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Numerical verification of an in-situ methodology for rail fasteners mechanical characterization

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Resumen

Hoy en día la industria gasta grandes cantidades de dinero en la supervisión y substitución de las sujeciones de las vías de tren. Esto es debido a que las sujeciones dañadas generan vibraciones y ruido que es incómodo y perjudicial para los habitantes de la zona, a parte de los peligros que puede conllevar. Estos costes podrían verse reducidos por la incorporación del método de caracterización in situ.

Este método se basa en la excitación y obtención de medidas en sitios específicos de la vía con la finalidad de poder recuperar la rigidez de cada una de las sujeciones.

El objetivo de esta tesis es verificar la viabilidad experimental del método de caracterización in situ para la obtención de la rigidez de las sujeciones en las vías de tren usando modelos numéricos. Para ello, se descartarán algunas de las medidas proporcionadas por la simulación (emulando así la falta de sensores, puesto que en teoría se deberían utilizar tantos como sujeciones haya en la vía) y se intentará obtener la rigidez de las sujeciones.

La tesis considerará dos simulaciones: un modelo simplificado, compuesto de elementos 1D, y un modelo más realista, incluyendo solidos 3D. Posteriormente, un código de MATLAB procesará los resultados y mostrará las rigideces obtenidas para cada sujeción.

Los resultados indican que tanto para el modelo simplificado como para el modelo 3D, el método in situ puede recuperar las rigideces cuando usan todas las medidas. Para ambos casos, también muestran que las sujeciones más cercanas a la sujeción que ha sido descartada obtienen una rigidez menos precisa, mientras que cuantas más sujeciones haya entre la sujeción estudiada y la descartada, más precisa es la rigidez. Además, las sujeciones más cercanas a la descartada obtienen una rigidez más elevada a frecuencias bajas, tomando en cuenta la pérdida de rigidez. Adicionalmente, los valores obtenidos de rigidez a altas frecuencias suelen tender al valor correcto. Por último, al descartar medidas, los valores de rigidez para el modelo 3D son más precisos que los valores obtenidos en el modelo simplificado.

La conclusión es que la tesis ha cumplido parcialmente su objetivo. Se necesitan hacer estudios más allá del abasto de la tesis para encontrar el número de sensores necesarios para recuperar la rigidez de las sujeciones con una precisión aceptable, pero los resultados de la tesis concluyen que el método es viable y presenta un buen punto de partida para futuras líneas de trabajo.

Abstract

Nowadays the industry spends massive amounts of money on the supervision and replacement of rail fasteners. This happens due to the fact that damaged fasteners generate vibrations and noise, which is uncomfortable and disturbing to the inhabitants of the area, in addition to the safety risks that can be associated with it. These costs could be reduced by incorporating the in-situ characterization method.

This method is based on the excitation and obtention of measurements at specific locations on the track to be able to recover the stiffness of each of the fasteners.

The objective of this thesis is to verify the experimental feasibility of the in-situ characterization method for obtaining the fasteners' stiffness in railway tracks using numerical models. For this purpose, some of the measurements provided by the simulation will be discarded (thus emulating the lack of sensors, since theoretically there should be as many as the number of fasteners on the track) and it will be attempted to obtain the stiffness of the fasteners.

The thesis will consider two simulations: a simplified model, including 1D elements, and a more realistic model, including 3D solids. Afterwards, a MATLAB code will process the results and show the stiffnesses obtained for each fastener.

The results indicate that for both the simplified model and the 3D model, the in-situ method can recover each stiffness when using all the measurements. For both cases, they also show that the closest fasteners to the one that has been discarded obtain a less accurate stiffness, while the more fasteners are between the studied and discarded fastener, the more accurate the stiffness is. In addition, the closest fasteners to the discarded one obtain a higher stiffness at low frequencies, considering the loss of stiffness. Another important fact is that the retrieved fasteners' stiffness at high frequencies usually tends to the right value. Finally, when disregarding measurements, the stiffness values for the 3D model are more accurate than the values obtained in the simplified model.

The conclusion is that the thesis has partially fulfilled its objective. Studies beyond the scope of the thesis are needed to find the required number of sensors to recover the stiffness of the fasteners with acceptable accuracy, but the results of the thesis conclude that the method is feasible and presents a good starting point for future lines of work.

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1. Introduction

1.1 Object

The objective of this thesis is to verify the experimental viability of a new method for the in-situ determination of the rail fasteners stiffness using numerical models.

Nowadays, the characterization of these components must be done in laboratories, extracting the component from its environment. The setups in the laboratory do not fully represent the real operational conditions of the component, making the characterization not totally accurate. This new method could potentially characterize the component, without the need of extracting it beforehand, only by performing measurements of the dynamic response of the track in which they are installed.

The validity of the proposed numerical approach will be firstly assessed using a simple model and validating every result with other sources. Then a more realistic model of a track stretch will be developed and used to extract the necessary data to carry out the new in-situ characterization method.

It should be mentioned that the aim of the developed models is to assess if a specific experimental setup is adequate or not for performing the in-situ characterization test on a specific track, and not to perform accurate predictions of the vibration levels induced by a specific source.

1.2 Scope

The scope of the project will be the development of a simple model for validating the proposed numerical strategy. Then, a detailed model of a floating slab track stretch will be developed to assess the viability of the experimental in-situ characterization for such type of track. Thus, it will be divided in two cases, with their corresponding subcases:

- Simplified Model: The rail, slab and fasteners will be represented as 1D elements. The dynamic behavior of each component will be also considered using separate models for verification purposes. Afterwards, a model consisting of two finite beams, representing a stretch of rail and a stretch of slab, connected by six fasteners, represented by ideal springs, will be developed. The receptance required for the characterization method will be extracted.

- 3D case: The rail and slab will be modelled as solids and discretized using 3D elements. On the other hand, the rail fasteners will be represented using 1D elements. As in the previous case, both slab and rail will be evaluated separately in order to compare the results with the ones obtained for the simple model. Then, they will be joined by six unidimensional fasteners and the data required for the characterization method will be extracted. Finally, a larger model with two rails, one slab and eleven fasteners will be considered

With the data extracted from these cases, the in-situ method will be executed and compared with the actual stiffness of the springs. For this purpose, a MATLAB code will be developed. The script will be used to compute the stiffness using dynamic responses associated to each fastener and, additionally, it will also evaluate the accuracy of the method when some of the rail fasteners measurements are disregarded.

Finally, there are some future lines of work that go beyond the scope of the project, such as developing a numerical model which includes all the problem details (soil modelling, periodical boundary conditions, 3D fasteners modelling) and the experimental testing of the in-situ method in a location where the rail fasteners stiffness is known.

1.3 Requirements

The requirement of this thesis is developing a model able to state how many sensors must be deployed to obtain rail fasteners' stiffness, with an acceptable accuracy, using the in-situ characterization method.

The biggest limitation in this solution is that, even if the method works correctly, it is yet dependent on the measurements made by the sensors. This method requires exciting and taking measures in specific points of the track and thus, experimental errors in these points could lead to a decrease in the method accuracy. Moreover, these measures are taken in-situ, which means that there may be significant levels of background noise, which may limit the applicability of the methodology.

In addition, another big limitation for this thesis, not for the method itself, is that the prediction models for the dynamical response of rail tracks are complex and computationally demanding. On account of this fact, the developed model should be simplified as far as possible.

1.4 Rationale

The industry expends vast amounts of money in the supervision and substitution of the rail fasteners. The main problem of a damaged rail fastener is the vibration and noise increase caused by the train circulation over the faulty component, which leads to comfort problems to the people living in the surrounding area. With the current methodology, the industry must stop the train circulation in the track under consideration, which is economically costly, and then proceed to the extraction, transportation and lab testing of the rail fasteners, which not only increases the maintenance costs of the train track but it is also undesirable environmentally speaking.

Moreover, train services are currently rising in importance due to the fact that countries are gaining ecological awareness and are trying to boost its use. If the method accomplishes its duty, the railways will not have to be inactive during certain periods of time, making them a more efficient and trustable mobility option.

2 Background and review of the state of the art

In this section the state-of-the-art methodologies for the mechanical characterization of rail fasteners will be explained. They will be divided into two main groups: the laboratory tests, in which the rail fastener must be extracted from the working environment to be characterized inside a lab, and the in-situ method, which relays on the dynamical response measures taken in specific points at the rail track.

2.1 Laboratory Tests

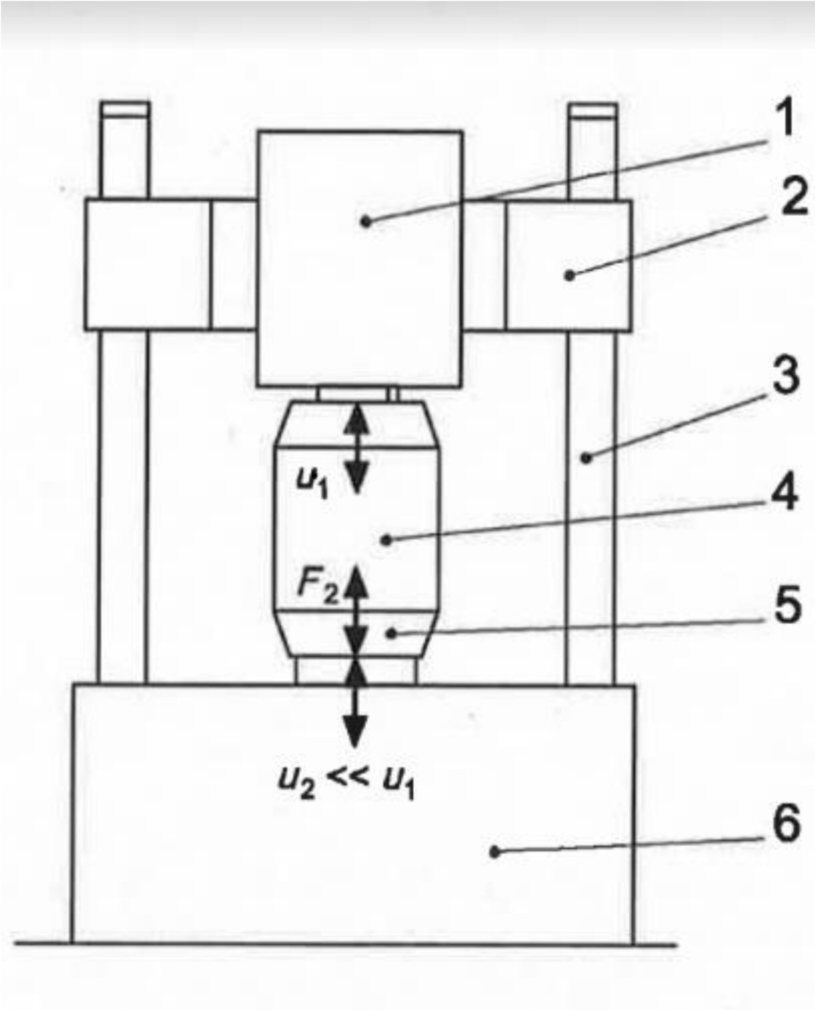
Nowadays, the mechanical characterization for rail fasteners is obtained through laboratory tests, which means that the component must be extracted from its working environment and transported to the lab. This is the first disadvantage of this type of mechanical characterization, as the conditions are altered, and the extracted properties will not necessarily represent accurately the component in its working conditions.

Then, the component to be evaluated is tested. There are different types of tests in order to measure the different mechanical properties of the component, such as torsion, bending, compression, tension, fatigue and resonant tests. This thesis will be mainly focused on the obtention of the axial stiffness, rather than torsional or bending components. Both, lab testing and in-situ method, are capable of retrieving the different components of stiffness, but this goes beyond the scope of the thesis.

The ISO 10846 **[1]** states three lab tests which can be used to obtain the stiffness of the tested component: the Direct Method (ISO 10846-2), the Indirect Method (ISO 10846-3) and the Application Point Method (ISO 10846-5).

2.1.1 Direct Method

The direct method consists in placing the component to be tested between a vibration exciter and a rigid end (see Figure 1). A transductor is placed between the tested isolator and the rigid end. A sensor must be placed between the vibration exciter and the tested isolator in order to measure acceleration, velocity or displacement. Moreover, the dynamical transfer stiffness is influenced by the static preload and thus, the measures must be taken with a nominal static preload.



Leyenda

1 actuador hidráulico (precarga estática y excitación dinámica)
2 barra transversal móvil
3 columnas
4 elemento de ensayo
5 sistema de medición de fuerza
6 base rígida

*Figure 1 - Direct Method Scheme **[1]***

After the measures have been retrieved, the transfer stiffness can be computed with the following equation considering that the rigid end does not move, or its movement is negligible. Note that the macron mark (¯) is used as a phasor notation for sinusoidal magnitudes:

$$\bar{K}_{21} = \left.\frac{\bar{F}_2}{\bar{u}_1}\right|_{\bar{u}_2 \approx 0}$$

One important drawback of this method is that the frequency range is limited to low frequencies, i.e., a maximum of around 500 Hz. For higher frequencies, the transmission through the structure's flanks used for the static preload alters the results.

2.1.2 Application Point Method

This method is almost the same as the direct method, only changing the transductor and force application point location (as can be seen in Figure 2), which will be between the vibration exciter and the tested isolator. The computation will rely on the fact that the rigid end practically does not move. Also, it will be assumed that at low frequencies the dynamic transfer stiffness ($\bar{K}_{21}$) is almost equal to the application point dynamical stiffness ($\bar{K}_{11}$). This can be explained due to the fact that, at these frequencies, inertia forces are insignificant compared to elastic forces. Thus, the equation used for the computation of the dynamical transfer stiffness is:

$$\bar{K}_{21} \approx \bar{K}_{11} = \left.\frac{\bar{F}_1}{\bar{u}_1}\right|_{\bar{u}_2 \approx 0}$$

The approximation of $\bar{K}_{21} \approx \bar{K}_{11}$ restricts the range of frequencies even more, being the maximum frequency for this method around 200 Hz.

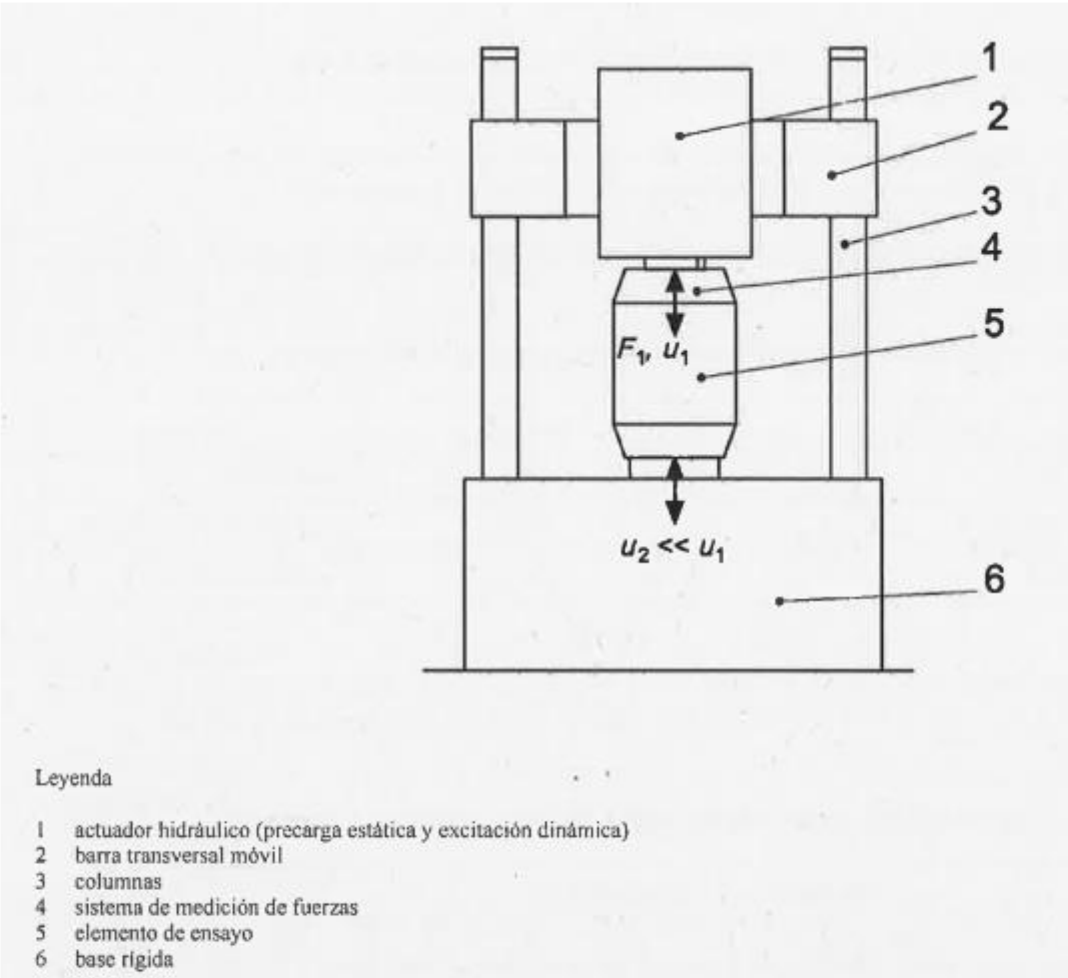


Figure 2 – Application Point Method Scheme ***[1]***

2.1.3 Indirect Method

The indirect method is different from the previous two methods explained in the past sections. The structure needed to perform this method must be one of the following two:

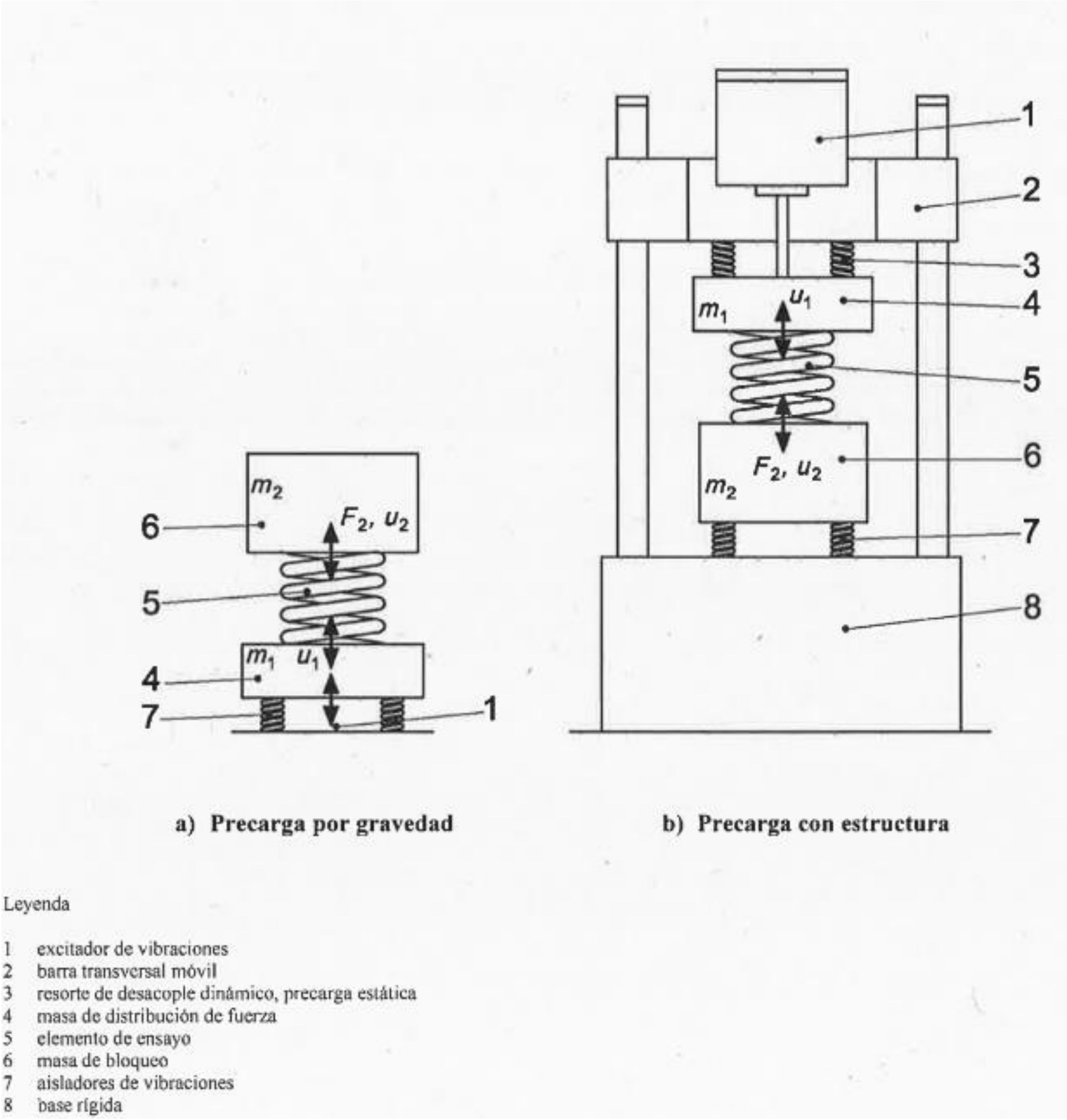


Figure 3 - Indirect Method Scheme ***[1]***

The configuration depends on how the preload is applied. Figure 3.a preload is done directly by the m_2 mass. On the other hand, Figure 3.b preload is done by an actuator. Two sensors are required for this test in order to retrieve the displacement, velocity or acceleration in both ends of the tested isolator. The auxiliar isolators added in this type of test improve the mitigation of the vibration transmission through the flanks.

On the other hand, the natural frequency of these isolators makes this type of test not convenient for low frequency analysis. A higher m_2 mass would decrease the natural frequency of the isolators, making the test more suitable for lower frequencies, but the non-rigid body behavior of the mass would lead to a lower suitability for high frequencies.

The equation used for this type of test is based on the relation between the displacements u_1 and u_2, called transmissibility. It assumes another time tiny u_2 displacements and is only valid for frequencies reasonably higher than the auxiliar isolator natural frequency.

$$\bar{K}_{21} \approx \frac{\bar{F}_2}{\bar{u}_1} \approx -(2\pi f)^2 m_2 \frac{\bar{u}_2}{\bar{u}_1}$$

With these considerations, the range of frequencies tested using this type of configuration is usually from 20-50 Hz to 2-5 kHz.

2.2 In-situ Method

The in-situ method is based on the experimental measurements taken by sensors in each fastener. The theory in which the method relies on is explained in **[2]**, but it will be briefly explained in this section.

For the sake of simplicity, a scheme of a source subsystem and a receiver subsystem joined by two isolators will be considered:

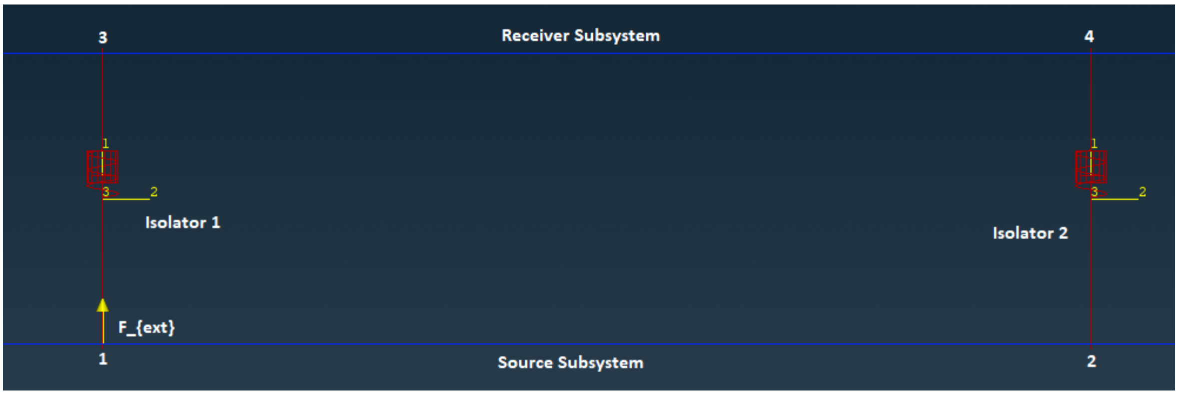


Figure 4 – Receiver-Isolator-Source Scheme

If the force analysis is carried out for each of the components and the equations are reorganized into a matrix form, the resulting equation is:

$$\begin{bmatrix} K_{11}^{S} + K_{11}^{I1} & K_{12}^{S} & K_{13}^{I1} & 0 \\ K_{21}^{S} & K_{22}^{S} + K_{22}^{I2} & 0 & K_{24}^{I2} \\ K_{31}^{I1} & 0 & K_{33}^{R} + K_{33}^{I1} & K_{34}^{R} \\ 0 & K_{42}^{I2} & K_{43}^{R} & K_{44}^{R} + K_{44}^{I2} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} F_{ext} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Where the superscript *R* refers to the receiver, *S* refers to the source, *I1* refers to the isolator 1 and *I2* refers to the isolator 2.

The stiffness matrix generated is very convenient, as the transfer stiffness of the isolators can be observed in specific elements of the matrix and can be directly retrieved (the ones in red).

The in-situ method is based on the obtention of the stiffness matrix through measurements so, in this case, four different force cases need to be measured for obtaining a determined system. The simplest cases are being selected, which is the application of a 1N force only in one point, different in each case. This subcase setup generates a identity matrix on the right side of the equation, which makes the stiffness matrix isolation easier.

Note that in the following matrix, the first subindex of u_{11} will mean the force case and the second one the point being displaced:

$$\begin{bmatrix} K_{11}^{M1}+K_{11}^{I1} & K_{12}^{M1} & K_{13}^{I1} & 0 \\ K_{21}^{M1} & K_{22}^{M1}+K_{22}^{I2} & 0 & K_{24}^{I2} \\ K_{31}^{I1} & 0 & K_{33}^{M2}+K_{33}^{I1} & K_{34}^{M2} \\ 0 & K_{42}^{I2} & K_{43}^{M2} & K_{44}^{M2}+K_{44}^{I2} \end{bmatrix} \begin{bmatrix} u_{11}u_{21}u_{31}u_{41} \\ u_{12}u_{22}u_{32}u_{42} \\ u_{13}u_{23}u_{33}u_{43} \\ u_{14}u_{24}u_{34}u_{44} \end{bmatrix} = \begin{bmatrix} 1000 \\ 0100 \\ 0010 \\ 0001 \end{bmatrix}$$

Eventually, this leads to the conclusion that, if the displacements of each point can be measured for each force case, the displacement matrix can be built. Its inverse will directly be the stiffness matrix from which the isolators transfer stiffness can finally be retrieved.

Receptance and dynamic stiffness are frequency response functions, i.e., their values are complex numbers accounting for the amplitude and phase shift for each of the excited frequencies.

$$\begin{bmatrix} \overline{K}_{11}^{M1}+\overline{K}_{11}^{I1} & \overline{K}_{12}^{M1} & \overline{K}_{13}^{I1} & 0 \\ \overline{K}_{21}^{M1} & \overline{K}_{22}^{M1}+\overline{K}_{22}^{I2} & 0 & \overline{K}_{24}^{I2} \\ \overline{K}_{31}^{I1} & 0 & \overline{K}_{33}^{M2}+\overline{K}_{33}^{I1} & \overline{K}_{34}^{M2} \\ 0 & \overline{K}_{42}^{I2} & \overline{K}_{43}^{M2} & \overline{K}_{44}^{M2}+\overline{K}_{44}^{I2} \end{bmatrix} \begin{bmatrix} \bar{u}_{11}\bar{u}_{21}\bar{u}_{31}\bar{u}_{41} \\ \bar{u}_{12}\bar{u}_{22}\bar{u}_{32}\bar{u}_{42} \\ \bar{u}_{13}\bar{u}_{23}\bar{u}_{33}\bar{u}_{43} \\ \bar{u}_{14}\bar{u}_{24}\bar{u}_{34}\bar{u}_{44} \end{bmatrix} = \begin{bmatrix} 1000 \\ 0100 \\ 0010 \\ 0001 \end{bmatrix}$$

3 Methodology

In this section, the different steps to accomplish the final objective of the thesis will be enumerated and explained.

The process to be followed is the one stated in the thesis scope (Section 1.2). Note that every time that a force is mentioned corresponds to a sinusoidal force. The simulations consider frequencies from 1Hz to 200Hz. Also, all the simulations consider a structural damping of 0.05. The dynamic analysis will be executed using direct frequency response solutions (108 Nastran solution). The frequencies evaluated are from 1Hz to 200Hz with 1Hz spacing. Different element sizes will be tried until finding convergence.

3.1 1D Elements

3.1.1 Rail

Firstly, the rail will be evaluated isolated. A modal analysis and a dynamic analysis will be performed and compared with data extracted from a reliable source in order to verify the results.

The properties used for the rail are the following:

Property	**Value**
Area	69.3 cm^2
Inertia Moment X-X	2337.9 cm^4
Inertia Moment Y-Y	419.2 cm^4
Young Modulus	200000 MPa
Poisson Coefficient	0.3
Density	7850 kg/m^3
Length	3.5 m

Table 1 - Rail Properties

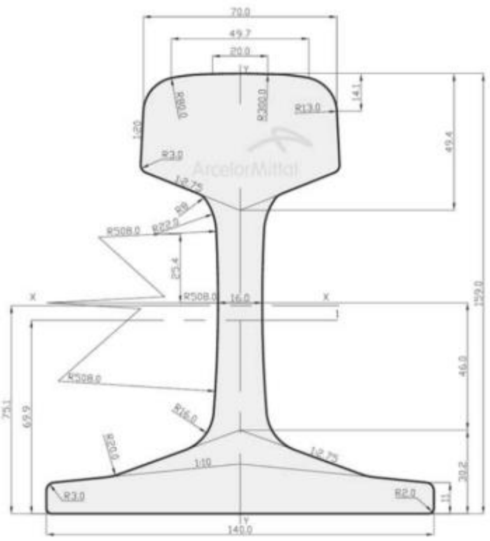


Figure 5 - Rail Schematics

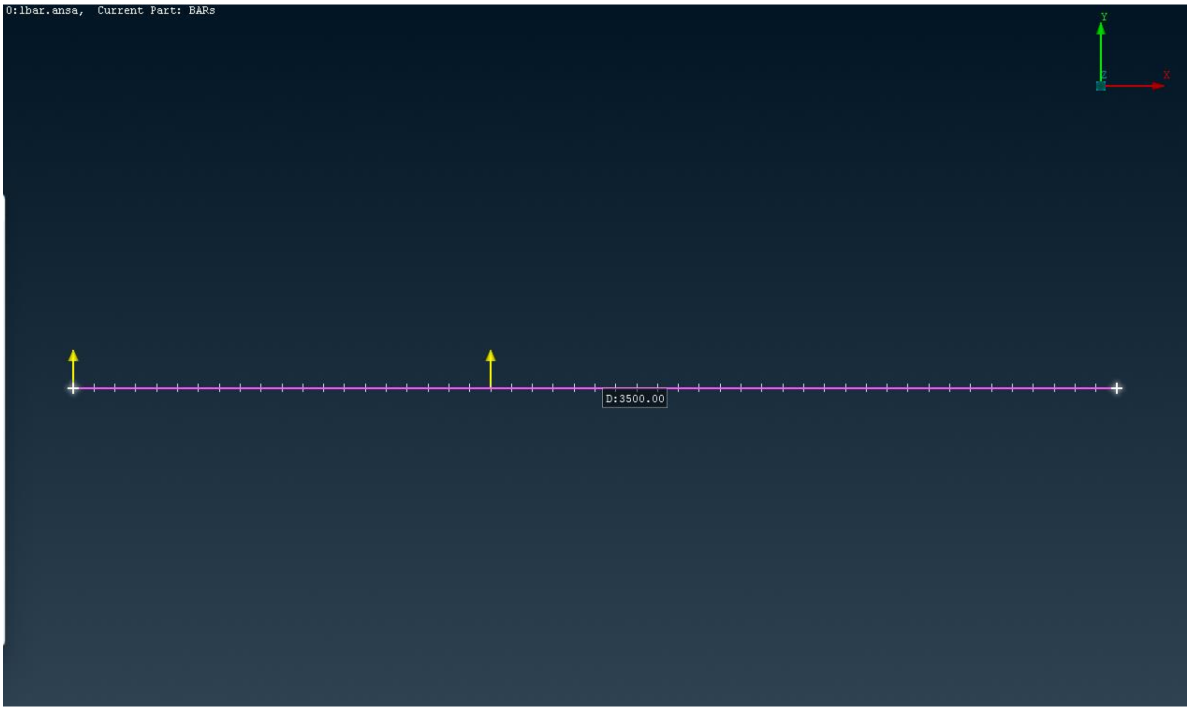


Figure 6 - 1D Rail Model

There will be two loads for the dynamic analysis located at (0,0,0) and (1.4m,0,0) as can be seen in Figure 6. The loads have a magnitude of 1N and they are oriented in the positive *y* direction. Furthermore, the range of frequencies analyzed will be from 0 to 200 Hz. The simulation will deliver the displacement of each point where the forces are applied.

The elements will be considered CBARS and not CRODS for taking into account bending, regarding the force is not applied axially.

3.1.2 Slab

Secondly, the slab will now be evaluated. The analysis carried out in the slab will be exactly the same as the one carried out in the rail.

The properties used for the slab are:

Property	**Value**
Stiffness	35 kN
Young Modulus	180 MPa
Poisson Coefficient	0.3
Density	2300 kg/m^3
Dimensions	3.5 x 2 x 0.3 m

Table 2 - Slab Properties

3.1.3 Rail-Slab-Fasteners

Finally, a complete 1D model will be evaluated following the same procedure as the previous two sections. The rail fasteners will be modeled as six 1D springs placed equidistantly, with a little offset at the beginning and at the end. This is made in order to be consistent with a 3D hypothetical fasteners case, as the 1D fastener should be placed in the middle of it. In this case a hypothetical 100mmx100mm 3D fastener will be considered, so the separation between each of them will be of 680 mm and the offset will be 50 mm, half of the 3D fastener length. The properties of both slab and rail will be the previous ones. Regarding the fasteners' stiffness, it will be the one shown in the table below:

Property	**Value**
Stiffness	35 kN/mm

Table 3 - Fasteners' Stiffness

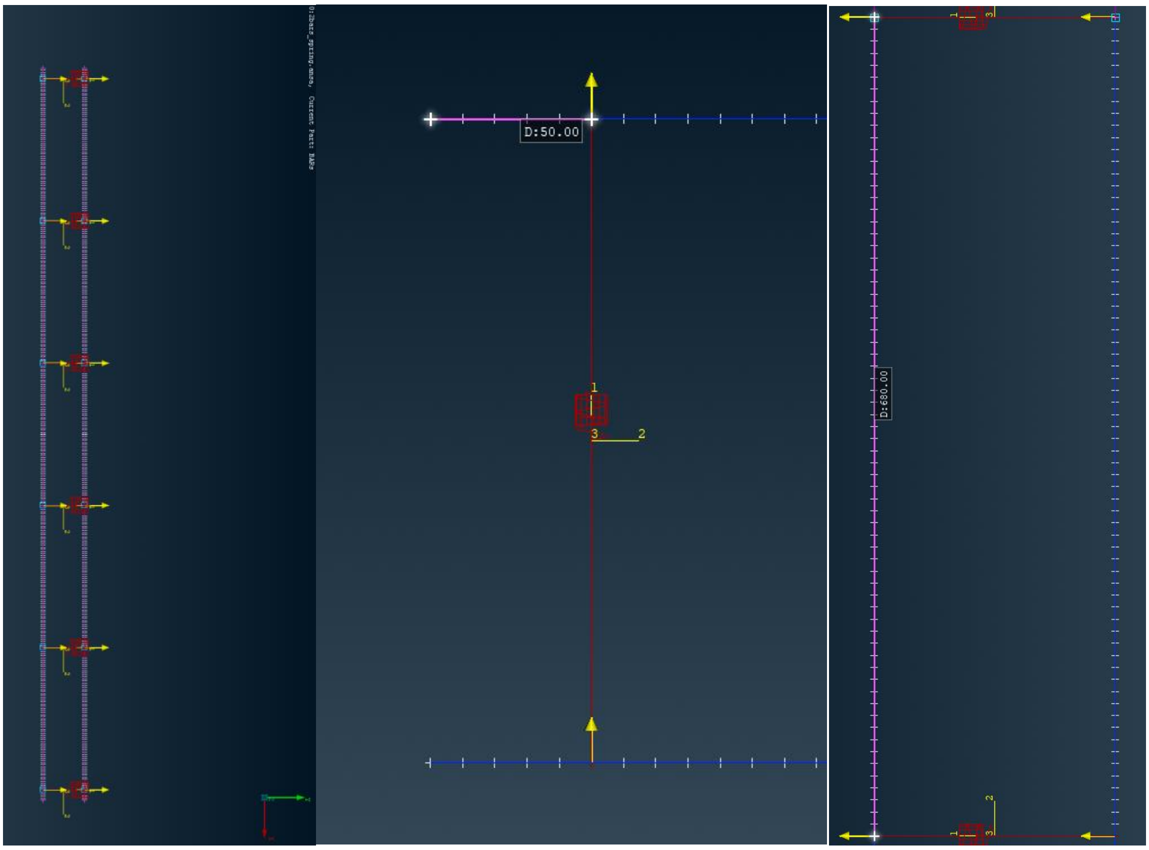


Figure 7 - 1D Rail-Slab-Fasteners Model

As can be seen in the above left figure, twelve forces will be applied, two in each end of each fastener. The displacements of this positions will be retrieved from the simulation.

3.2 3D Elements

In this section, both rail and slab will be tested as 3D elements. The objective is finding out if the 1D element simulation is similar to the 3D simulation or, on the other hand, the results for the 1D simulation are not applicable for a 3D case.

3.2.1 Rail

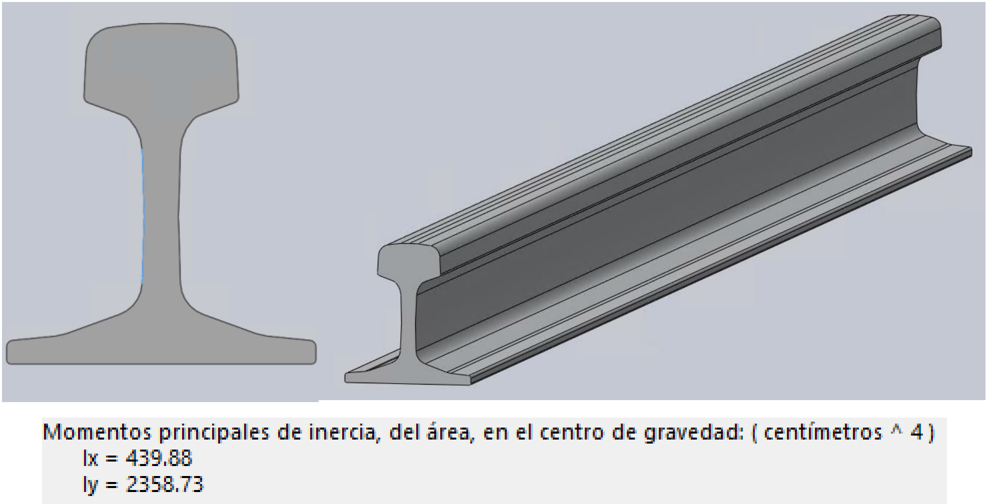


Figure 8 - Rail 3D Model and Area Moments of Inertia

Figure 8 shows the 3D rail model that will be used in the simulation. This model has been created using SolidWorks and can be verified comparing it with the properties used in the 1D simulations, as the scheme followed is the one in Figure 5. Note that the axes of the area moment of inertia used by SolidWorks are interchanged compared to the ones in Figure 5. The X-X area moment of inertia from the properties was 2337.9 cm^4 and the one for the model is 2358.73 cm^4. On the other hand, the Y-Y area moment of inertia from the properties was 419.2 cm^4 and the one for the model is 439.88 cm^4. Finally, the area from the properties was 69.3 cm^2, while the one from the model is 70.3 cm^2. The other properties remain equal. The highest difference is less than 5%, which verifies the 3D model designed.

The simulation that will be carried out is the same one as it was for the 1D rail. Two forces of 1N will be applied at 0 and 1.4m on the lower part of the rail, where the fastener would be in contact.

3.2.2 Slab

The slab will be a 3.5 x 2 x 0.3 m block. The properties are the ones used for the 1D simulation. The simulation will also be equivalent to the 1D slab simulation, in order to compare results. Two forces of 1N will be applied at 0 and 1.4m on the upper face of the slab, where the fasteners would be in contact.

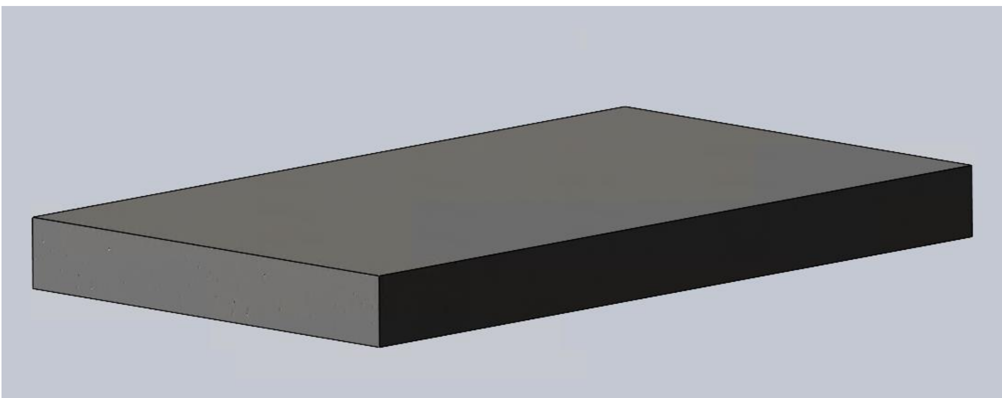


Figure 9 - Slab 3D Model

3.2.3 Rail-Slab-Fasteners

The simulation will contain the two previous models joined equidistantly by six unidimensional springs representing the fasteners. A 50 mm offset and a 680 mm spacing will be considered as explained in Section 3.1.3. Both simulations, the one in Section 3.1.3 and this one, will be comparable as all the properties for the models are identical. The objective is the assessment of the importance of 3D elements in the in-situ characterization method using numerical simulations.

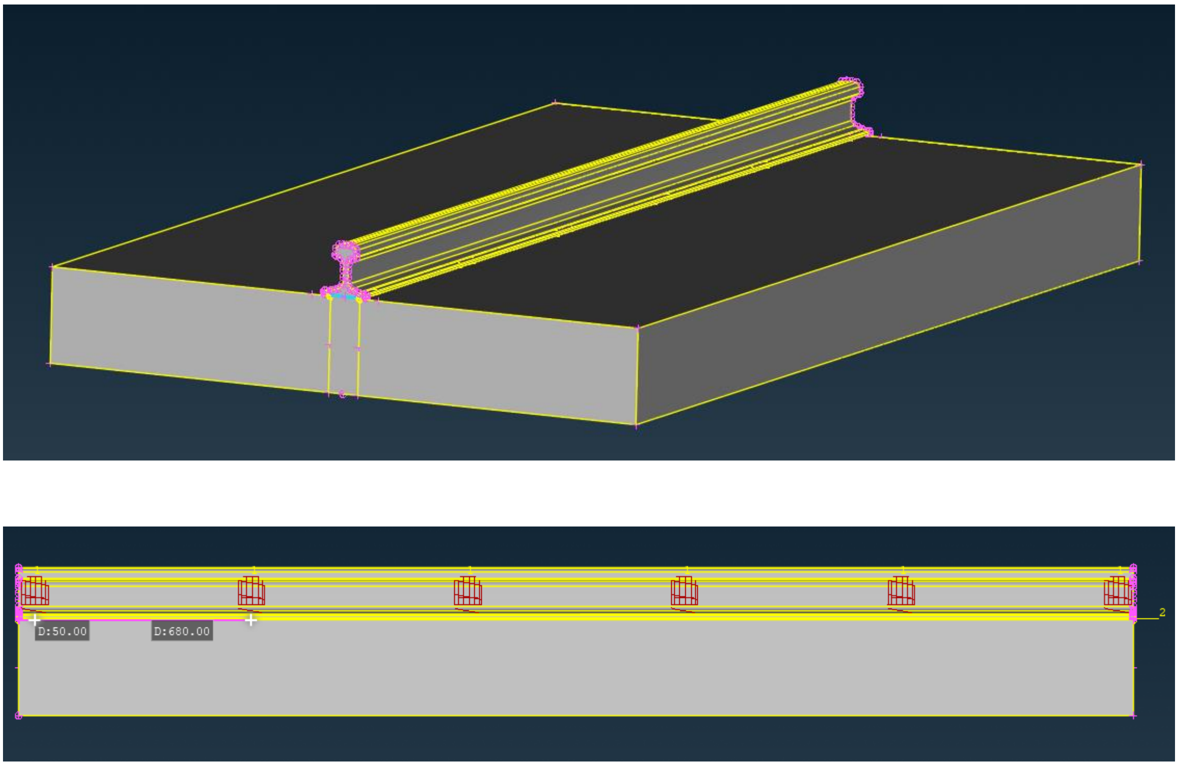


Figure 10 - 3D Rail-Slab-Fasteners Model

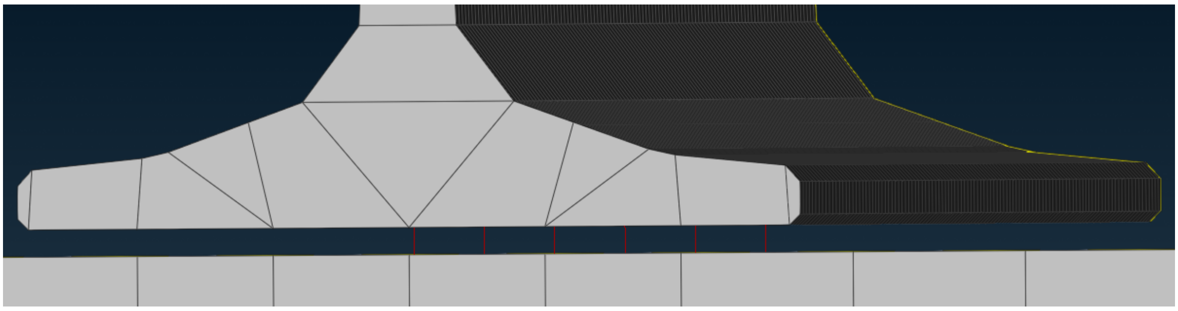


Figure 11 - 3D Rail-Slab-Fasteners Detailed Fastener View

Figure 10 shows the 3D model that will be simulated and the aforementioned offset and spacing (the springs size is maximized for the better understanding of the location, but it is only a visual reference, Figure 11 shows the actual size of the springs). The springs will have the same stiffness as previously, 35 kN/mm.

The force subcases are identical as the ones simulated for the simplified model of Section 3.1.3. There will be two force subcases for each fastener. The figure below shows a scheme of them:

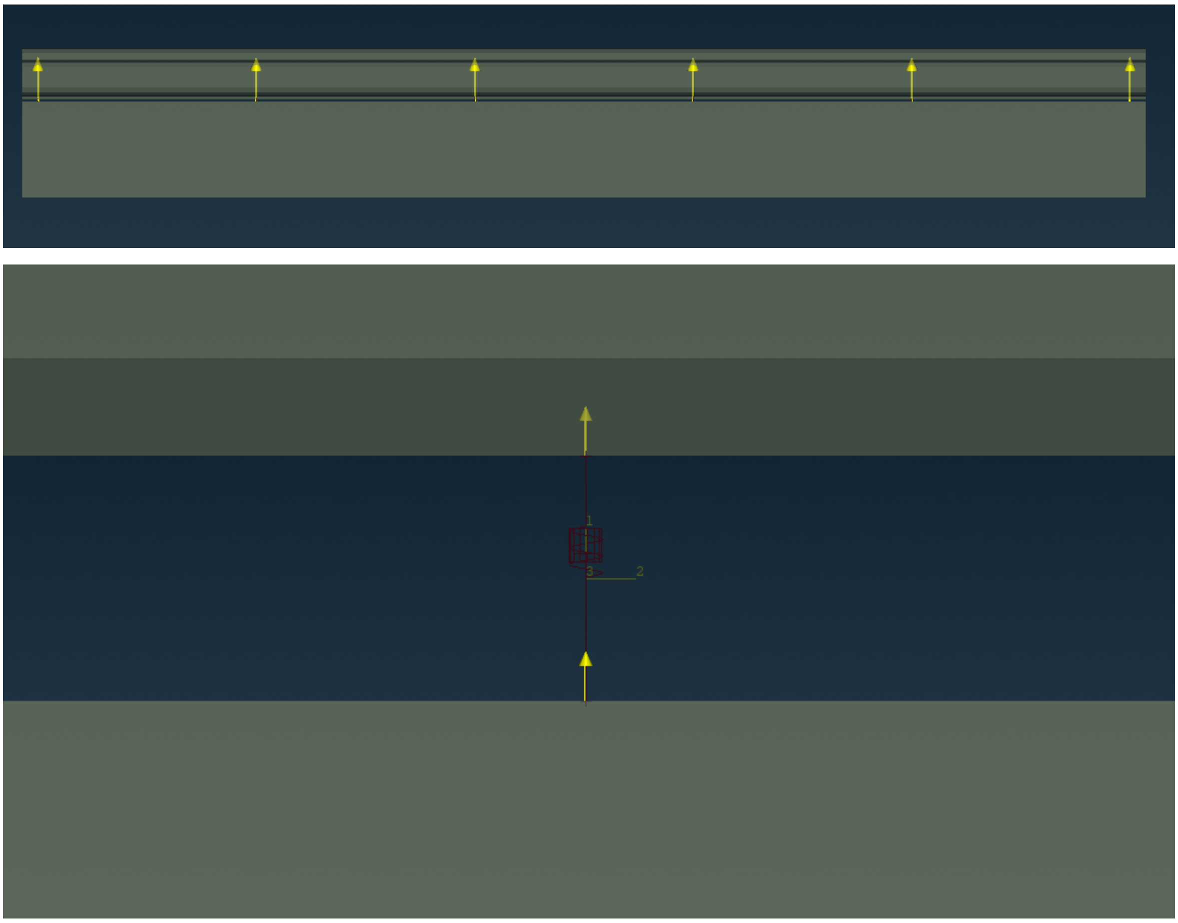


Figure 12 - 3D Rail-Slab-Fasteners Force Subcases

3.2.4 Final Model

The final model simulation is similar to the previous model simulation but trying to emulate a real rail track. The model is composed by two 6.9 m long rails (the previous simulation was 3.5 m long) spaced 1.445m (Madrid track width), 6.9x2.5x0.3 m slab and eleven 1D ideal springs representing the fasteners. The spacing and offset for the springs remain identical. The properties of all the elements are kept the same. The following figure shows the model for clarification purposes:

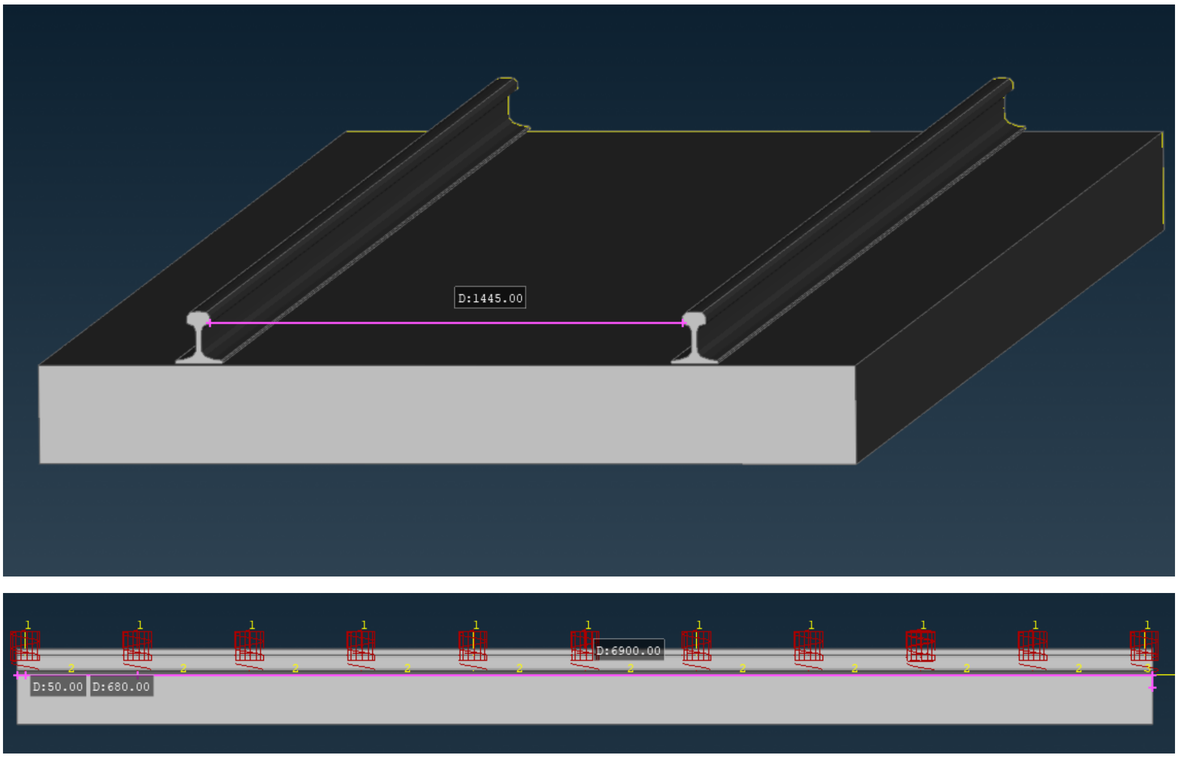


Figure 13 – Final Model

Finally, there will be twenty-two force subcases for this simulation as two subcases per fastener are required.

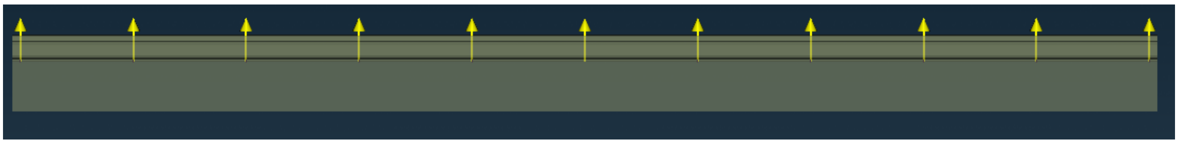


Figure 14 - Final Model Force Subcases Scheme

3.3 MATLAB Script

The simulation data will be exported to a .h5 file. This file will contain all the relevant data: displacement of each point, subcase force (point of application), range of frequencies, etc. Then, the MATLAB script will retrieve these data from the file, organize it into a matrix as explained in Section 2.2 and perform the inverse, resulting in the obtention of the stiffness matrix.

The next step will be the plotting of each fastener stiffness through all the frequencies. Then, the displacement data of one or some fasteners will be disregarded and the effect of not having these measures will be evaluated plotting the stiffness retrieved of the remaining fasteners under these circumstances.

The MATLAB code has been commented and it is included in the Annex Section 9.1.

4 Results

This section will contain all the data extracted from the simulations carried out, comparisons and the corresponding analysis of these results. The section will be structured in different subsections, the same ones as the previous section (3 Methodology).

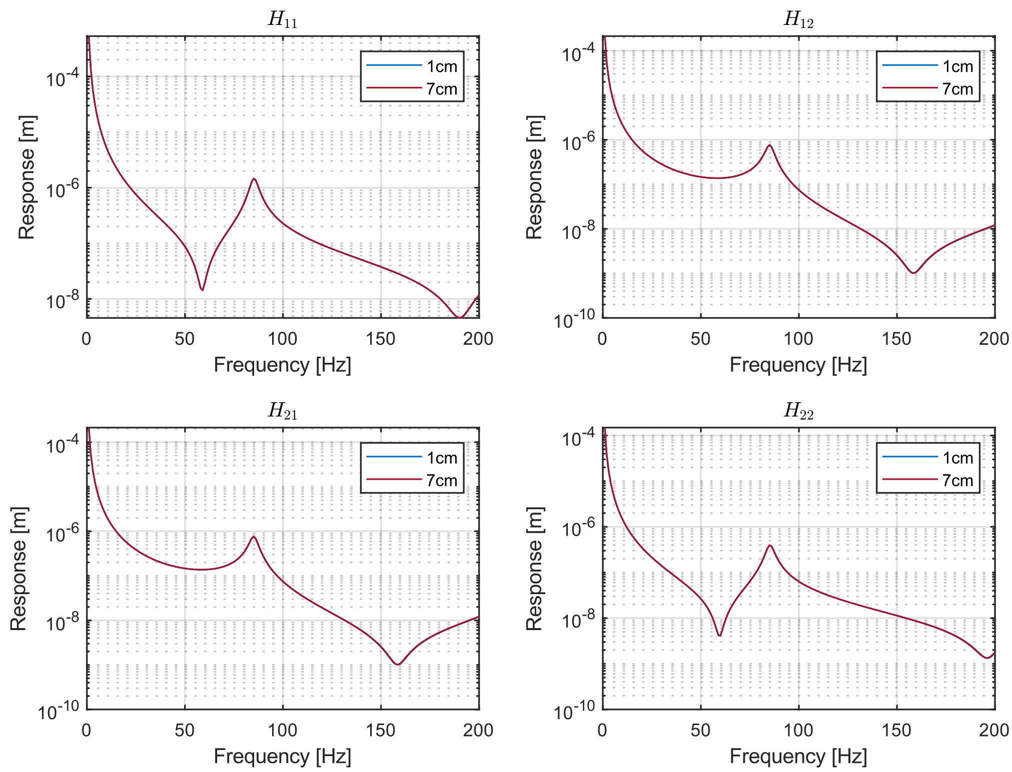
Important: The first subindex for the displacement or stiffness matrix refers to the force subcase (in this simulation each subcase has only one force, so the subindex would represent the point of application of the force) and the second subindex refers to the displacement point. For example, H_{12} would mean the displacement in point 2 due to the force applied in point 1. K_{12} would mean the necessary force applied in point 1 for having one unit of displacement in point 2 if all the other points were blocked.

4.1 1D Elements

4.1.1 Rail

After performing the simulation of the isolated rail, these are the results obtained for the displacements using elements of 7cm and 1cm:

Figure 15 – 1D Rail Point Clarification



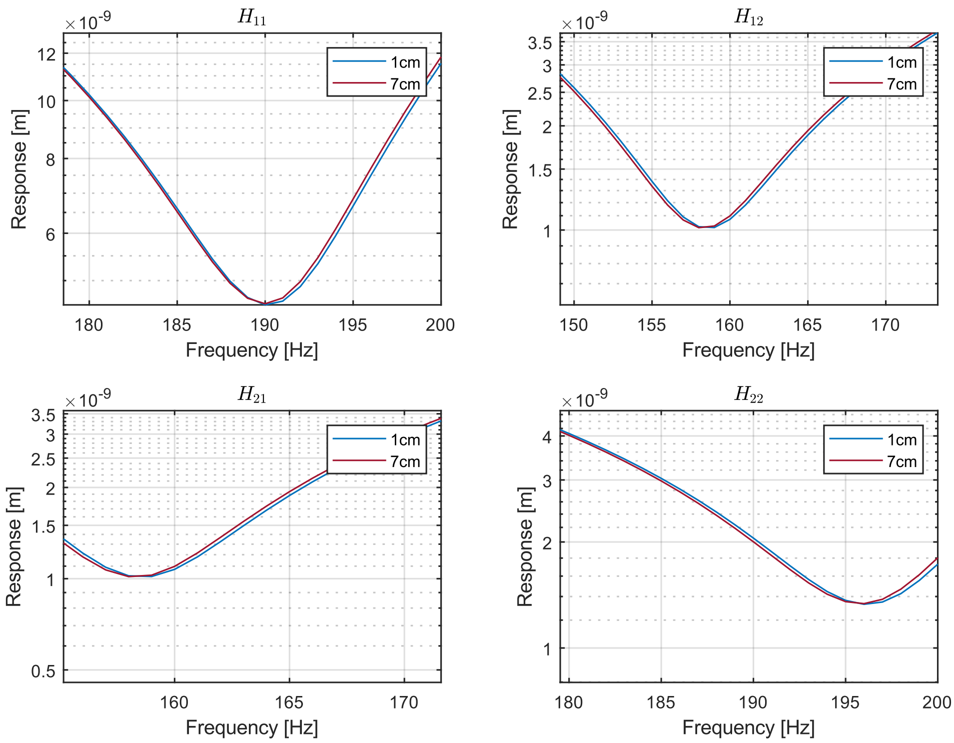


Figure 16 - Comparison of displacement vs frequency using different element sizes + Detailed view (Rail)

The figure shows that the element size of 7 cm is enough to obtain accurate results. Then, the simulation results will be compared with a trustable external software:

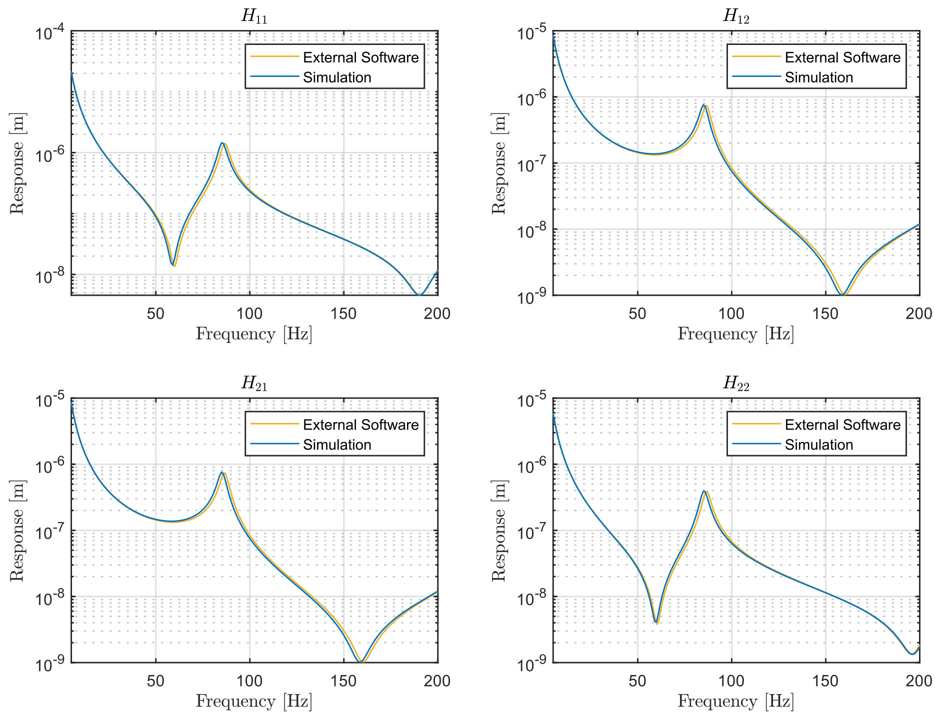


Figure 17 - External Software vs Simulation Rail

The results point out that the simulation has been successful as both plots are almost identical. Thus, the simulation of the isolated rail is verified.

4.1.2 Slab

As stated previously, the isolated slab simulation had the same forces and application points. In this case, the element sizes are 7cm, 1cm and 1mm:

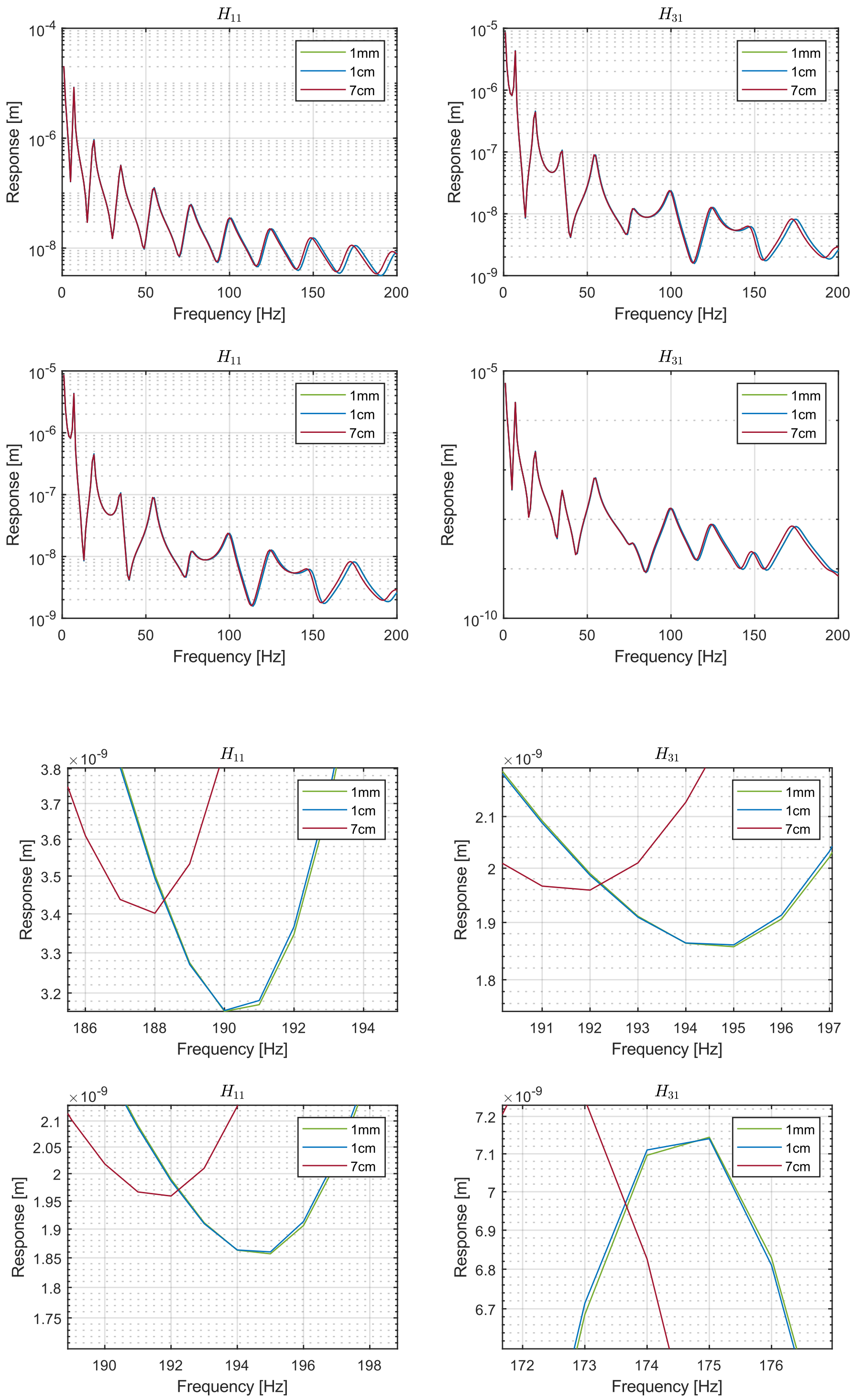


Figure 18 - Comparison of displacement vs frequency using different element sizes + Detailed view (Slab)

Figure 18 shows a difference between 7cm elements and 1cm elements. The displacement is similar but not as accurate as it was in the rail simulation. This can be explained by the increase in frequency modes the slab has compared to the rail, making the discretization error greater. When comparing the 1cm elements against the 1mm elements there are no remarkable discrepancies.

The results of the 1cm elements will be compared with the external software and the comparison will be shown below:

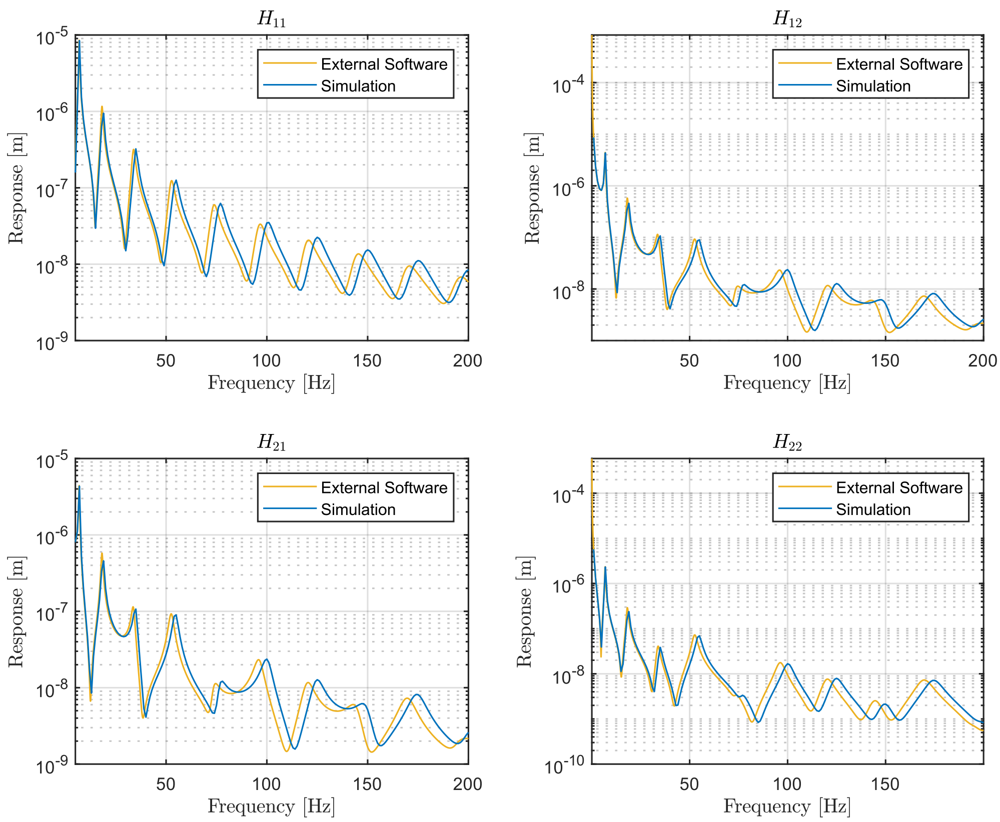


Figure 19 - External Software vs Simulation Slab

These results are also pretty similar even though they are less similar than the ones of the rail. This was expected, as explained before, because there are much more eigenmodes in the slab structure than in the rail structure, which makes the simulation more difficult and less accurate. This fact leads to the differences seen in Figure 19. The simulation is verified.

4.1.3 Rail-Slab-Fasteners

Eventually, the simulation combining both rail and slab joined by the 1D fasteners will be carried out.

Figure 20 – Rail-Slab-Fasteners Point Clarification

Note that the element size selected for the simulation is 1cm, as it was accurate enough for both previous isolated simulations.

With all the displacements extracted from the simulation, a 12x12 matrix will be built as explained in Section 2.2 and the corresponding inverse matrix will deliver the stiffness matrix. The external software that was used in the previous simulations cannot perform this simulation combining all the elements, but if the results show a 35 kN/mm stiffness when taking into consideration all the fasteners, the simulation will be verified too.

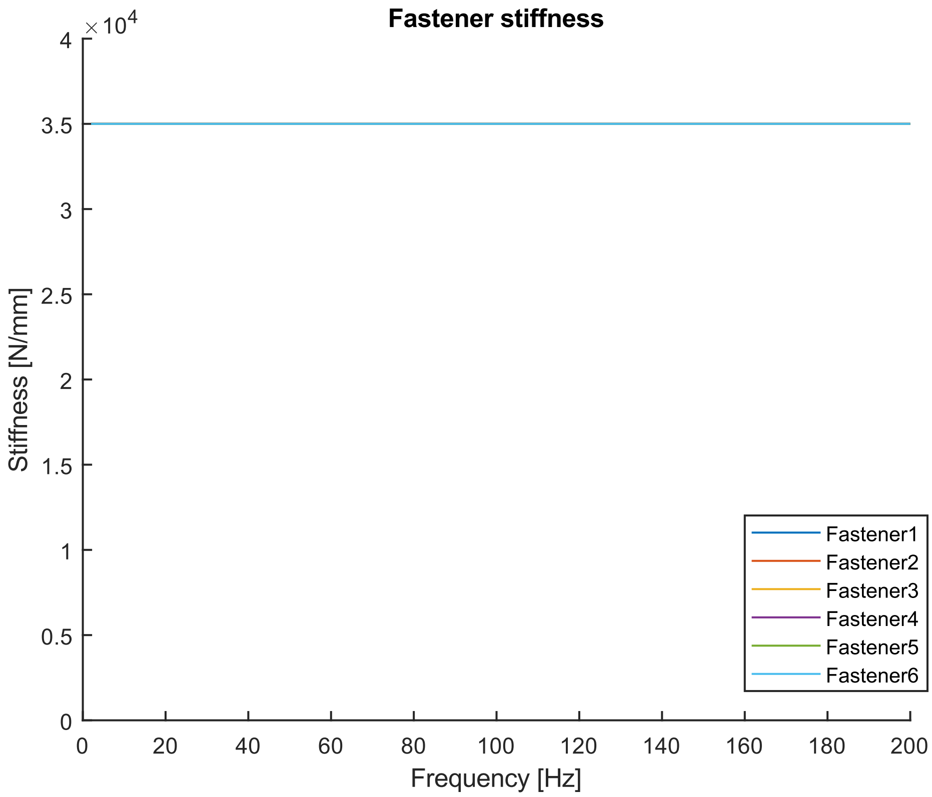


Figure 21 – Simplified Model Fasteners' Stiffness with all measures

The figure shows that all fasteners have a constant stiffness through all the frequencies of 35 kN/mm, which means the simulation is verified.

Finally, the influence of disregarding the measurements of one or more fasteners will be studied. The fasteners measurements will be disregarded from the 6th fastener to the 2nd one and the change in stiffness induced in the other fasteners will be evaluated.

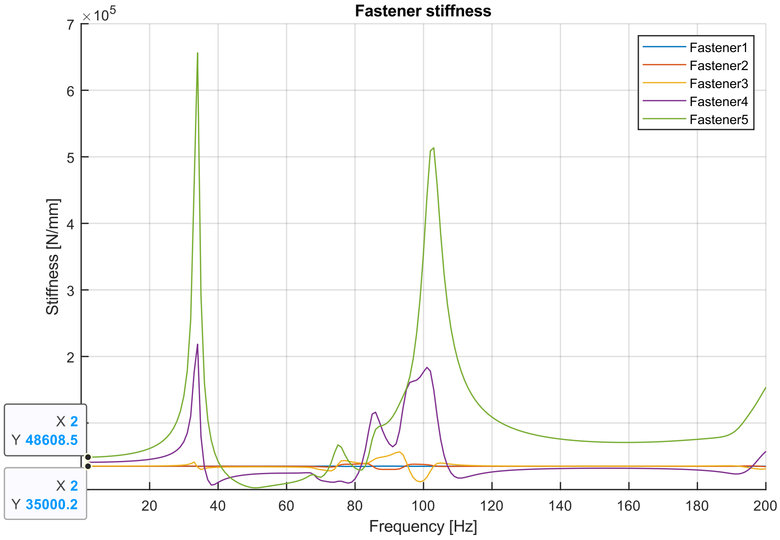


Figure 22 - Simplified Model Fasteners' Stiffness with Fastener 6 disregarded

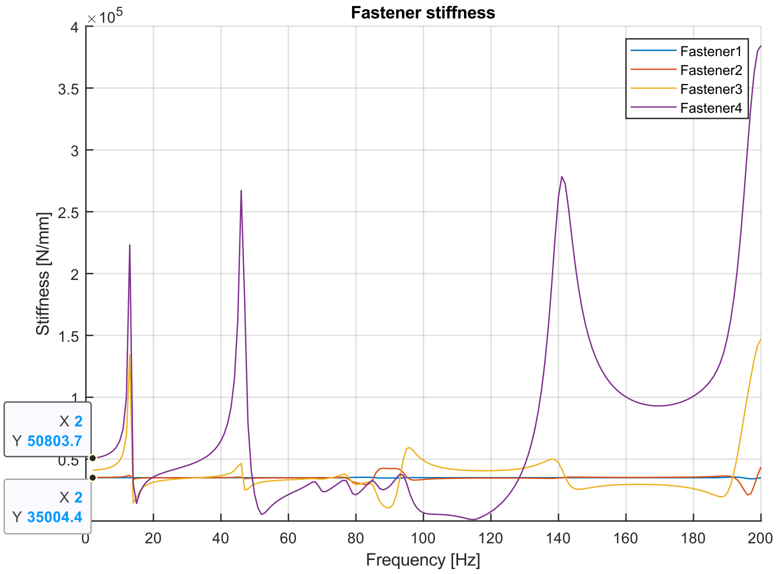


Figure 23 – Simplified Model Fasteners' Stiffness with Fasteners 5-6 disregarded

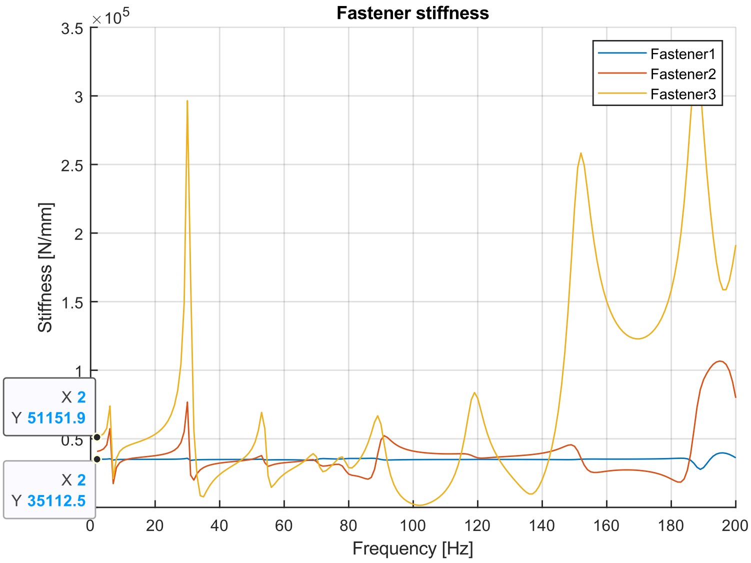


Figure 24 – Simplified Model Fasteners' Stiffness with Fasteners 4-5-6 disregarded

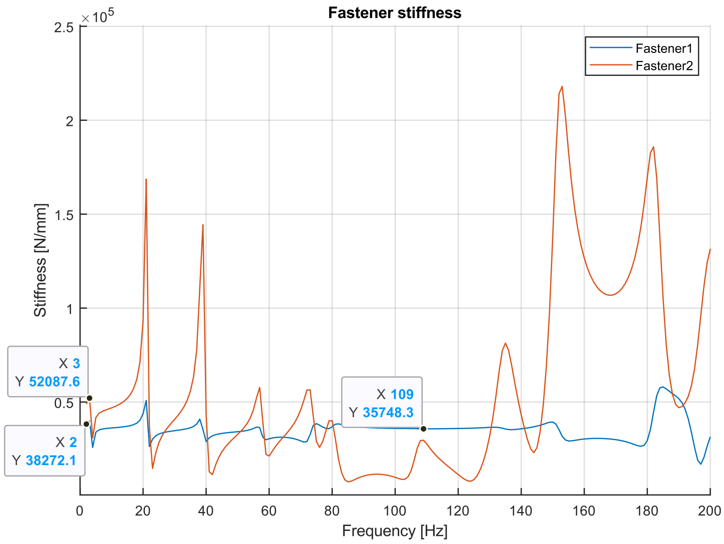


Figure 25 – Simplified Model Fasteners' Stiffness with Fasteners 3-4-5-6 disregarded

The results extracted can report some interesting conclusions.

Firstly, it can be seen that the fastener which is closer to the one disregarded is the one which is affected the most, as expected. Figure 22 shows how Fastener 5 is changing in stiffness through all the frequency spectrum in order to compensate the lack of data from the 6th fastener. Moreover, at the beginning, the stiffness at low frequencies is higher than 35 kN/mm, which can be interpreted as if the 5th fastener was incorporating part of the stiffness of the 6th one in order to account for the lack of this component. After that, frequency modes start affecting and the stiffness begins to fluctuate.

Secondly, the results show that the 1st fastener's stiffness does not change significantly until the 3rd fastener is removed, which means that in this case, if the measurements of the two contiguous fasteners are obtained the stiffness retrieved is correct. This statement is only valid for this simulation, as if the same procedure is made and the 1st and 6th fasteners are disregarded, the resulting plot is:

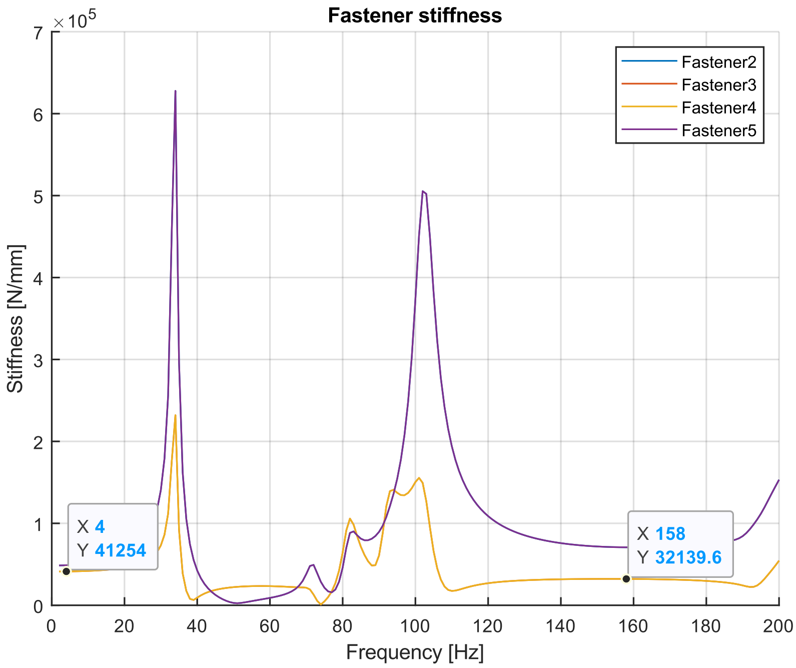


Figure 26 - Simplified Model Fasteners' Stiffness with Fasteners 1-6 disregarded

This gives and approximate value for the fastener but is not as accurate as the previous case. Thus, it can be concluded that more simulations should be performed, with a larger number of fasteners integrating the structure, in order to know how many fasteners should be measured around the one of interest. In addition, there is the fact that this model of the rail is finite, while in reality the railway could be considered infinite.

To sum up, these results show that the method works, but deeper research must be performed in order to extract rigorous statements, which means, more fasteners, 3D elements and a larger model.

4.2 3D Elements

Now that the 1D simulation is completed, the next step is substituting the 1D rail and slab by their correspondent 3D elements shown in Section 3.2.

4.2.1 Rail

The rail simulation will consider elements of 3x3x2cm. After performing the simulation of the 3D rail, the following plots comparing the extracted results with the 1D results can be obtained:

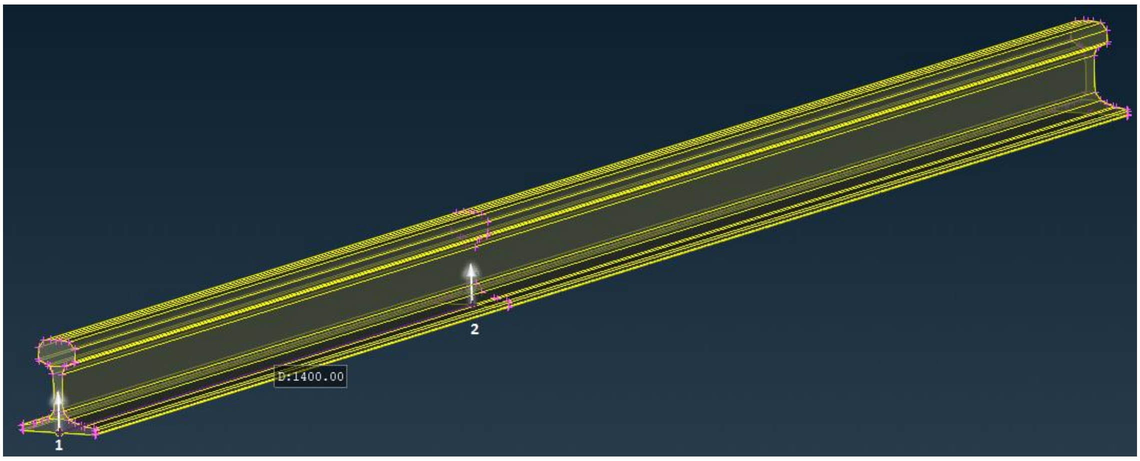


Figure 27 - 3D Rail Point Clarification

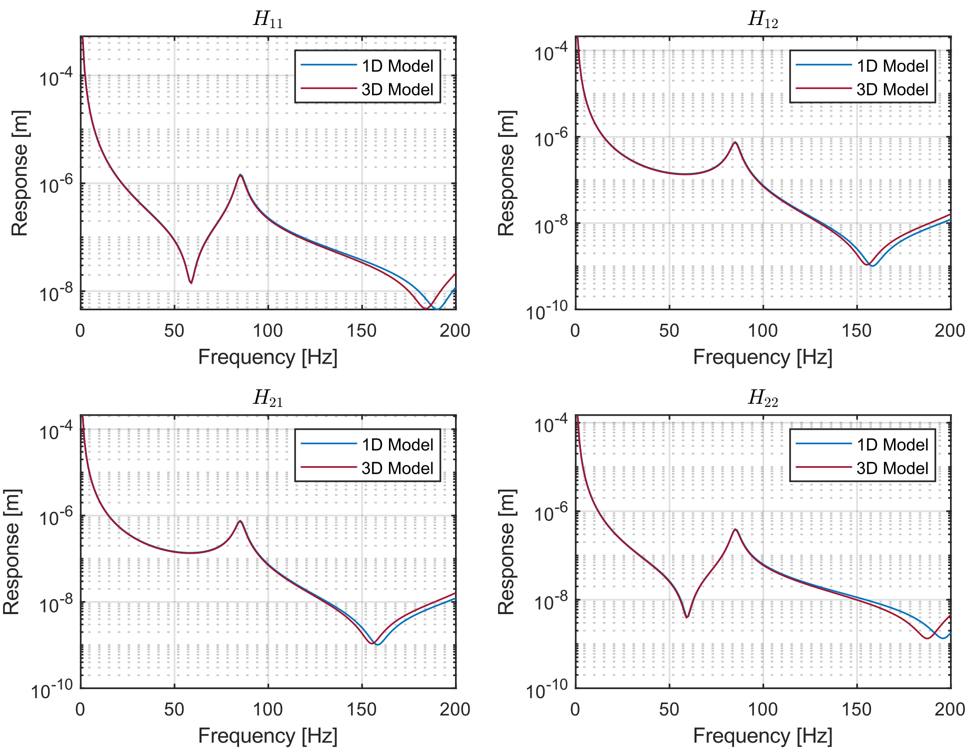


Figure 28 - 1D vs 3D Isolated Rail Simulation

Figure 28 shows a slight difference between the 1D and 3D model at high frequencies, but the overall results are pretty similar, which means that the 1D model emulates the real model with an acceptable accuracy.

4.2.2 Slab

The next simulation to be carried out is the same one for the 3D slab. First, different element sizes will be evaluated. Then, the results will be also compared to the 1D model:

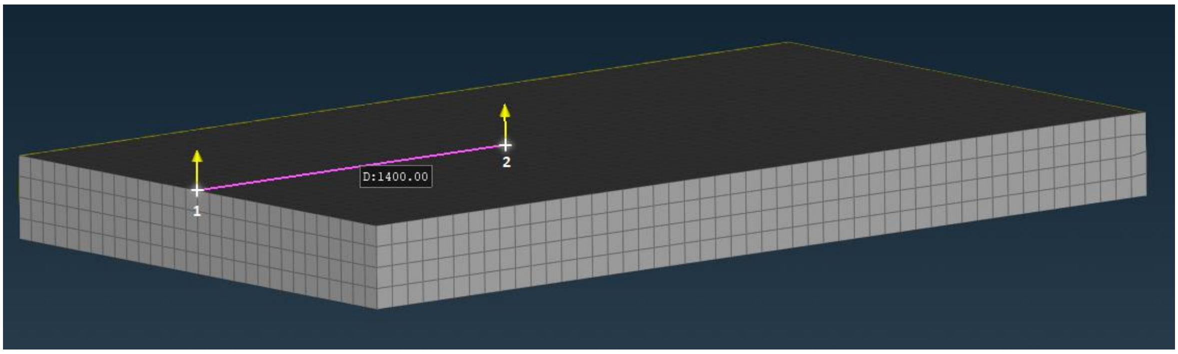
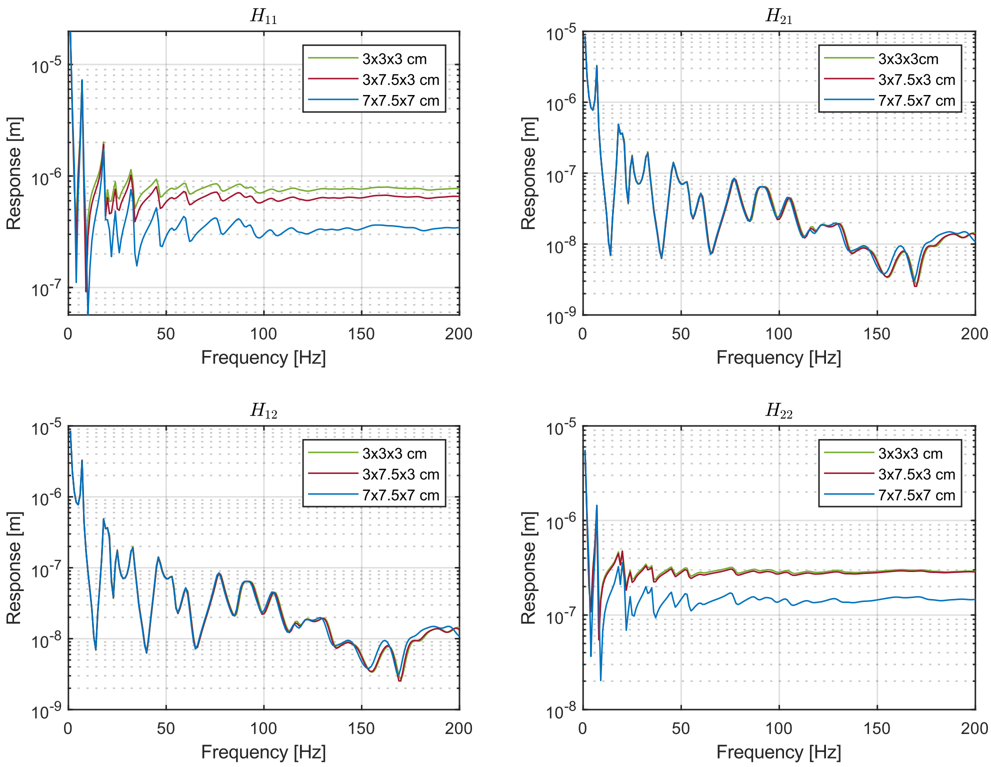


Figure 29 - 3D Slab Point Clarification



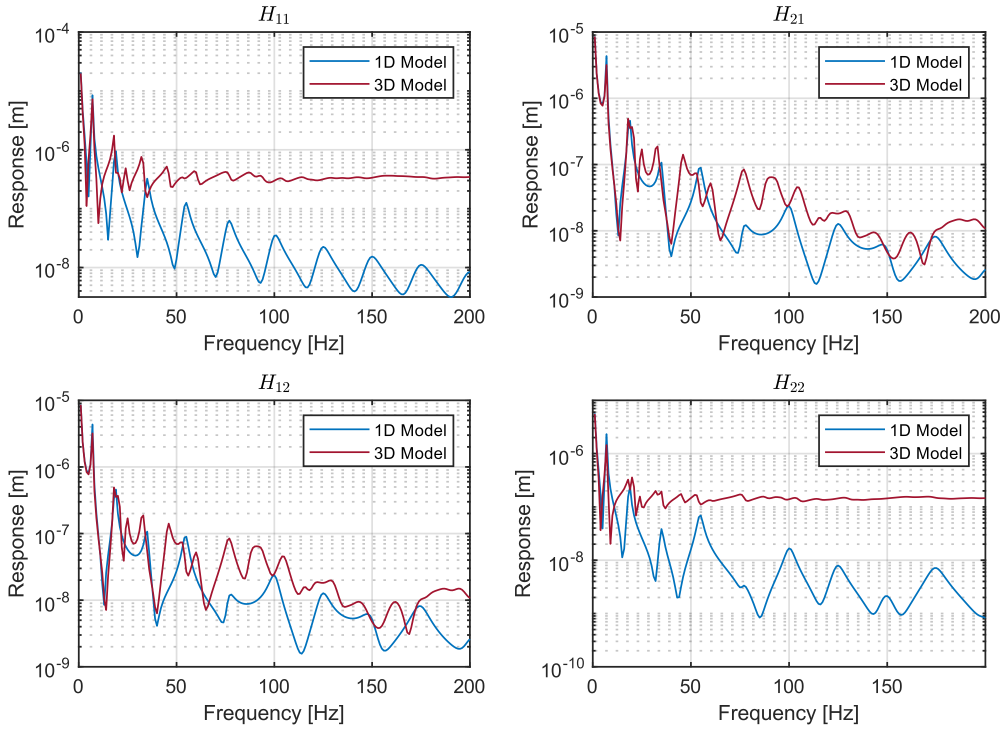


Figure 30 - 1D vs 3D Isolated Slab Simulation

Figure 30 highlights the importance of the 3D elements in this type of component. The rail could be represented with high accuracy as a 1D bar, but the slab is not. The slab has wider dimensions that make the 1D model not consistent with the real behavior, having the 3D model a much higher amount of eigenmodes (the number of eigenmodes for the 3D model until 400Hz is around ten times higher than the one for the 1D model).

Then, the 3D simulation of all the components (3D rail + 3D slab + 1D fasteners) is expected to be different than the 1D simulation.

4.2.3 Rail-Slab-Fasteners

Hereunder, the simulation joining the previous to components by six 1D ideal springs representing the rail fasteners will be performed. The element size used for the meshing is around 3x3x2 cm for the rail and 3x3x7.5 cm for the slab. The meshed model can be seen in Figure 31.

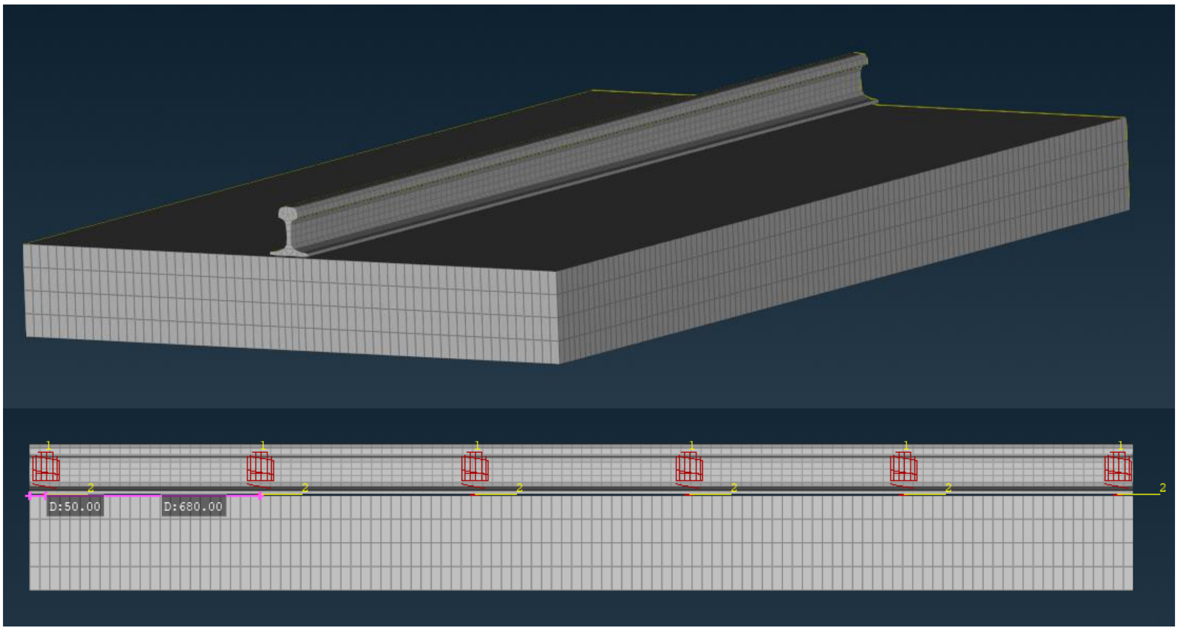


Figure 31 - 3D Rail-Slab-Fasteners Meshing

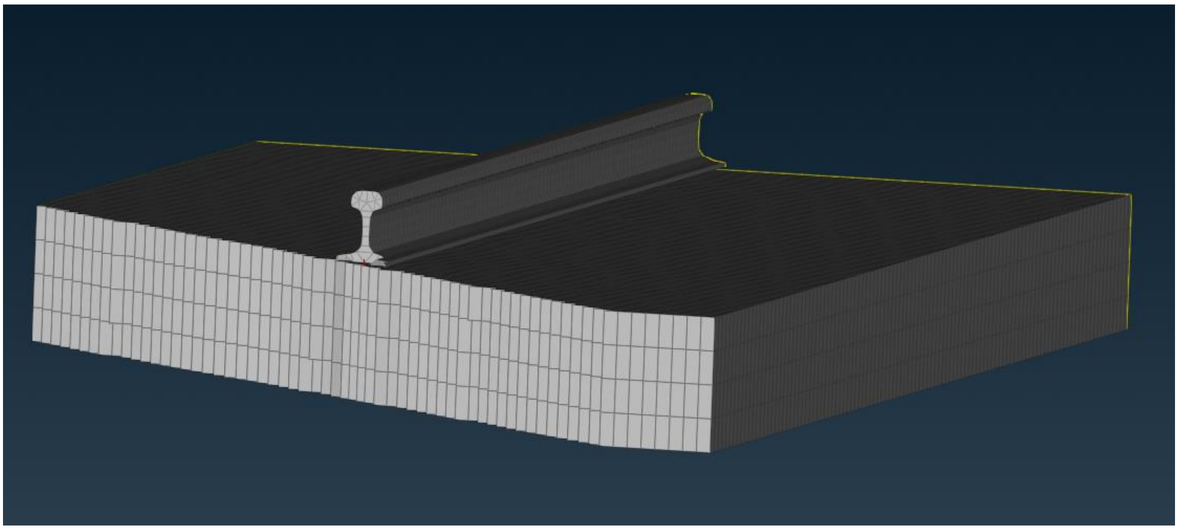


Figure 32 - 3D Rail-Slab-Fasteners Diagonal Cross Section

Figure 32 shows a diagonal cross section of the model in order to prove that a 3D element meshing has been performed for the simulation.

The verification method applied will be based in the obtention of the fasteners' stiffness when all the measures are considered, which was the one used for the simplified model too.

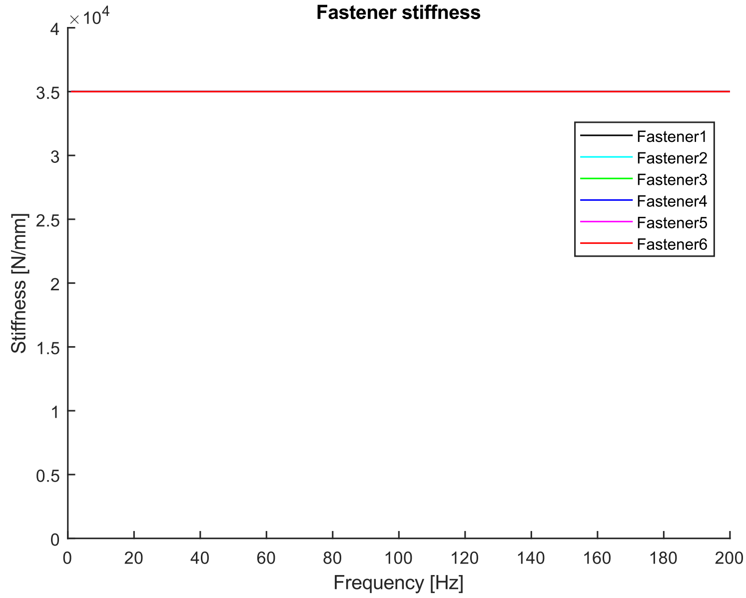


Figure 33 – 3D Model Fasteners' Stiffness with all measures

Figure 33 verifies the simulation as the fasteners' stiffness is retrieved correctly. Hence, the procedure of disregarding measures will be carried out. The same procedure as Section 4.1.3 will be followed for comparison purposes.

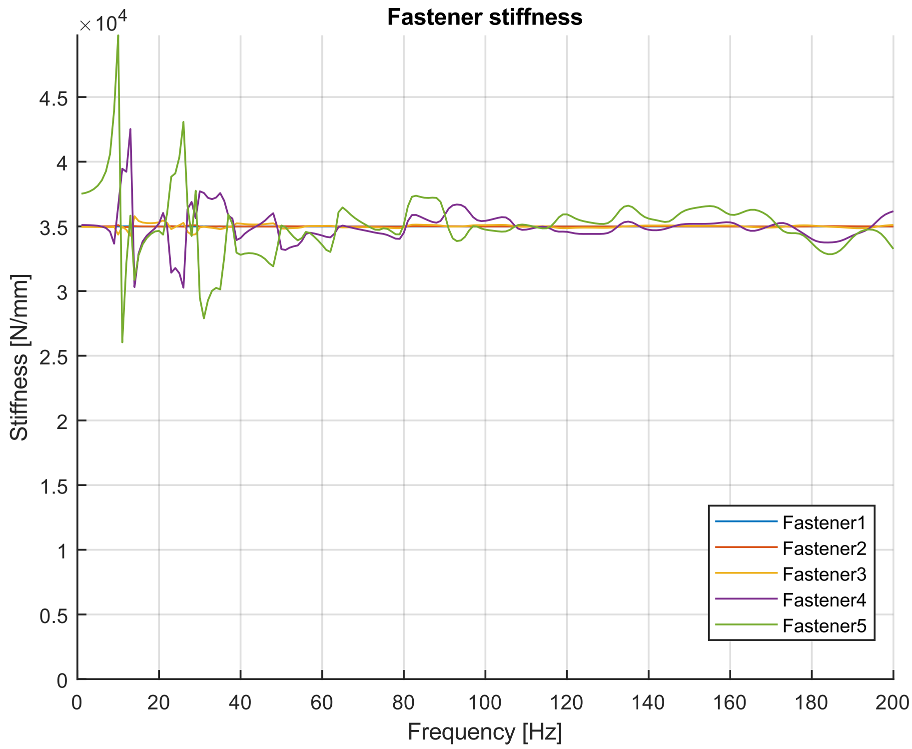


Figure 34 - 3D Model Fasteners' Stiffness with Fastener 6 disregarded

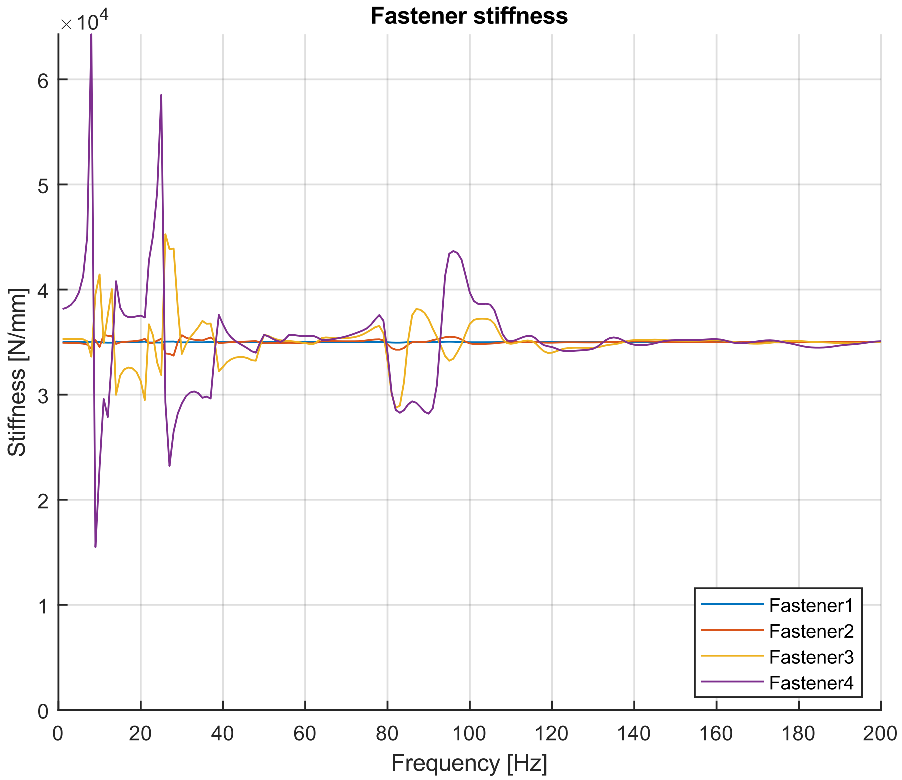


Figure 35 – 3D Model Fasteners' Stiffness with Fasteners 5-6 disregarded

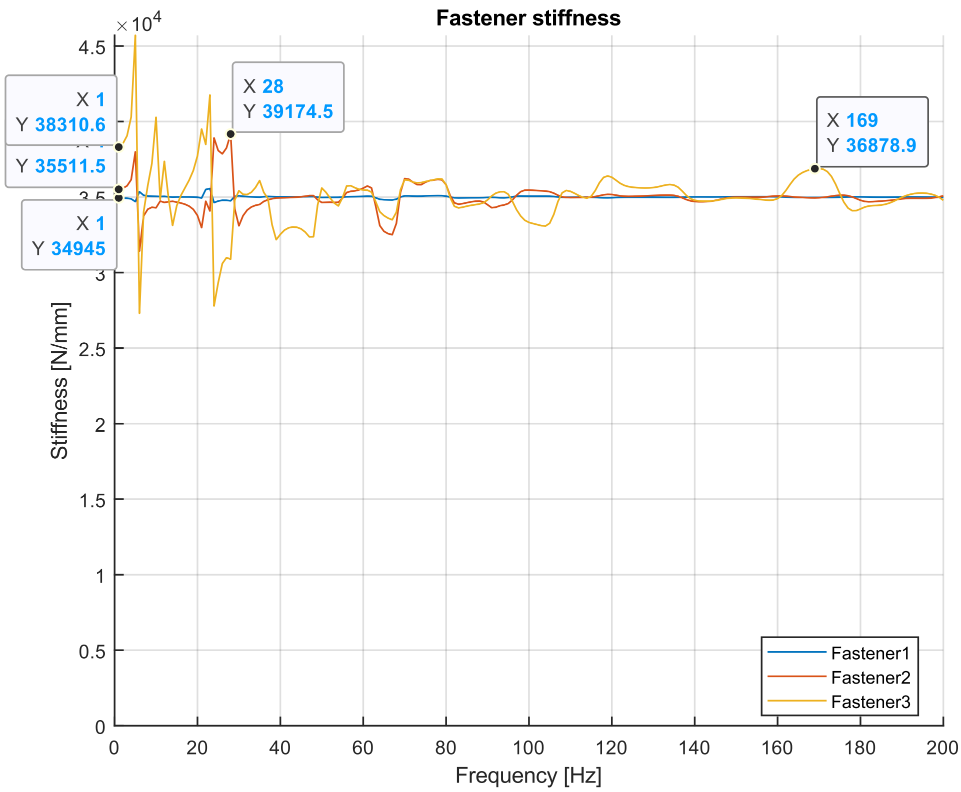


Figure 36 – 3D Model Fasteners' Stiffness with Fasteners 4-5-6 disregarded

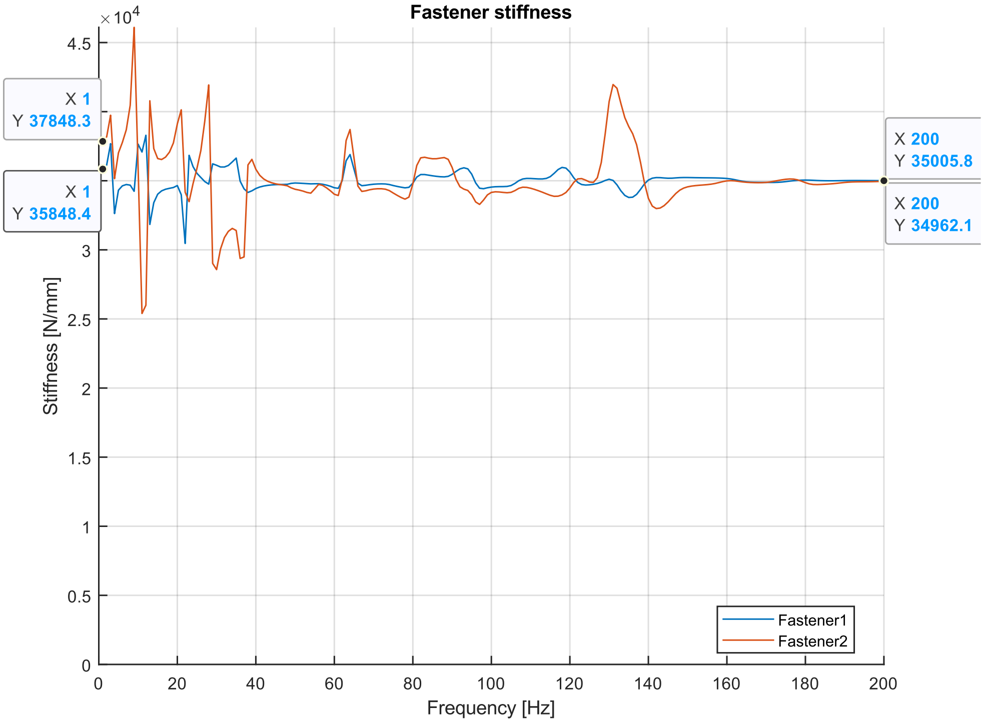


Figure 37 – 3D Model Fasteners' Stiffness with Fasteners 3-4-5-6 disregarded

Once that all these simulations are concluded and the results have been analyzed, there are some conclusions that can be extracted. The simplified and 3D simulations have some points in common. The closest fasteners to the one disregarded are the ones that are more affected and, therefore, their stiffness is less accurate. Moreover, the stiffness of the closest fasteners to the disregarded one is increased at low frequencies.

In contrast, the difference between the real value and the computed one using the in-situ characterization method is much smaller in the 3D simulation than in the simplified model, being in some cases even ten times smaller. Another important fact when observing the previous plots is that, when the frequency is high, the values usually tend to the correct stiffness value (within a certain margin error).

The simplified model simulation highlighted that the 1st and 6th fasteners had a higher importance when selecting which fasteners were being disregarded. The same simulation will be made for comparison purposes.

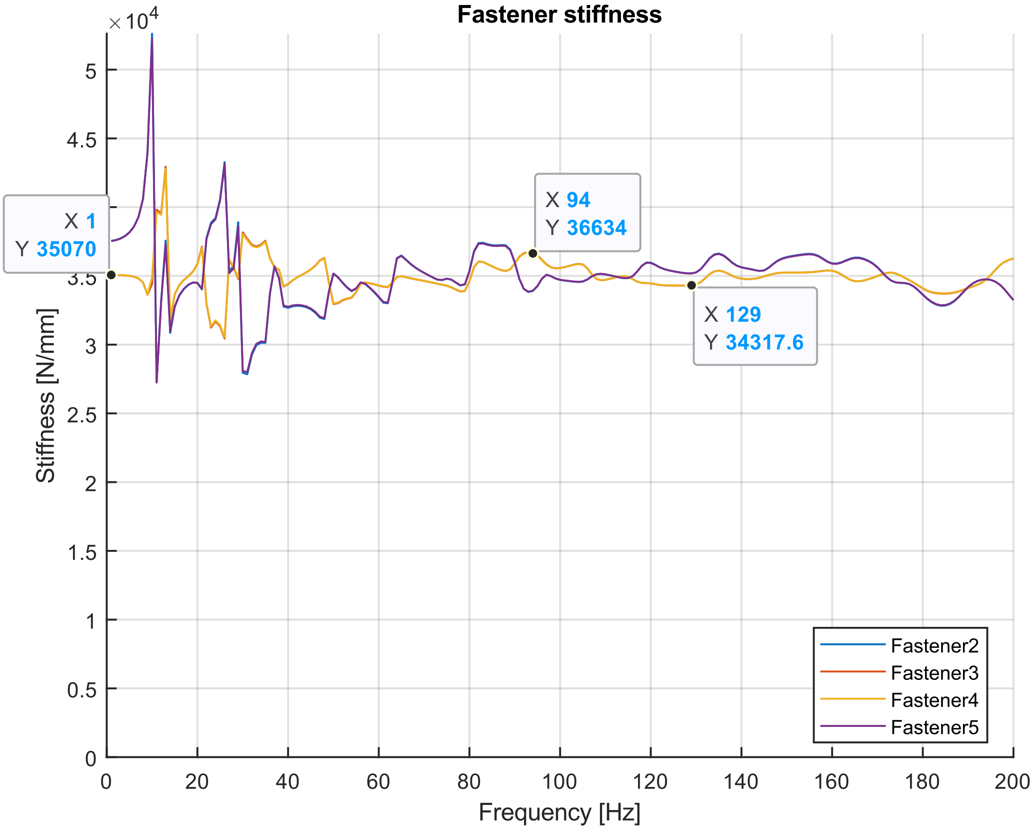


Figure 38 – 3D Model Fasteners' Stiffness with Fasteners 1-6 disregarded

When the Fastener 1 was not disregarded, the measures were accurate enough if two consecutive fasteners were considered. This configuration cannot be performed as there are only six fasteners and each end fastener would be disregarded. Consequently, a larger model must be developed. Nevertheless, Figure 38 shows worse accuracy for Fasteners 3 and 4 than the accuracy of the Fastener 2 in Figure 35, which is probably caused by the finite model problem.

4.2.4 Final Model

Eventually, the simulation of the complete rail track is carried out. The rail and slab meshing parameters are the same ones as the previous simulation, resulting in 3x3x2 cm elements for the rail and 3x3x7.5 cm elements for the slab. The meshed final model is shown in Figure 39 and Figure 40.

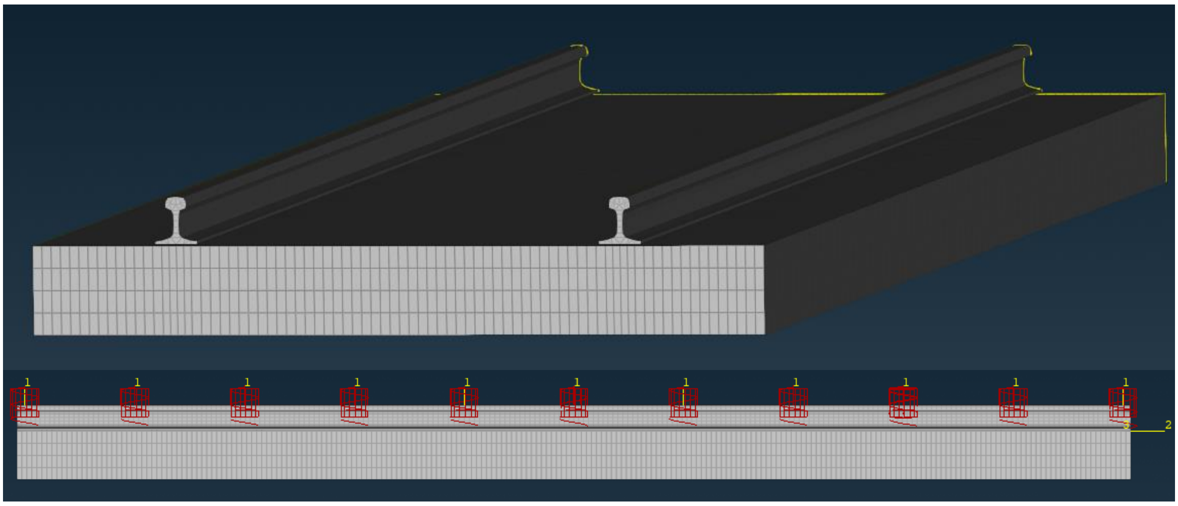


Figure 39 – Final Model Meshing

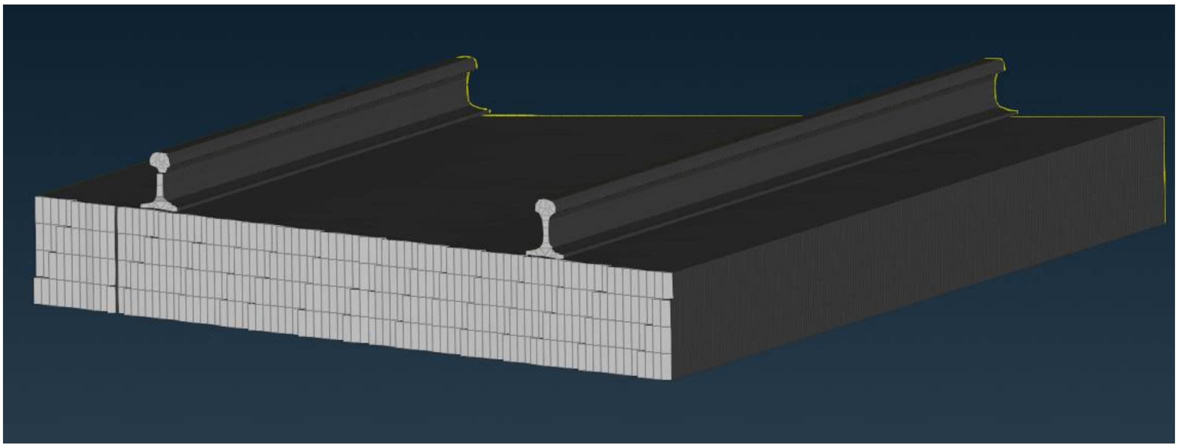


Figure 40 – Final Model Diagonal Cross Section

The first step is the verification of the simulation checking if the retrieved fastener's stiffness is correct considering all the measures. As this simulation is larger, the frequency spacing has been increased to 5 Hz with a range of 5Hz to 200Hz.

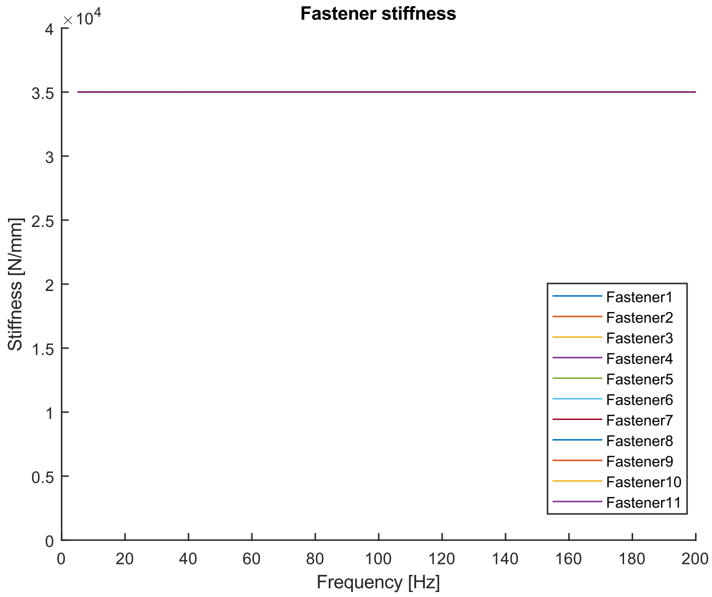


Figure 41 – Final model Fasteners' Stiffness with all measures

Figure 41 verifies the simulation. Thanks to this larger model, the finite model problem can be mitigated, and the in-situ characterization method can be assessed. To do so, the outer fasteners will be gradually disregarded, and the change in the fasteners' stiffness due to this fact will be assessed.

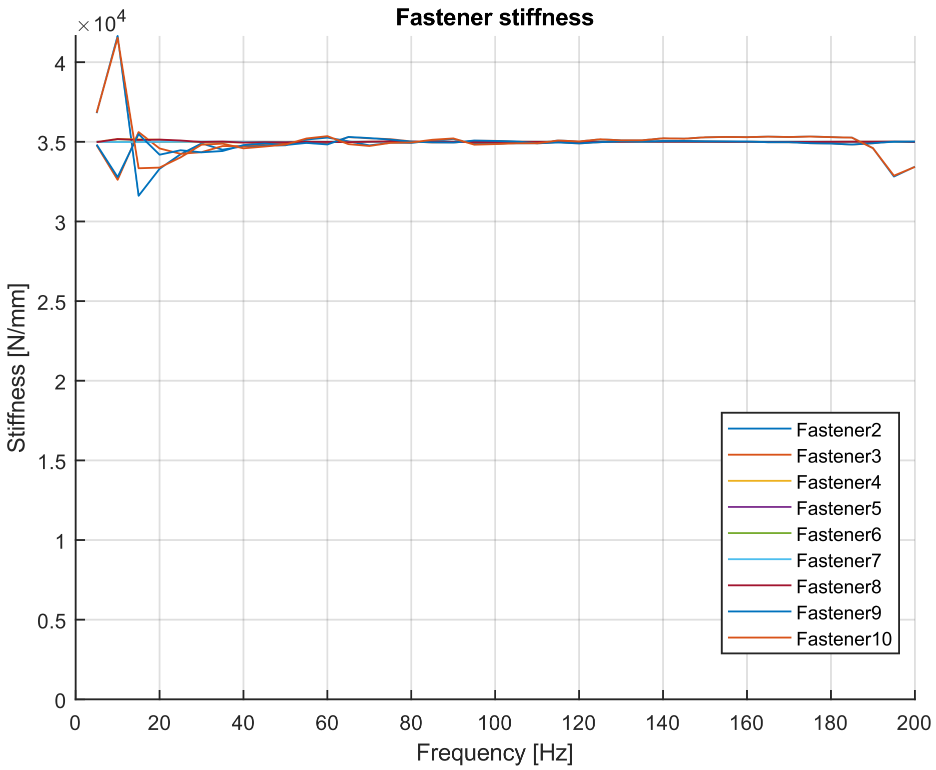


Figure 42 - Final model Fasteners' Stiffness with Fasteners 1-11 disregarded

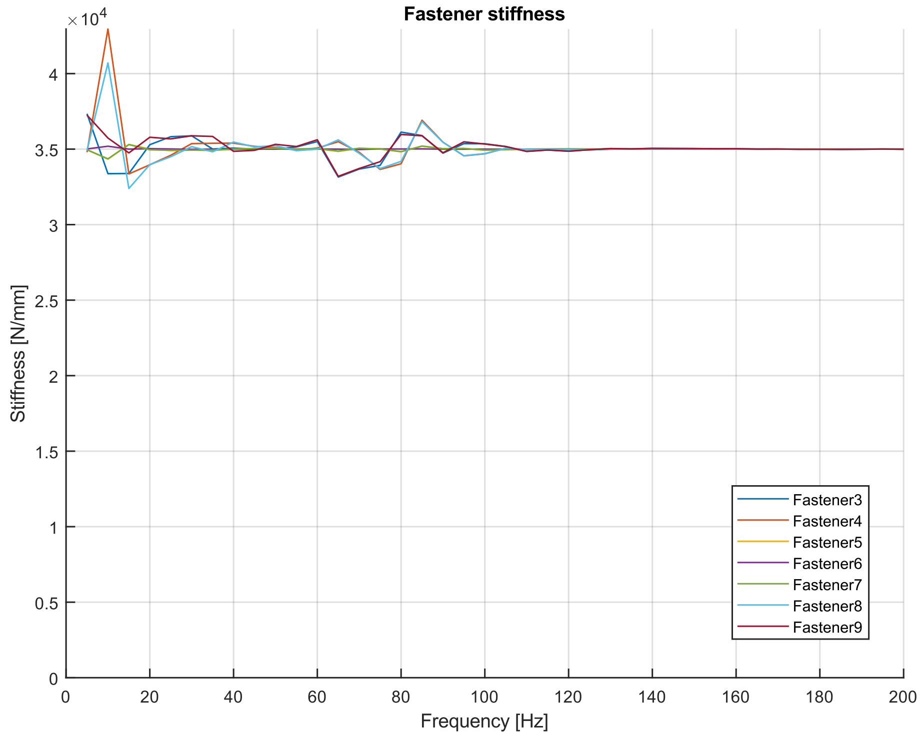


Figure 43 – Simple model Fasteners' Stiffness with Fasteners 1-2-10-11 disregarded

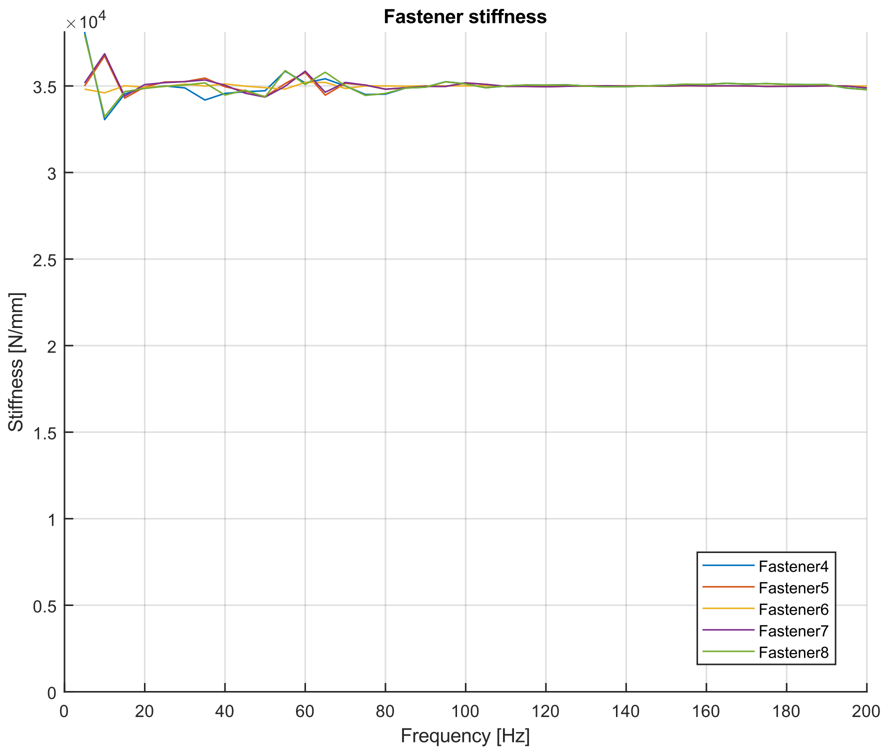


Figure 44 – Simple model Fasteners' Stiffness with Fasteners 1-2-3-9-10-11 disregarded

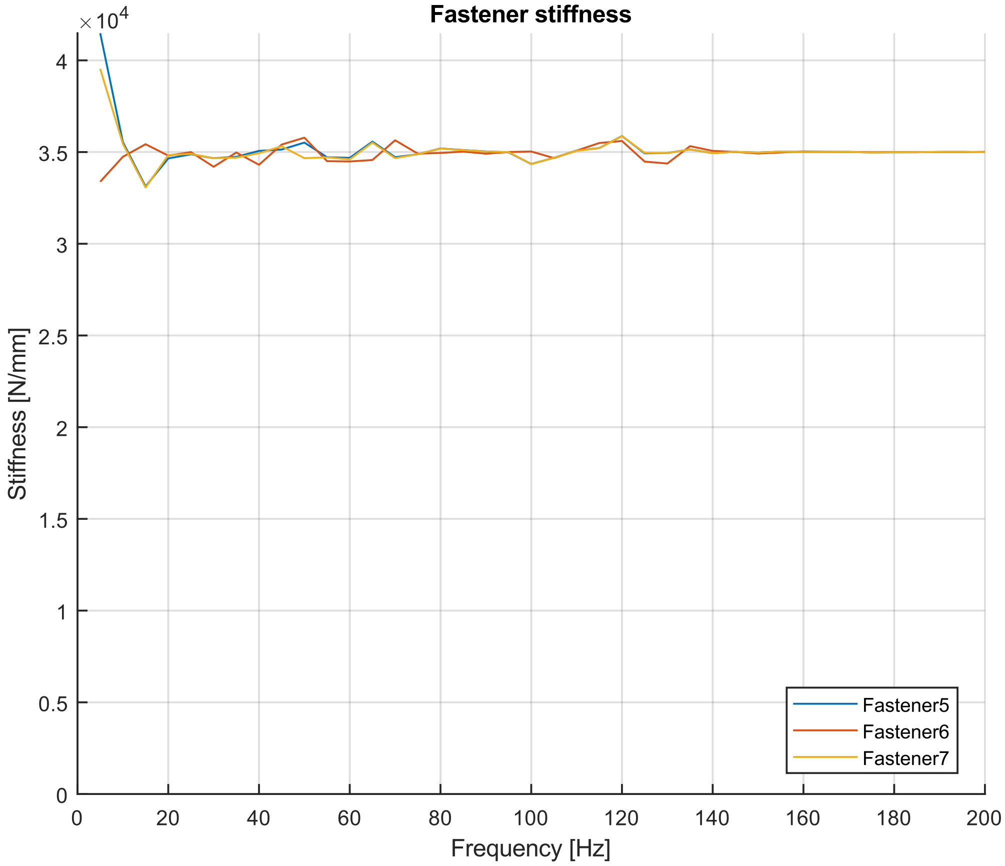


Figure 45 – Simple model Fasteners' Stiffness with Fasteners 1-2-3-4-8-9-10-11 disregarded

The resulting plots are not as smooth as the plots obtained in the previous sections due to the increased frequency spacing. Nevertheless, the results show that even though both fasteners at the endpoints were disregarded, the stiffness could be obtained with a reasonable accuracy even for the 3-fastener configuration. The simulation results are similar to the 3D simulation carried out previously, with a margin error similar. It must be considered that the increased spacing in frequencies does not allow to see the peaks in stiffness that could be seen in the other simulations.

These results show that the in-situ characterization method is viable regarding the numerical models developed. Nevertheless, further work is needed to assess the application of these method in a real environment.

5 Budget summary and/or economic feasibility study

The Budget document has a detailed breakdown of the different costs. The study has considered a cost for an academic research center and a commercial company. The academic research center should expect a cost around 7000€ while the commercial company would have to invest around 21000€.

6 Analysis and assessment of environmental and social implications

The rail fasteners are damaged because they are exposed to elevated number of fatigue cycles, environmental conditions and high stresses. This fact makes these components an element that can be potentially damaged.

As explained in previous sections, faulty fasteners can lead to vibrations and noise which disturb and discomforts the habitants of the area. The current methodology to characterize the mechanical properties of a fastener is lab testing, which makes the train circulation to stop. This produces a decrease in the reliability of the train services and people are inclined to change their mobility options, normally more pollutant as using their own vehicle.

The in-situ method is based on measurements taken on the train track itself, which does not disrupt any kind of train activity. Moreover, there is no transportation phase neither, which avoids the pollution of the car fuel combustion.

7 Conclusions

As a conclusion, the objective of the thesis is partially accomplished.

The simplified model simulation shows that the in-situ method works for 1D elements, being able to retrieve the stiffness of each rail fastener when the receptance matrix is complete. Then, the procedure of disregarding fastener's measures shows that the stiffness of the closest fasteners is heavily affected while, as there are more fasteners between the disregarded and the studied one, the stiffness is less affected. Another important result is that, for low frequencies, the closest fasteners to the one disregarded experience an increase in stiffness, accounting for its loss.

The 3D model simulation shows that the in-situ method works for 3D elements and ideal 1D springs, being also able to retrieve the stiffness matrix if the receptance matrix is complete. The 3D simulation shows that the 1D slab is not an acceptable model while the 1D rail is. The results when the procedure of disregarding fastener's measures is carried out have similarities with the simplified model (the closest fasteners to the disregarded ones are the most affected and their stiffness is boosted at low frequencies) but have a significant difference. The stiffness values when disregarding fastener's measures in the 3D model are much closer to the correct value than the ones corresponding to the simplified model. Furthermore, when high frequencies are reached, retrieved fasteners' stiffness usually tend to the correct value within a margin error.

The final model mitigates the finite model problem. Its results show that the rail fasteners' stiffness can be retrieved with the two surrounding fasteners with a reasonable accuracy. This reinforces the idea of the in-situ characterization method as a viable method. Nevertheless, this simulation is not enough to determine if this is the right number of required measures, as some details of the simulation should be improved.

Therefore, further work must be done in order to obtain the number of required sensors for retrieving the rail fasteners' stiffness. Nonetheless, the thesis has verified the viability of the method and makes a good starting point for future lines of work.

There are two main future lines of work for this study. On one hand the simulations should consider larger models of train tracks in order to have more fasteners. The increment in fasteners adds more combinations when disregarding measures, which can lead to a deeper understanding of how many sensors must be deployed for an accurate stiffness characterization. Additionally, periodical boundary conditions must be added to the model, as the behavior of disregarding the fasteners at the ends were not the same as disregarding the middle ones. Another future line of work for improving the simulation would be the modeling of 3D fasteners and soil in order to have a more realistic and detailed simulation.

On the other hand, the method should be tested experimentally in a location where the rail fasteners' stiffness is already known. Then, the resulting stiffness should be evaluated and compared with the improved simulations. These experimental measures will most certainly have background noise, which will have to be studied and filtered.

8 References

[1] Asociación Española de Normalización y Certificación. (2009). *International Standard - 2009 - UNE-EN ISO 10846-12008.* Madrid: AENOR.

[2] Meggitt, J. W. R., Elliott, A. S., Moorhouse, A. T., & Lai, H. K. (2016). In situ determination of dynamic stiffness for resilient elements. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 230(6), 986–993. https://doi.org/10.1177/0954406215618986

9 Annex

9.1 Matlab Code

```
%% Data extraction from input files
freqStruct=h5read("ensamblaje2.h5","/NASTRAN/INPUT/DYNAMIC/FREQ1");
displacementStruct=h5read("ensamblaje2.h5","/NASTRAN/RESULT/NODAL/DISPLACE-
MENT_CPLX");
subcaseStruct=h5read("ensamblaje2.h5","/NASTRAN/INPUT/PARAMETER/CASECC/SUB-
CASE");
freq=double(freqStruct.F1):double(freqStruct.DF):double(freqStruct.NDF); %Fre-
quency vector is generated
numOfNodes=length(displacementStruct.DOMAIN_ID(displacementStruct.DO-
MAIN_ID==2)); %Number of displacement points being studied
numOfSubcases=length(subcaseStruct.SID); %Number of force cases (i.e. applica-
tion points)

%% Receptance matrix generation
%Matrix initialization
Ax=zeros(numOfNodes,numOfSubcases,length(freq));
Ay=Ax;
Az=Ax;

%Vector containing all the receptance data for all frecuencies and force
%cases
x=displacementStruct.XR+1i*displacementStruct.XI;
y=displacementStruct.YR+1i*displacementStruct.YI;
z=displacementStruct.ZR+1i*displacementStruct.ZI;

%Reorganization of the vector data into the receptance matrix
for j=1:numOfSubcases
    for k=1:length(freq)

        range= (1:numOfNodes)+(k-1)*numOfNodes+(j-1)*length(freq)*numOfNodes;

        Ax(:,j,k)=x(range);
        Ay(:,j,k)=y(range);
        Az(:,j,k)=z(range);

    end
end

%% Stiffness obtention
%Matrix inversion which provides the stiffness matrix
invAx=pageinv(Ax);
invAy=pageinv(Ay);
invAz=pageinv(Az);

%The selected fasteners will be disregarded, which in the code means that
%the row and column of the two points in each end of the fastener must be
%excluded from the matrix.
retrieved_fasteners = [6]; %Select which fasteners must be disregarded
retieved_nodes      = [retrieved_fasteners,retrieved_fasteners + numOfNodes/2];
retieved_nodes      = sort(retieved_nodes,2);
remaining_nodes     = 1:numOfNodes;
for i=retieved_nodes
    remaining_nodes(remaining_nodes==i) = [];
end
```

```
%The inverse is performed with the remaining receptance matrix, once the
%correspondent nodes have been disregarded
pseudo_invAx=pageinv(Ax(remaining_nodes,remaining_nodes,:));
pseudo_invAy=pageinv(Ay(remaining_nodes,remaining_nodes,:));
pseudo_invAz=pageinv(Az(remaining_nodes,remaining_nodes,:));

%Plot of the receptance in two selected points through the frequency range
%spectrum
figure
subplot(2,2,1)
semilogy(freq(2:end),reshape(abs(Ay(1,1,2:end)),1,length(freq)-1)*10^-3)
title("$H_{11}$","Interpreter","latex");
ylabel("Response [m]")
xlabel("Frequency [Hz]")
subplot(2,2,2)
semilogy(freq(2:end),reshape(abs(Ay(10,1,2:end)),1,length(freq)-1)*10^-3)
title("$H_{81}$","Interpreter","latex");
ylabel("Response [m]")
xlabel("Frequency [Hz]")
subplot(2,2,3)
semilogy(freq(2:end),reshape(abs(Ay(1,10,2:end)),1,length(freq)-1)*10^-3)
title("$H_{18}$","Interpreter","latex");
ylabel("Response [m]")
xlabel("Frequency [Hz]")
subplot(2,2,4)
semilogy(freq(2:end),reshape(abs(Ay(10,10,2:end)),1,length(freq)-1)*10^-3)
title("$H_{88}$","Interpreter","latex");
ylabel("Response [m]")
xlabel("Frequency [Hz]")

%% Plotting

%Plot of the stiffness od each rail fastener
figure
hold on
plot(freq(2:end),reshape(abs(invAy(7,1,2:end)),1,length(freq)-1),'k')
plot(freq(2:end),reshape(abs(invAy(8,2,2:end)),1,length(freq)-1),'cyan')
plot(freq(2:end),reshape(abs(invAy(9,3,2:end)),1,length(freq)-1),'g')
plot(freq(2:end),reshape(abs(invAy(10,4,2:end)),1,length(freq)-1),'b')
plot(freq(2:end),reshape(abs(invAy(11,5,2:end)),1,length(freq)-1),'m')
plot(freq(2:end),reshape(abs(invAy(12,6,2:end)),1,length(freq)-1),'red')
title("Fastener stiffness")
ylabel("Stiffness [N/mm]")
xlabel("Frequency [Hz]")
ylim([0,40000])

%Plot of the stifness of the remaining fasteners. The code performs a
%previous operation in order to know the position of each fastener's points
% in the new matrix, as its dimensions have been reduced.
legend_vec = strings(1,length(remaining_nodes)/2);
figure
hold on
for i=1:length(remaining_nodes)/2
    count=0;
    for j=1:length(retrieved_fasteners)
        if remaining_nodes(i)>retrieved_fasteners(j)
            count=count+1;
        end
```

```
    end
    plot(freq(2:end),reshape(abs(pseudo_invAy(remaining_nodes(i)-
count+length(remaining_nodes)/2,remaining_nodes(i)-
count,2:end)),1,length(freq)-1))
    legend_vec(i) = string(strcat('Fastener ',string(remaining_nodes(i))));
end

title("Fastener stiffness")
ylabel("Stiffness [N/mm]")
xlabel("Frequency [Hz]")
legend(legend_vec)
```