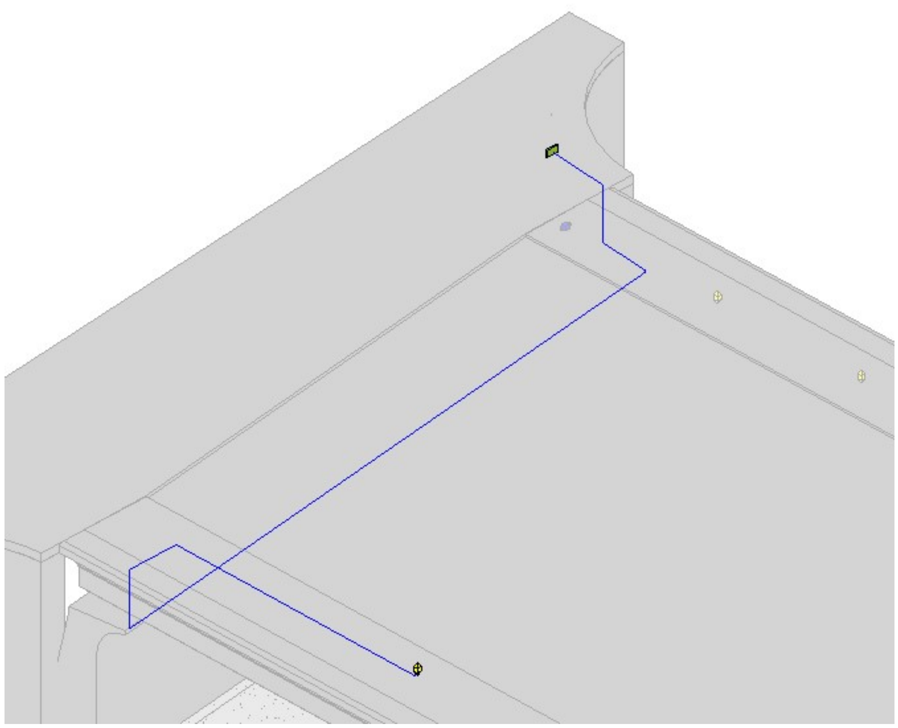


Figure 126. Circuit for a sensor located on the opposite side of the deck with respect to the data receiver.

In particular, as concerns the second figure, the circuits related to the sensors placed on the opposite side of the deck cross the bridge in transversal direction at the level of the pier cap.

In order to visualize all the circuits at the same, a possibility that is not allowed by the Revit settings, a Dynamo script has been created. The script recognize all the circuits in the model and trace them with model line that can be seen in every moment and enable a clear vision of the wires paths.

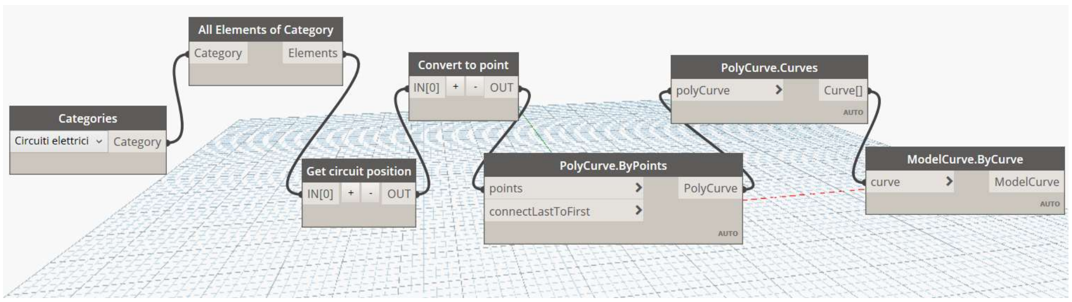
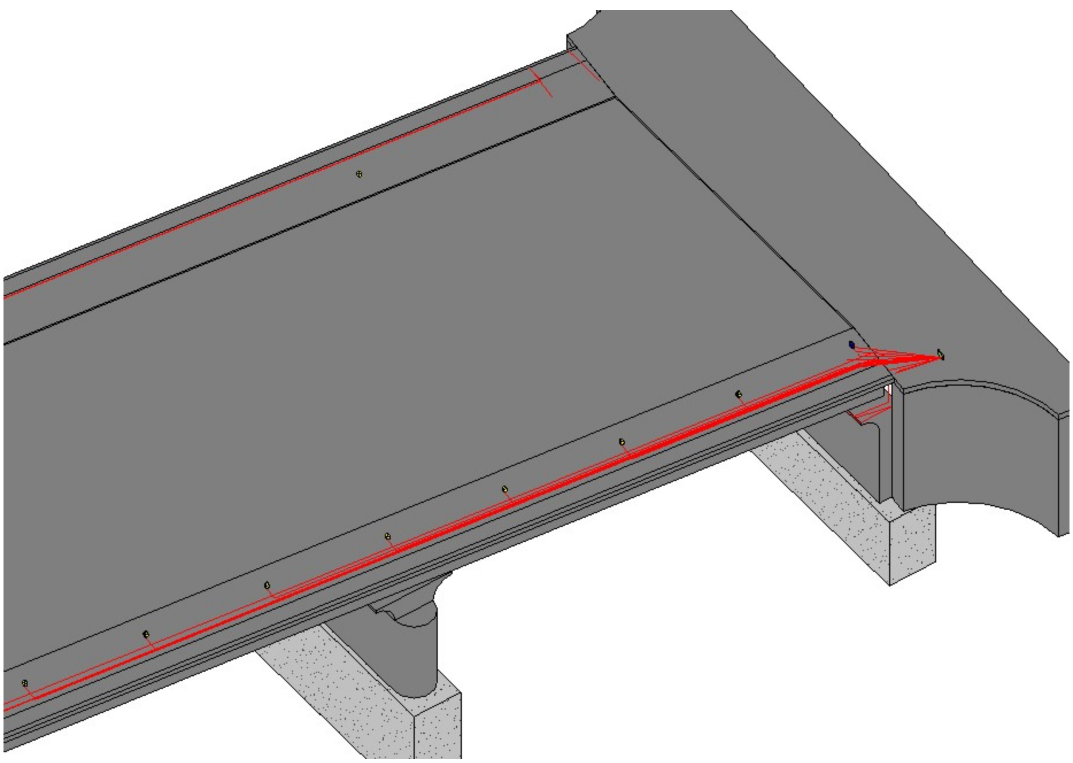


Figure 127. Dynamo script for circuit path visualization

The following images show the paths of the circuits highlighted in red.



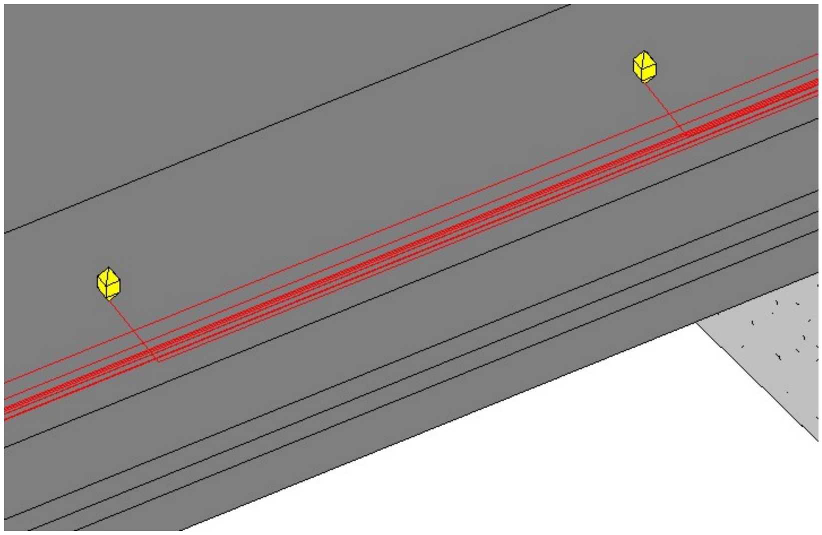


Figure 128. Circuit paths visualization.

5.2 Other Structural Health Monitoring applications

Two other Revit model have been realized representing SHM systems based on S3 smart sensors in the context of a road underpass in the city of Turin.

In particular the first one is related to a railway underpass composed by two allignment of pile foundations on which are placed the kerbs that support the precast concrete beams. In this case the monitored element is a precasted beam that is equipped with two alignments of smart bars containing a total number of 20 S3 sensors and a data logger.

The monitored element is located in a section of the underpass that is characterized by a slight curve.

The Revit model is composed by:

- 20 foundation piles with an height of 11 m and a diameter of 1 m,
- 2 kerbs that covers the top of the piles,
- 5 precast concrete beams.

The most interesting elements are the beams, that have been obtained by the creation of a new family containing different extrusions merged together, due to their irregular shape.

In the following images are shown a precast concrete beam in the 3D view and three transversal sections.

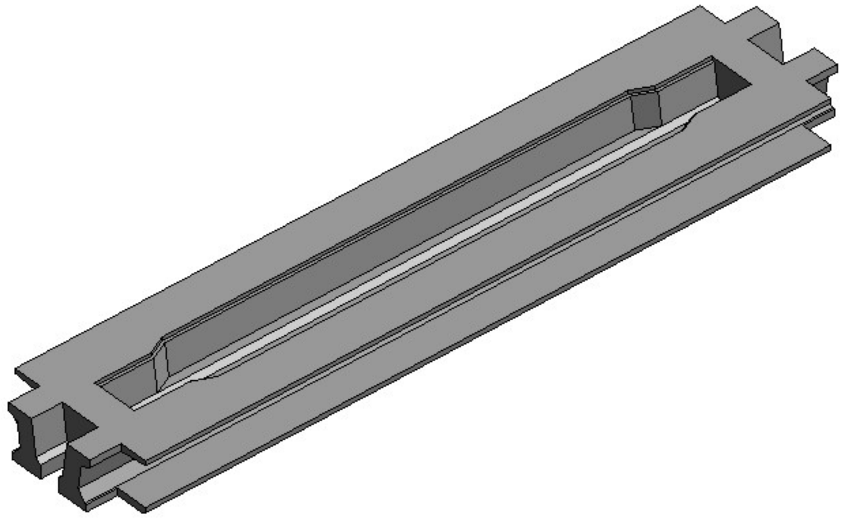


Figure 129. Precasted concrete beam Revit family.

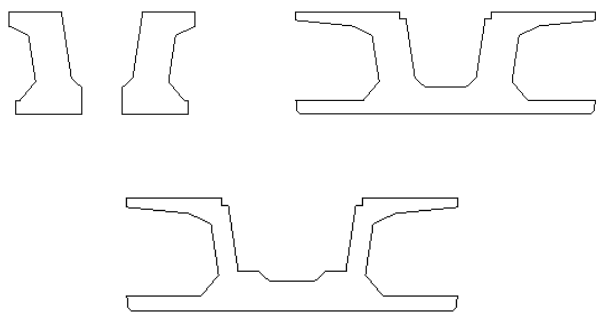


Figure 130. Precasted concrete beam transversal sections.

The complete model is shown in the following figures that represent a 3D view of the model, a plan view at the level of the beams and a elevation view.

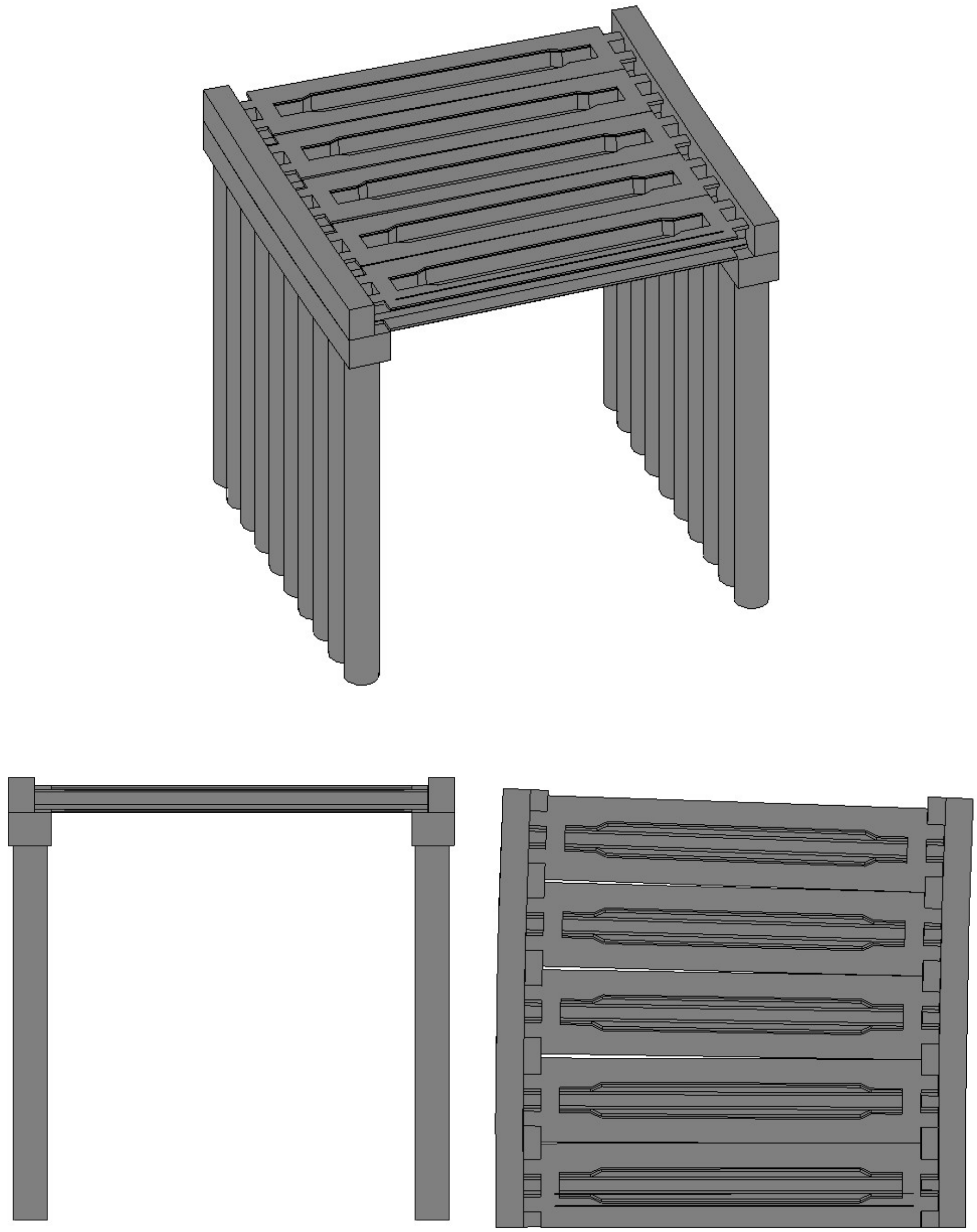


Figure 131. 3D view (above), plan and elevation of the structure (below).

Once the model of the structure has been created, the following step is the representation of the Structural Health Monitoring system . The smart bars, coloured in red in the following pictures, has been positioned in two alignments, one in the intrados and the other in the extrados, and for each alignment have been placed 5 rebars containing 2 sensors each one. The bars belonging to the same alignment are connected together with steel couplers.

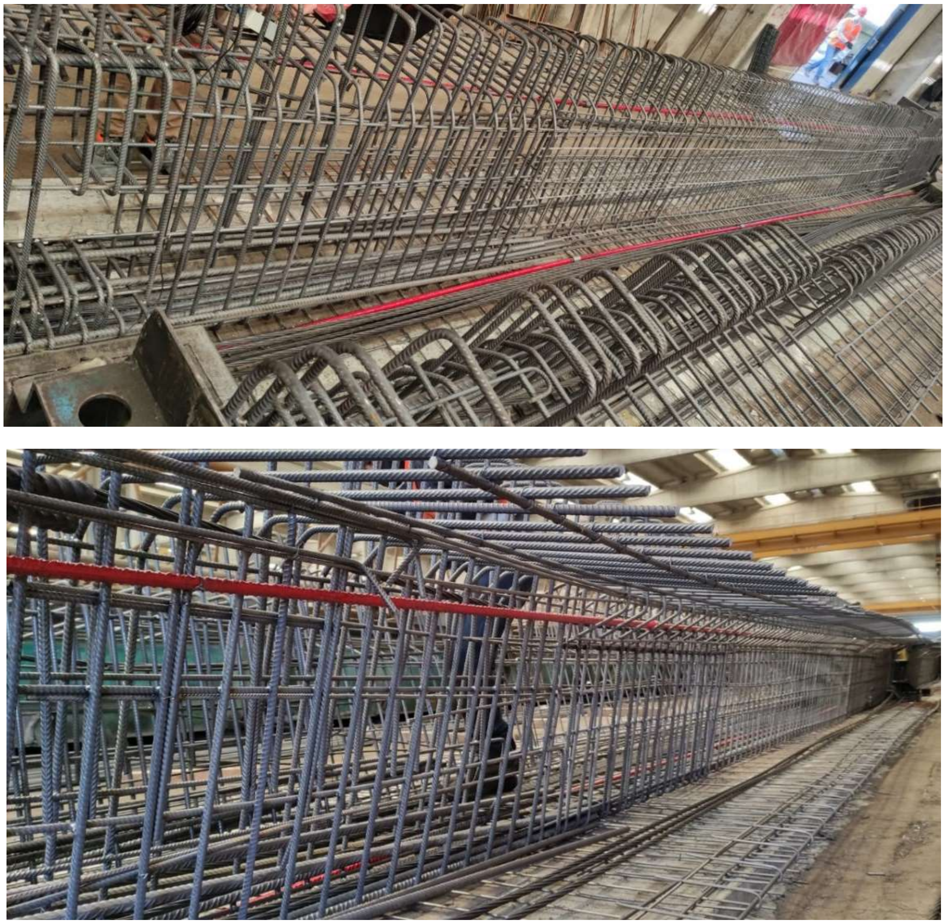


Figure 131. Photos of the instrumented beam taken on site.

The data logger has been placed at the intrados of the beam in order to create the shortest circuits possible for the smart bars and at the same time to allow the communication between the device and the gateway. The two circuits are parallel to the relative rebars and then are connected to the device with a short linear path.

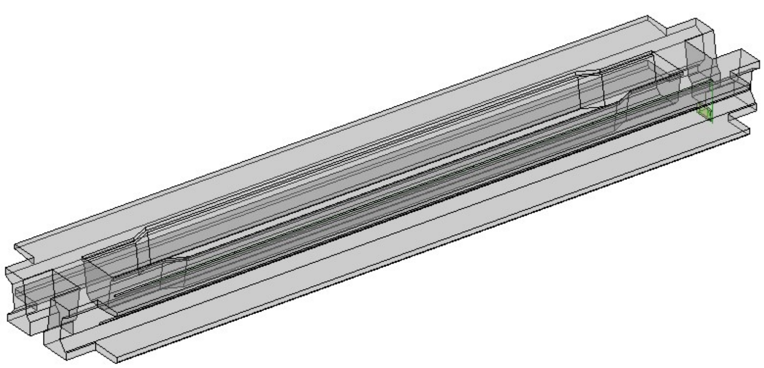


Figure 131. 3D view of the monitored beam.

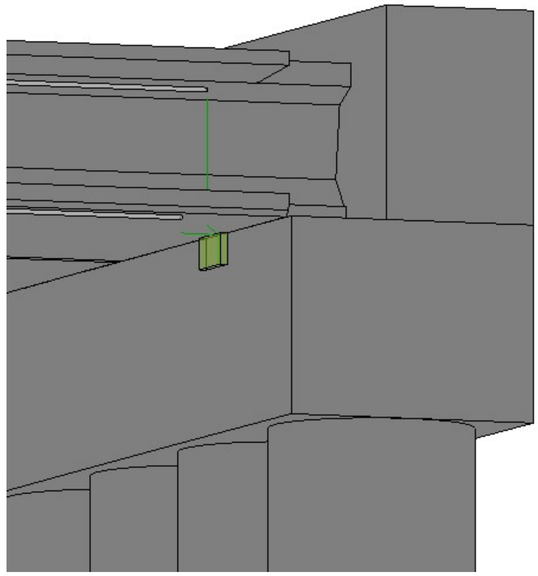


Figure 132. Focus on the data logger connections.

The second model is related to a road underpass composed by two allignment of pile foundations on which are placed the kerbs that support the precast concrete beams. In contrast to the first case, the monitored element is a pile foundation that is equipped with four alignments of smart bars containing a total number of 40 S3 sensors and a data logger.

The Revit model is composed by:

- 20 foundation piles with an height of 13 m and a diameter of 1 m,
- 2 kerbs that covers the top of the piles,
- 6 precast concrete beams.

As for the previous model the beams have been obtained by the creation of a new family containing an extrusion.

In the following images are shown a precast concrete beam in the 3D view and a transversal section.

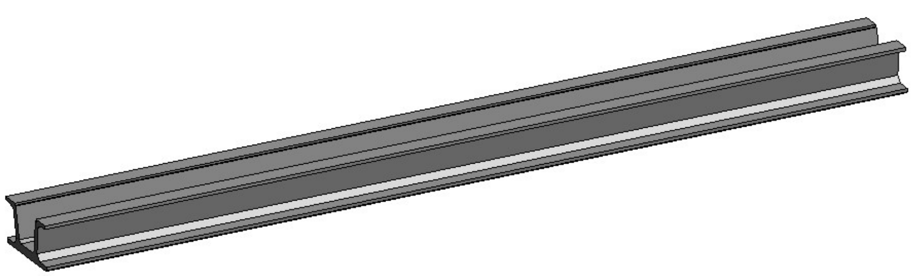


Figure 133. 3D view of the precast concrete beam.

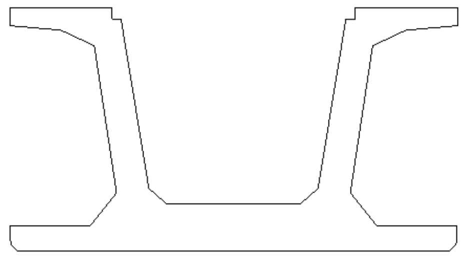


Figure 134. Transversal section of the precast concrete beam.

The two kerbs have differents heights and this results in an inclined configuration for the concrete beams that can be seen in the Figure 136. The complete model is shown in the following figures that represent a 3D view of the model, a plan view at the level of the beams and a elevation view.

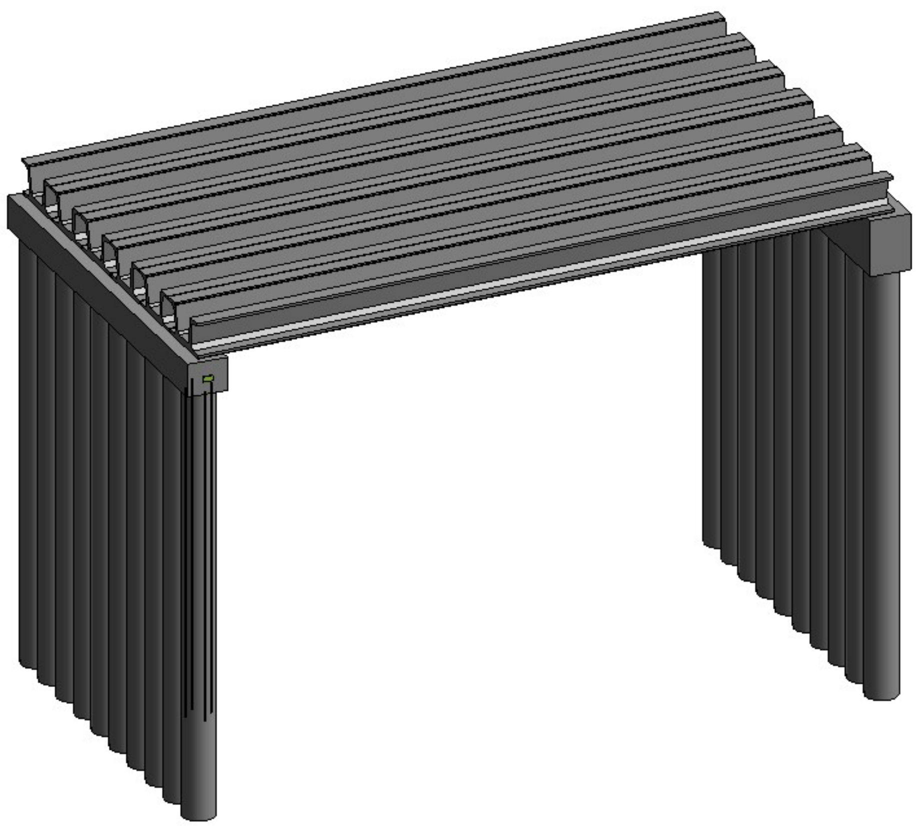


Figure 135. 3D model of the road underpass.

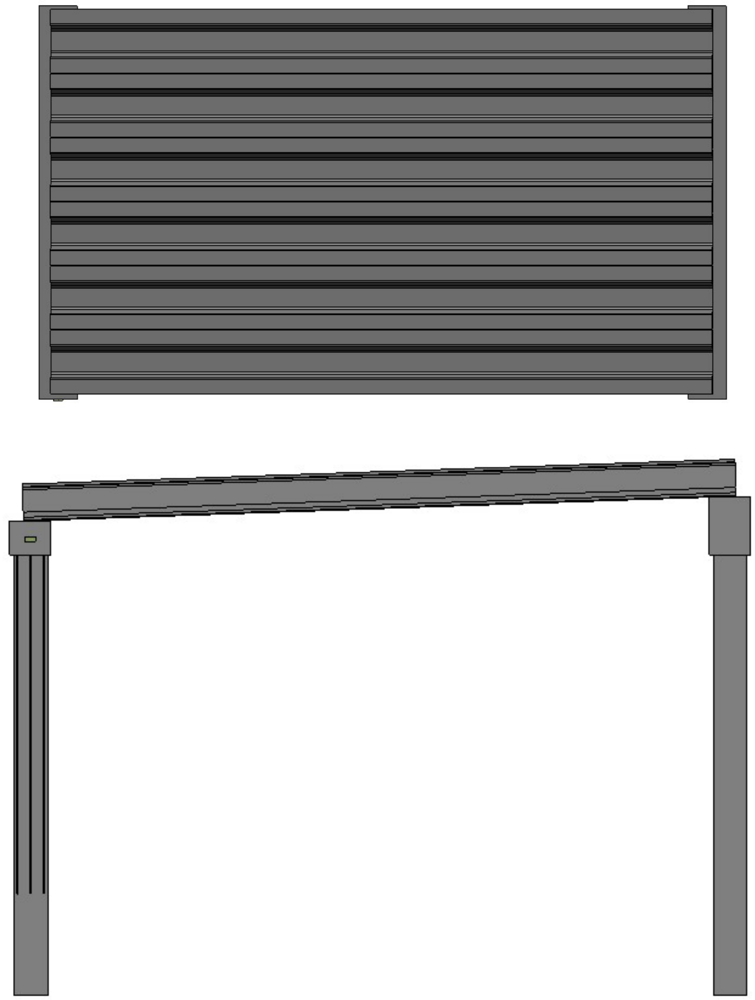


Figure 136. Plan (above) and elevation (below) of the road underpass.

As regards the Structural Health Monitoring system, the smart bars, coloured in red in the following pictures, has been positioned in four alignments, one in the intrados and the other in the extrados, and for each alignment have been placed 5 rebars containing 2 sensors each one.

The sensors are placed both at a distance of 50 cm respectively from the start and the end of the 2 m long rebar. The reinforcements belonging to the same alignment are connected together with steel couplers.

As shown in the following pictures the smart bars are not belonging to the reinforcements designed for the strucuture resistance and are added to it and bounded to the reinforcement cage.

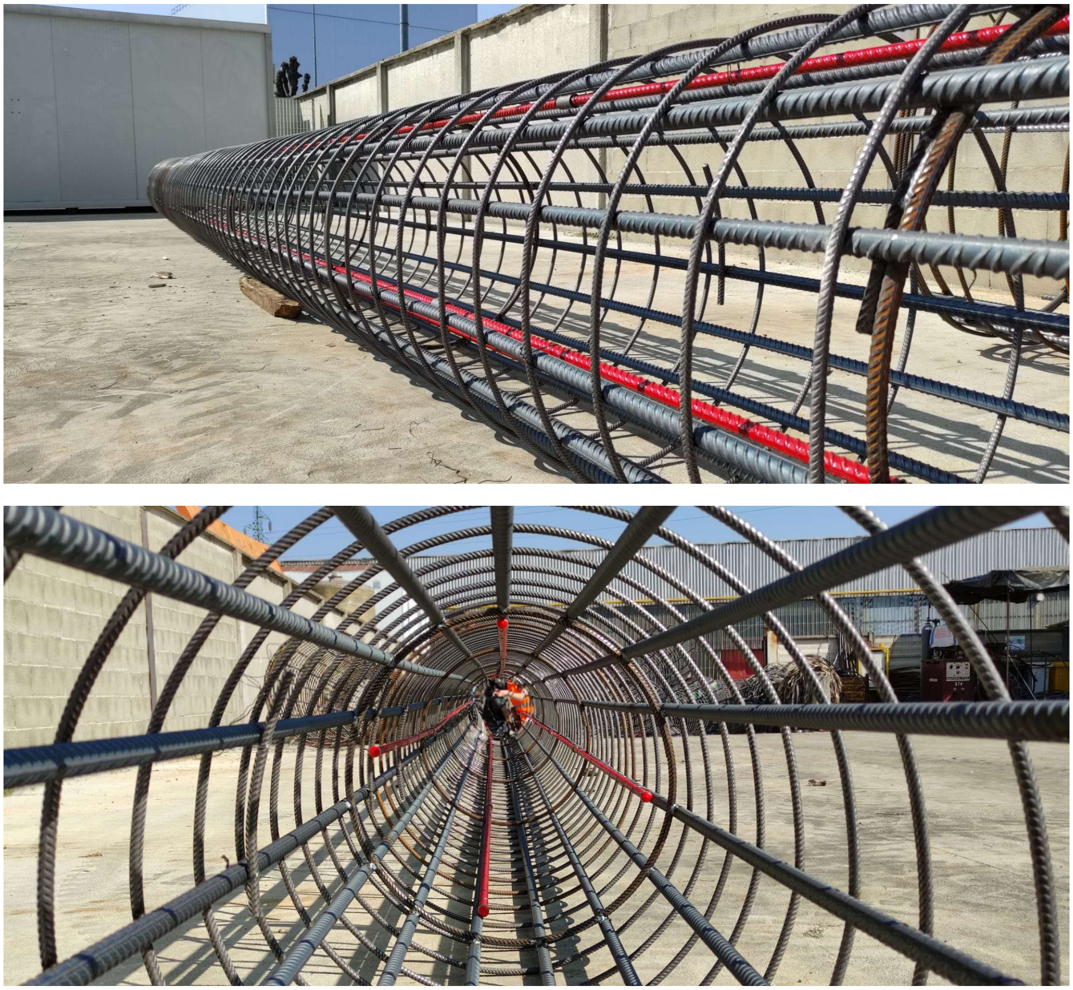


Figure 137. Photos of the instrumented pile taken on site.

The data logger has been placed on the kerb near the top of the monitored pile in order to create the shortest circuits possible for the smart bars and to allow an efficient communication with the gateway. The four circuits are parallel to the relative rebars and then are connected to the device with a short linear path.

As can be seen from the photos and the following Revit representation, only the first 10 m of the pile starting from the top have been instrumented.

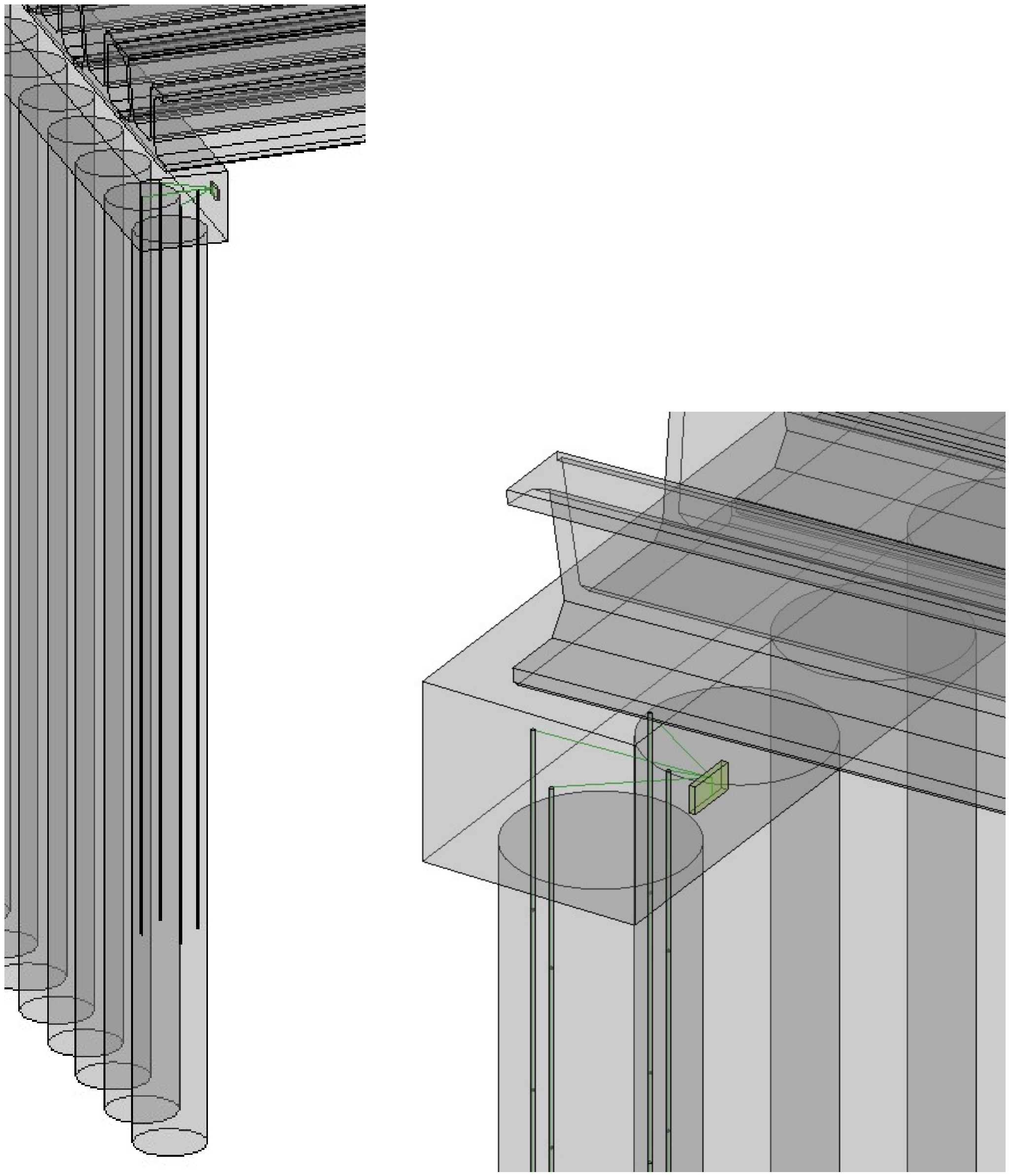


Figure 138. Views of the monitored pile and relative connections to the data logger.

Chapter 6: Results, conclusions and future works

6.1 Results of the work

The BIM methodology offers many features that can be usefull for Structural Health Monitoring purposes and the aim of the thesis was the evaluation of its suitability and potential by the application to case study both for classical SHM systems on existing structures and innovative SHM systems in new constructions. The focus of the work was on the bridge structural typology. The main points related to the work's results will be discussed below:

- *BIM model creation and interoperability with structural softwares:*

  For the creation of the model has been used Revit and the representation of the structures was quite easy due to the many design options offered by the software that allows the user to create many different shapes and meet different needs. Another important characteristic of the software is its interoperability with different softwares, even if the process is not always working properly.

  An example of imperfect interoperability is the connection between Revit and Robot, the structural analysis that has been chosen for this work, that has shown many problems due to the loss of the connections between strucutral elements that caused a loss of time for the manual resetting of the structural model.

  On the other hand the exportation process is quite easy and convenient thanks to the dedicated plug in, and the structural analysis provides good results.

- *Structural analysis data management:*

  The results of the structural analysis have been organized with Excel in order to design different monitoring levels and then tha visual programming tool Dynamo, that is integrated in Revit, has been used to place in the model the components of the SHM system and, in some cases, also the values measured by the real monitoring devices.

  The Dynamo language has proved to be an excellent tool for the previously described purposes due to its great capability and versatility combined with a simple structure that can used and understood by a wide range of users, even the ones that do not programming experience.

- *SHM system's components creation and visualization:*

  The software Revit, combined with visual programming tool Dynamo, has proved to be suited to the creation of electrical components such as the data logger, the accelerometers and the S3 sensors that can be place automatically without particular difficulties with few dedicated scripts.

On the other hand, the Revit's features related to electrical connections showed to be an incomplete area of the software that needs to be developped more in depth and has not reach its full potential. In particular many problems occurred during the design phase related to the visualization of the electrical circuits and the possibility to edit their path.

As concerns the possibility to visualize the SHM system in the 3D model, Revit proved to be the best solution for the purpose due to its great visual power and thanks to the possibility to customize the created items with different parameters. This capability has been used to store the values of measured deformations in the S3 sensors.

6.2 Conclusions

After the realizations of many different SHM system models with the halep of BIM methodology, the following conclusions can be drawn:

- BIM softwares, such as Revit, are suitable for the creation of the elements of the SHM systems and for the storing of monitoring data enabling a more complete model and creating a dynamic graphical visualization.

- The interoperability between different softwares and tools is a precious help for the many professional figures involved in the design, construction and monitoring of new bridges or simply for the monitoring phases of existing ones due to the capability to exchange informations starting from a common model. On the other hand difficulties in the connections have shown that highlights the need of further developments in the BIM softwares.

- The visual programming tool Dynamo plays a key role in the positioning process and allows the user to create quick and precise algorithm for the automatic creation of a SHM system starting from the structural anlysis data. This tool allows the user to deal with a great amount of information in an interactive and customizable way by creating interfaces that can be used later also by professional figures that do not possess visual programming skills.

- The Dynamo tool allows the user to create electrical connections between the sensors and the data loggers that is really helpful in order to obtain a complete version of the SHM system model. On the other hand this feature has shown a lack of flexibility and it is desiderable that further improvements will be made to augment the suitability to the monitoring purposes.

6.3 Future work and recommendations

With this thesis work the many possibilities and benefits of the application of the BIM methodology to the Structural Health Monitoring has been tested with encouraging results that highlights its suitability to the matter. On the other hand there are plenty aspects that still require improvements and the work to be done is a lot.

Revit is a skillful software with a great capability of creating different istances and families in order to represent the SHM system's components and each element could be customized according to the user's needs but sometimes the operations seems to be not particularly quick and quite repetitive. The cause of this problems is the lack of a section dedicated to SHM that induces the users to adapt components from different areas.

Another issue in the process of the design and implementation of an SHM system in BIM is the connection between Revit and structural softwares. For the realization of this work has been chosen the strucutral analysis software Robot because of the common origin with Revit (they are developped by the same software house) but the connection's results were not excellent. This issue could be solved both by desiderable improvements by the software houses in order to reach a real interoperability and by a future work, starting from the bases posed with this thesis work, with the aim to test the connection with other structural analysis softwares.

A future improvement concerning the structural analysis could be the inclusion of normal and shear forces, in addition to the already used bending moment, in the parameters considered for the setting of the SHM system. Furthermore the ratio between the acting forces and the resistance values could be setted as the main parameter inn order to choose the monitored elements.

As regards the visualization and automatization of the design process the visual programming tool Dynamo has demonstrated to be incredibly useful with its ability to manage great amounts of data and connect with Excel files. Many packages are available by default and a big community of users is available and can be a helpful in order to solve problems and find the best solutions. In addition the possibility to create custom routines is allowed and became as much important as the program became more complex and extended.

Even if the results obtained with the use of Dynamo are great, if a more complex application of the problem needs to be developped, the use of an higher programming language such as C++, Java and others.

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