Horizontal and Vertical BIM Interoperability Aimed at Seismic Vulnerability Assessment

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Abstract. A vital task of this millennium is to protect the existing heritage, also through the adoption of resilient management systems. In this framework, the organization of knowledge remains one of the critical points. For this reason, new methodologies and cross-disciplinary technologies are increasingly being chosen to optimize resources toward more sustainable interventions. Therefore, the ability to model the building geometry and behavior must be maximized through interoperable processes between Building Information Modeling and Finite Element Modeling methods aimed at the seismic vulnerability assessment. Setting up an integrated digitalization process is undoubtedly challenging initially but returns more significant benefits during the infrastructure life cycle. The interoperability tests' bi-directionality is essential for constantly evaluating activities to update data following facilities' modifications. The Modal Assurance Criterion indicator is used to assess the coherence of the models after possible simplifications introduced for non-linear state analyses.

Keywords: Building Information Modeling, Finite Element Modeling, Interoperability, Seismic Vulnerability, Level Of Knowledge.

1 Introduction

Nowadays, built environment management is increasingly evolving towards systematizing knowledge through integrated systems based on three-dimensional parametric representation. The Building Information Modeling (BIM) methodology aims to create a service model where processes, tools and people can interact in the best way. This approach is increasingly deepened and declined in the Italian and European contexts as the most significant benefits are primarily observed in the operation phase. The reference existing heritage requires considerable care from the point of view of maintenance, monitoring and preservation, even concerning catastrophic natural events such as landslides or earthquakes. Moreover, buildings with historical and artistic value often host strategic functions fundamental to the community, such as public offices, hospitals, schools, and power systems. The interruption or limitation of these buildings' usability can strongly impact the social activities, logistics, and economy. For these reasons, the adoption of streamlined processes for the organization and retrieval of available documentation plays a key role whenever it is necessary to carry out actions on these infrastructures. The Italian NTC 2018 [1] standard and its Circular [2], in line with the Eurocodes, outlined the procedure for assessing structure knowledge. BIM tools are evaluated to standardize and speed up that procedure so that more resources can be invested in evaluating design interventions than returning models. Professionals can set the seismic vulnerability assessment from a digital model conceived as a collector of information updated over time, valuable to return a coherent representation of the state of the art and to map the level of knowledge of the asset in an appropriate and shared way. The testing of integrated BIM-FEM (Finite Element Modeling) processes for modeling, management, and structural analysis establishes a multidisciplinary research field that enriches traditional investigation practices. Currently, lots of research focuses on specific aspects that integrate a particular process moment. A central element is using a physical model in the context of calculation software [3] [4] [5], also starting from laser scanner surveys in the case of interest in accurately rendering construction irregularities [6]. Conversely, the export of analytical models in the BIM environment is evaluated [7]. Within this framework, this study primary aims to check the horizontal and vertical interoperability between Model Authoring and Structural Calculation software to optimize the workflow and guarantee a correct information transfer.

2 Methodology

The study's objective is to define an optimized workflow to manage the knowledge processes and seismic vulnerability assessment of a point-type infrastructure employing a three-dimensional model associated with an information database. This approach effectively addresses the steps defined in the NTC 2018 [1], including historical-critical analysis, geometric-structural survey, mechanical characterization of materials, knowledge levels and confidence factors, actions and structural analysis. Fig. 1 summarizes the procedural workflow.

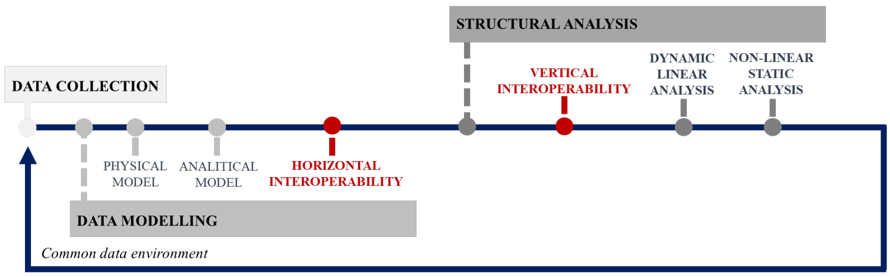


Fig. 1. Seismic vulnerability assessment methodological workflow

Within this framework, the concept of interoperability represents one of the critical issues. For this reason, the transfer of information between Model Authoring and calculation software is tested to identify the most efficient path. The FEM model resulting from this activity is made available for specialized simulations.

The approach is validated by applying it to a real case study [8] [9]: a hydroelectric power plant of the early 1900s in the center of Italy. It is a multi-storey reinforced concrete structure spread over around 2000 square meters of three adjacent parts built at different times. The maximum height is 40 meters.

2.1 Data Collection

A rigorous data collection process is essential to provide a coherent summary of the information contained in the digital models. An expeditious field survey must follow the drawings drawn up during construction time to verify the information. The geometric check of the visible elements constitutes the first step from which to recreate the model according to the actual state. The restitution of the structural component requires a thermographic analysis to identify the elements and diagnostic tests to assess the type of materials used and their mechanical characteristics. In the case under study, the following tests were carried out: pacometric analysis, scarification and removal of reinforcement, analysis and hardness of the reinforcement, sclerometric analysis, concrete sampling and carbonation depth analysis. BIM environment can be exploited both for (i) set up an optimal survey plan depending on the components that can be investigated on-site, (ii) map destructive tests, (iii) gather the data collected during the survey [10].

2.2 Data Modeling

The BIM model must be designed in the most practical and versatile way to be helpful in the building life cycle. For this reason, it is essential to carefully project the model's architecture at an early stage to handle its overall coordination and facilitate the work of individual professionals. It is therefore considered appropriate to set up a federated model (Fig. 2) that combines the various disciplines' contributions with the most appropriate tools for geometric restitution and simulation activities. This integration makes it possible to detect possible inconsistencies and optimize the assessment phase.

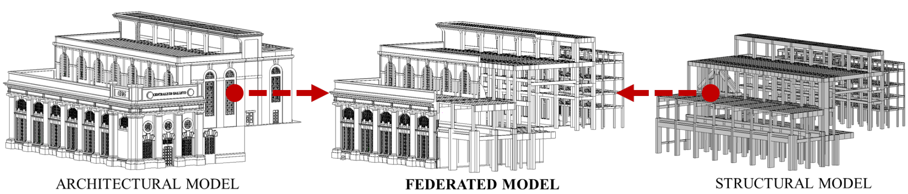


Fig. 2. BIM federated model

Concerning the objectives of the study, Autodesk Revit and Tekla Structures were selected as Model Authoring software, while Midas Structure Midas Gen for Finite Element analysis tool. Autodesk Revit is one of the world's most widely used parametric programs. It is suitable for modeling in different disciplines and integrated with the visual programming application Dynamo, which extends its ability to manipulate data and generate complex geometries. Tekla Structures adopt the truly constructible BIM process making it possible to model any structure with the highest Level of Detail (LOD) regardless of its size or material. Midas Structure Midas Gen has the highest market share in the seismic region. It offers advanced seismic analyses such as pushover analysis, nonlinear time history analysis, nonlinear boundary analysis and fiber analysis, and conventional seismic analysis such as static seismic and response spectrum analysis. The object modeling method and the most appropriate environment to do this are derived from the interoperability texts discussed below.

Through the use of a Model Authoring software, the physical and analytical modeling of the components is accompanied by the automatic setting up of a database of information which, if carefully entered, can accompany the assessments of the building throughout its life cycle. At this stage, it is beneficial to set up schedules and thematic views so that the information in the digital model can be easily accessed, even by those who have not done the modeling. Geometrical information on structural components can therefore be accompanied by information on materials, reinforcement, loads, as well as images or links to external documents or platforms. In general, a LOD 350 [11] has been evaluated for the seismic vulnerability assessment of an existing structure. The introduction of additional parameters associated with objects makes it possible to extend the range of data that can be managed and to provide information on the use of the model. For example, defining the level of knowledge of the asset under study (Fig. 4) is crucial to identifying the most appropriate structural analysis for assessing seismic vulnerability as required by Italian regulations.

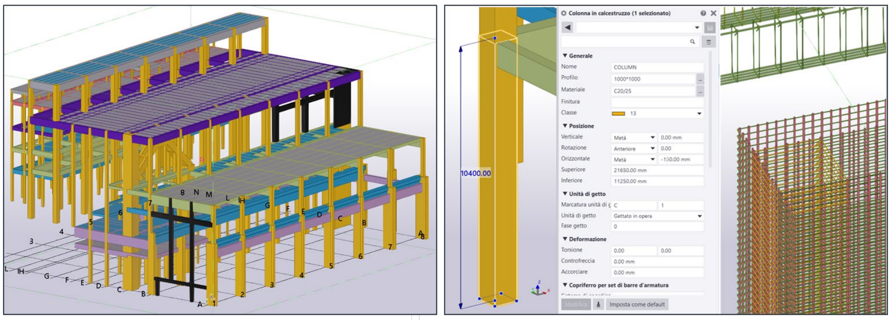
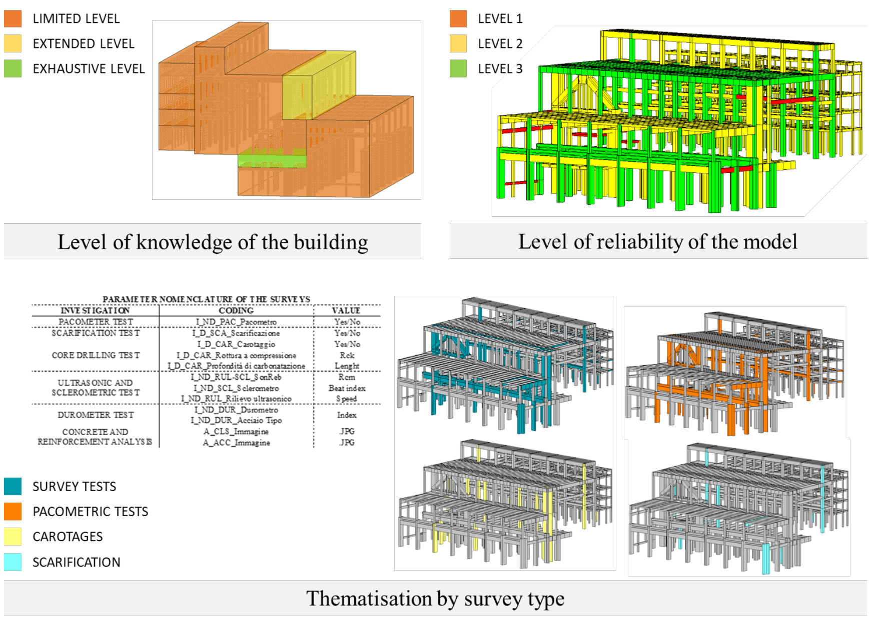


Fig. 3 Tekla structures BIM model



PARAMETER NOMENCLATURE OF THE SURVEYS

INVESTIGATION	CODING	VALUE
PACOMETER TEST	I_ND_PAC_Pacometro	Yes/No
SCARIFICATION TEST	I_D_SCA_Scarificazione	Yes/No
CORE DRILLING TEST	I_D_CAR_Carotaggio	Yes/No
	I_D_CAR_Rottura a compressione	Rck
	I_D_CAR_Profondità di carbonatazione	Lenght
ULTRASONIC AND SCLEROMETRIC TEST	I_ND_RUL-SCL_SonReb	Rcm
	I_ND_SCL_Sclerometro	Beat index
	I_ND_RUL_Rilievo ultrasonico	Speed
DUROMETER TEST	I_ND_DUR_Durometro	Index
	I_ND_DUR_Acciaio Tipo	
CONCRETE AND REINFORCEMENT ANALYSIS	A_CLS_Immagine	.JPG
	A_ACC_Immagine	.JPG

Fig. 4. Accessibility of the information in the Autodesk Revit BIM model

2.3 Interoperability Tests

Interoperability is the principle around which the BIM methodology is hinged, i.e. the possibility of exchanging data without loss of information throughout the building lifecycle. Horizontal interoperability makes it possible to bring together representations obtained through software programs that perform the same functions from different vendors. An example is the integration of different disciplines - architectural, structural and systems - whose three-dimensional modeling can be managed with different software. On the other hand, vertical interoperability concerns complementary tools such as simulation or calculation. Data exchange can occur via open or proprietary formats in both cases. Interoperability tests were carried out to optimize the workflow and to limit as far as possible the loss of data or the transfer of incorrect information, which are difficult to detect when the model is used by different users than those who generated it. The consequences are errors, even significant ones, in the subsequent analysis and evaluation stages. Therefore, this phase aims to identify the most efficient path using different software and exchange formats within an integrated process between disciplines and professionals. As shown in Fig. 5, interoperability is assessed from one Model Authoring software to another (Tekla Structure and Autodesk Revit) and from the Model Authoring software (Tekla Structure and Autodesk Revit) to the Finite Element software (Midas Gen) in a cross- and bi-directional manner.

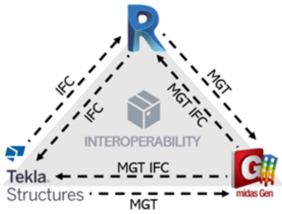


Fig. 5. Interoperability tests carried out.

Table 1. Horizontal interoperability overview tests.

Input model	Output model	Exchange format	Issue
Tekla Structures 2020	Autodesk Revit 2020	IFC2x3 Coordination view 2.0	*Issue* Adequate mapping of IFC classes is required to ensure proper association of objects to Revit categories. *Outcome* All elements were imported in the proper position and with the correct attributes assigned. The only exception is a personalized section.
Autodesk Revit 2020	Tekla Structures 2020	IFC2x3 Coordination view 2.0	*Issue* Adequate mapping of IFC classes is required to ensure proper association of Revit categories to objects. The import of reinforcement is allowed by changing the IFC class from *IFCReinforcingBar* to *IfcBuildingElementProxy*. This makes it possible to recognize the presence of reinforcement within a structural object and its quantity, even if this involves associating the Revit category with a generic IFC object. The imported model must undergo a conversion to transform the objects into native elements of the output software. Verification of material and section recognition settings is required. *Outcome* All elements were exported correctly, except for some critical issues such as: the lack of some customized sections, the rotation of some elements according to their barycentric axis, and some elements incorrectly imported as extrusion solids. The reinforcement is exported but is recognized as *Proxy construction elements* and not as *Reinforcement*. Longitudinal bars are detected by the software as *Beam* elements, with the material set during the mapping process. In contrast, cross bars are correctly assigned to the reinforcement bar templates but lose their material information.

Table 2. Vertical interoperability overview tests.

Input	Output	Exchange	Issue and Outcome
Tekla Structures 2020	Midas GEN 2021	Bidirectional Plug-in (MGT)	*Issue* The plug-in converts all structural model objects into analytical elements in the MGT format. A text file is generated to inform about problems that occurred during the export. Subsequently, the model must be cleaned, i.e. all information not useful for structural analysis must be removed. *Outcome* Section geometries were exported correctly, except for customized sections that retained their mechanical properties. Reinforcement was not exported.
Midas GEN 2021	Tekla Structures 2020	Bidirectional Plug-in (MGT)	*Issue* The plug-in updates the Tekla model in terms of: material, sections, position. Once the file has been imported, Tekla starts converting all analytical elements into native elements. *Outcome* All elements were imported in the proper position and with the correct section geometries and material. Importing via MGT files is not suitable when custom sections are to be exported, as the software cannot find a match with those in its own catalogue. Reinforcement was not exported.
		IFC	*Issue* Imported elements are initially recognized as IFC elements, after a conversion to native Tekla elements is possible. Material and sections can be mapped, so that this conversion can take place correctly. *Outcome* Many elements have not been transferred, although the sections are correctly located, including the customized ones. Overall, the positioning of the elements is correct, with the exception of one section that is rotated with respect to its center of gravity. Reinforcement was not imported.

Autodesk Revit 2020	Midas GEN 2021	Plug-in (MGT)	*Issue* The plug-in generates an MGT format file containing all valuable information for creating the analytical model, identifying materials, sections, the orientation of elements, and coordinates of start and end nodes. A dedicated interface makes it possible to map the elements by controlling the symbologies managed by both software. Once the parameter association has been defined for a section, the plug-in can recognize all similar sections and apply the parameter association. For Midas Gen, the presence of an offset corresponds to the insertion of a rigid link between an element's axis passing through the section's geometric center of gravity and the calculation axis. Whereas Midas Gen offsets are considered element section properties, Revit defines them through constraints or geometric position. Offsets in pillars can only be defined as constraints, considering a change in the start and end node height leaving the analytical axis passing through the center of gravity of the section unchanged. On Midas Gen, this will correspond to a Z-axis translation of the node. As far as beams are concerned, *offsets* can be defined as a constraint or a geometric position. In the first case, constraints are vertical and define how far the element is from the level to which it belongs and the position of the analytical axis to the level. It will result in Midas Gen translating the analytical axis to a different height from the real one, with the consequent division of the columns at the beginning and end of the beam. In the second case, Revit sets by default the analytical axis in the extrados of the beam. This aspect will be recognized as a property of the section. *Outcome* Objects are only transferred if the elements match the predefined Midas Gen sections. Custom sections are therefore not exported. In the case of rectangular sections, the plugin fails to associate the corresponding parameters for the use of capital letters in Midas Gen. All elements are assigned to the correct type, with the exception of *Plate* elements for which a mesh is recreated. It is better to define offsets in the geometric position in Revit to have a clearer view of the beams' positioning and avoid errors. Reinforcement was not exported.

Midas GEN 2021	Autodesk Revit 2020	Plug-in (MGT)	*Issue* It is not possible to export non-standard geometric shapes. Unlike Midas Gen, the Revit software platform is not based on standards for defining the material of elements. Because of this, the material is not assigned correctly. Supporting schedules can be used for the reassignment task. *Outcome* Some elements, such as shear walls and everything connected to them, are not imported. The presence of custom sections creates problems and it is necessary to remove them at the export stage. Furthermore, a visual analysis of the analytical model shows that elements are assigned to parametric families with an inversion of the base and height parameters. The unit of measurement is incorrect.
		IFC	*Issue* Midas Gen does not provide the possibility of selecting and managing the elements to be exported. Therefore, it is not possible to assign IFC classes to analytical objects (as is the case when exporting a Tekla Structures model in IFC format). The IFC map of elements is done directly from Revit. *Outcome* All elements, including custom sections, are transferred and assigned to the correct Revit categories. However, the imported components do not result as parametric families. In addition, there is no center of gravity axis and the associated elevations. All objects are connected at the same level: their position is only defined via the "base offset" parameter. No structural material is maintained. For these reasons, the resulting model is not suitable for the structural discipline, although it can be a reference for the architectural component. For example, if you want to use the analytical model, you have to modify each beam manually and sometimes reshape them. Columns must be replaced with parametric families, such as the default Revit ones or those created by the user, so the exact position of the center of gravity can be defined. Missing information requires a not inconsiderable amount of time.

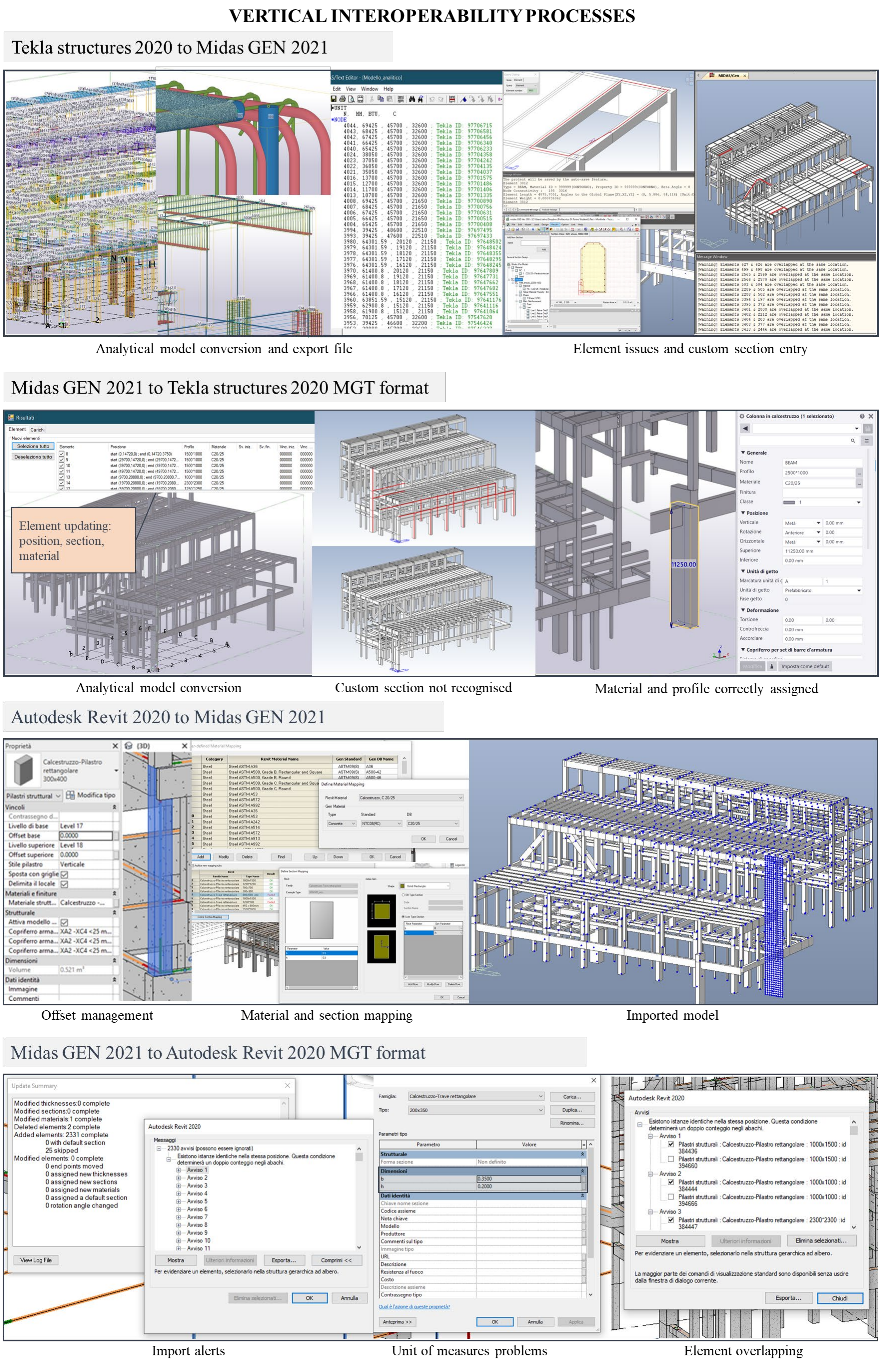


Fig. 6. Vertical interoperability procedures.

The interoperability tests have been evaluated through the formulation of comparison parameters. A score from 0 to 3 is assigned based on the goodness and correctness of the information transferred. Table 3 shows the categories of information considered and the weights assigned according to the effort required for their correction or re-input. Table 4 shows the results obtained for the interoperability processes considered. In general, it can be noted that the horizontal interoperability flow via open IFC format scored best. However, the same consideration does not apply in the case of vertical interoperability, i.e. in the case of the connection between BIM-FEM models. Although a substantial research line is oriented towards the correct mapping of fields according to the open Industry Foundation Classes (IFC) data model, the exchange process between different applications is not yet regulated by a perfectly codified workflow. Dedicated plug-ins made on the basis of proprietary formats, e.g. MGT, ensure a sufficient level of interoperability. A very critical aspect lies in the management of reinforcement. These, which are essential for structural analyses, are not maintained in the exchange processes between the different software. Only in the case of horizontal interoperability between Tekla Structure and Autodesk Revit have desirable results been achieved. This undoubtedly entails a considerable amount of data re-entry work, even if supported by the models produced.

Table 3. Comparison parameters for interoperability score evaluation

Comparison parameters	**Weight [%]**
Material	10
Elements	20
Reinforcement	15
Generic section	12
Customized section	20
Position	15
Unit of measures	8

Table 4. Interoperability tests score.

Comparison parameters	IFC				MGT			
	Tekla Structures → R	Tekla Structures ← R	Tekla Structures ← midas Gen	R ← midas Gen	Tekla Structures → midas Gen	R → midas Gen	Tekla Structures ← midas Gen	R ← midas Gen
Material	3	3	3	0	3	2.5	3	1
Elements	3	2.5	2	3	2.5	3	2.5	2.5
Reinforcement	3	1	0	0	0	0	0	0
Generic section	2.5	3	3	2	3	2.5	3	2
Customized section	2.5	2.5	3	3	1.5	0	0	0
Position	3	3	2.5	3	2	3	3	3
Unit of measures	3	3	3	3	3	3	3	0
Score	**2.8**	**2.5**	**2.3**	**2.1**	**2.0**	**1.8**	**1.9**	**1.3**

2.4 Structural Analysis

FEM modeling

The structural analysis is performed by preparing a suitable structural model from the results of BIM-FEM interoperability. Based on the performed interoperability tests, the Midas Gen - Tekla structures software association has been chosen. The starting analytical model from Tekla Structures 2020 was then imported into the Midas GEN 21 structural analysis software (Fig. 7).

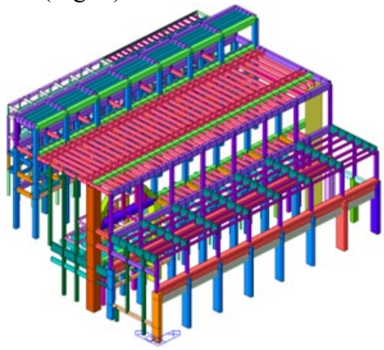


Fig. 7. Imported Tekla structures model in Midas GEN for structural analysis

The pushover analysis conducted on the refined model is definitely complex due to the amount of details that affect the analysis result and significantly increase the computational burden. Therefore, it has been decided to reasonably simplify and replace the custom sections with equivalent elements (Fig. 8). Then, by merging the three separated buildings into a single structural body by removing the rigid links that had been previously inserted (Fig. 8). To further reduce the computational burden, additional information inherent to secondary elements that were not useful for structural analysis has been removed (Fig.8). These simplifications have been introduced one by one, verifying the equivalence of the results in terms of static and dynamic response between the model before and after the specific simplification adopted.

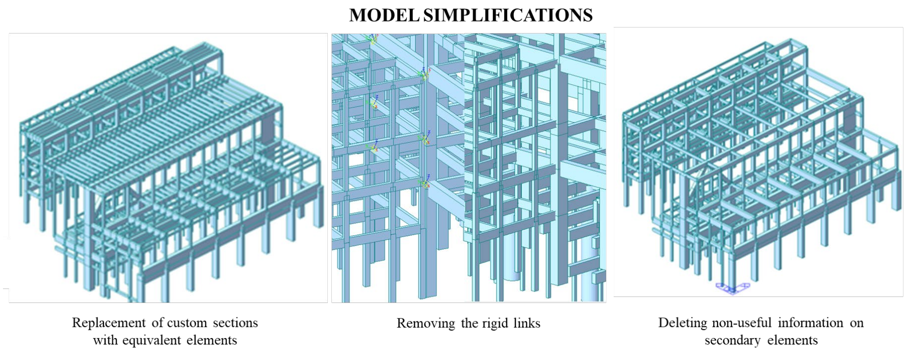


Fig. 8. Model simplifications for structural analysis

A linear dynamic analysis has been performed by evaluating the consistency in modal shapes and eigenfrequencies, employing the Modal Assurance Criterion (MAC) [12] to compare the dynamic range. Modal analysis associated with the design spectrum (linear dynamic analysis) has also been carried out, considering a sufficient number of vibration modes for 85% of the participating mass to be reached in each direction. The natural modes obtained for the analytical model have been compared in Table 5. A reasonable coherency of the mode shapes between the two models is highlighted. Then the MAC was used for a quantitative assessment of the equivalence.

Table 5. Comparison between refined model and simplified model

N° MODE	FREQUENCIES [rad/sec]		PERIOD [s]	
	MR	MS	MR	MS
1	6.185	6.421	1.02	0.98
2	6.858	7.078	0.92	0.89
3	8.358	8.726	0.75	0.72
4	15.157	14.837	0.41	0.42
5	18.552	19.397	0.34	0.32
6	19.846	20.815	0.32	0.30
7	21.150	21.216	0.30	0.30
8	21.764	21.723	0.29	0.29
9	22.047	22.331	0.29	0.28
10	22.736	23.041	0.28	0.27

The MAC allows to evaluate the correlation between two vectors of real or complex elements. For the present study, the MAC is applied to two eigenvectors, $\{\varphi_r\}$ and $\{\varphi_s\}$, representing the mode shapes associated with two different FEM models with different levels of refinement. In particular, the eigenvectors associated with the MR and MS models have been compared in their respective vibration modes and directions. MAC is evaluated as:

$$MAC(r,s) = \frac{|\{\varphi_r\}^T \cdot \{\varphi_s\}|^2}{(\{\varphi_r\}^T \cdot \{\varphi_r\})(\{\varphi_s\}^T \cdot \{\varphi_s\})}$$

Where {φr} is the eigenvector representing the mode shape of the considered vibration mode, for the refined model MR; {φs} is the associated eigenvector for the simplified model MS. The computational process has been implemented in Matlab.

Since the MAC values returned for the pairs of eigenvectors of interest are always higher than 0.8 and higher than 0.9 for the first modes, the two models can be considered reasonable equivalent, which implies that the results performed on the simplified model do not differ essentially from the detailed one. Thus, the simplified FEM model is adopted for seismic capacity verifications.

Seismic vulnerability assessment

The Pushover analysis is used for the vulnerability assessment of the building to compute the performance point. It is done by exploiting the capacity curve (Fig. 9). It is bilinearized according to the procedures defined in the NTC-2018 as method A - also known as method N2, based on the identification of the inelastic demand through the equal displacements or equal energy rule, and method B - also known as method CSM, based on the construction of a capacity spectrum.

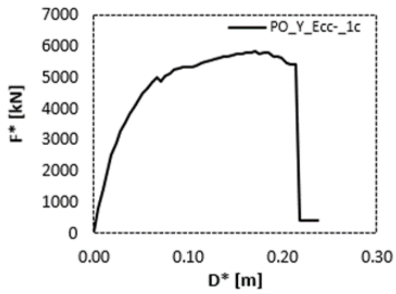


Fig. 9. Capacity curve

Bilinearization results in transformation of the capacity curve into an equivalent elasto-plastic system, where the performance point of the structure is determined. The Italian regulations do not give guidance on what values to use for evaluating the seismic vulnerability index (ζ_E). For this reason, it has been evaluated through three formulations in terms of: (i) base shear; (ii) displacements; (iii) PGA.

(i) Base shear. The first formulation is based on the N2 and CSM methods provided by the NTCs, bilinearizing the capacity curve and identifying performance point to evaluate the demand, i.e., the maximum base shear. While the capacity is the maximum force, i.e., the collapse shear force (Fig. 11). The results vulnerability indices for the N2 and CSM methods are $\zeta_E = 1{,}07$ and $\zeta_E = 1{,}11$, respectively.

$$\zeta_E = \frac{F^*_{COLL}}{F^*_{MAX}} \qquad (i)$$

(ii) Displacements. The second formulation is based on N2 and CSM methods again but considers the maximum displacement demand, while the capacity is the displacement at the collapse state (Fig. 11). The computed results are the following ones: $\zeta_E = 1{,}78$ and $\zeta_E = 1{,}54$, respectively.

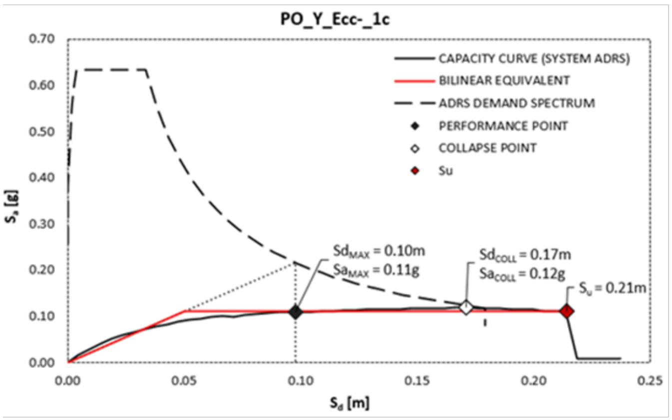
$$\zeta_E = \frac{S^*_{COLL}}{S^*_{MAX}} \qquad (ii)$$

(iii) PGA. In this case the demand is evaluated as the PGA at the reference site, while the capacity is that one obtained by a scaling procedure so as the elastic displacement at the reference period of the structure coincides with the ultimate displacement evaluated on the bilinearized curve by the N2 method (Fig.10). The results show $\zeta_E = 1{,}78$.

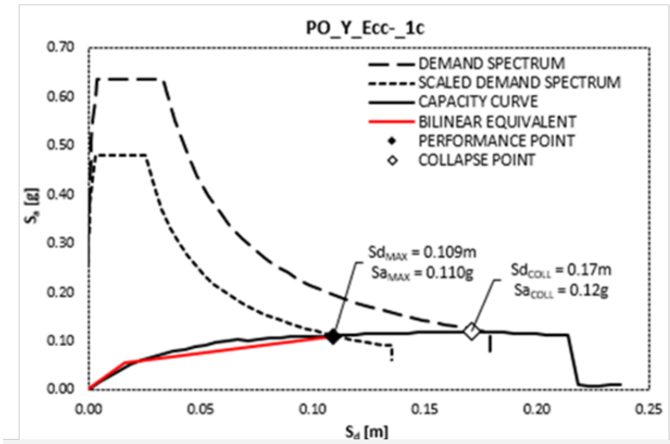
$$\zeta_E = \frac{PGA_{CAP}}{PGA_{SITE}} \qquad (iii)$$

An alternative to the (iii) formulation considers the vulnerability index as the ratio of the maximum force of the bilinearized capacity curve, divided by the mass of the equivalent single degree of freedom system, and the design PGA at the site, i.e., the spectrum value at the null period.

N2 method



CSM method



PGA formulation of the vulnerability index

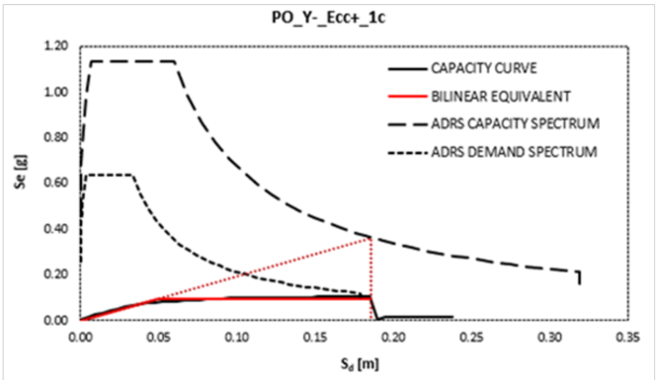


Fig. 10. Evaluation of the seismic vulnerability index methods

Results analysis

The resulting capacity curves allow to investigate the structural behavior through different aspects, evaluating demand and capacity. First and foremost is the ratio of the collapse base shear to the maximum shear demand, which indicates the structure's strength. Another aspect is related to the results in displacements, which indicates the structure's capacity to absorb the seismic demand in terms of ductility. Indeed, very high values of the displacement ratio indicate a high dissipative capacity.

These NTC-2018 seismic vulnerability indices are based on finding a performance point on the capacity curve of the structure to be compared with the capacity of the system represented. In the case study, by the collapse base shear, as well as the highest value from the capacity curve. However, such approaches (i and ii) do not allow obtaining values of ζ_E less than 1. The only exception is the limit case, and the dangerous one, because not verified, with very high seismic demand and thus the absence of the performance point. The described approaches have been compared with an incremental dynamic analysis [13] performed on an example FEM model (Fig. 11) to give validity to the last consideration.

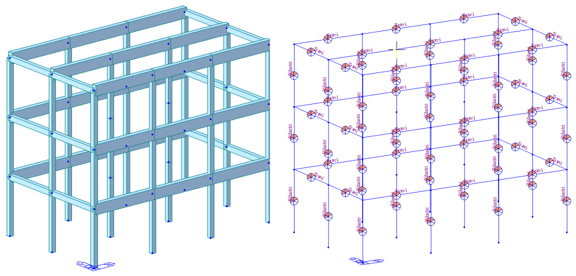


Fig. 11 Example model

The different scenarios in terms of ζ_E as a function of the seismic hazard at three different sites have been considered (CO, ME, SR). Accelerograms compatible with the spectra at the sites have been selected (Fig. 12).

According to the literature [14], the maximum inter-story drift has been chosen to evaluate the system capacity and vulnerability index evaluated by exploiting the formulation of method one from [15].

$$\zeta_E = \frac{PGA_{CAP}}{PGA_{SITE}}$$

where the PGA_{SITE} is the seismic demand at the reference site, while PGA_{CAP} is the capacity PGA, that one that scales the compatible spectrum accelerograms until the predetermined inter-story displacement is reached (Fig. 13).

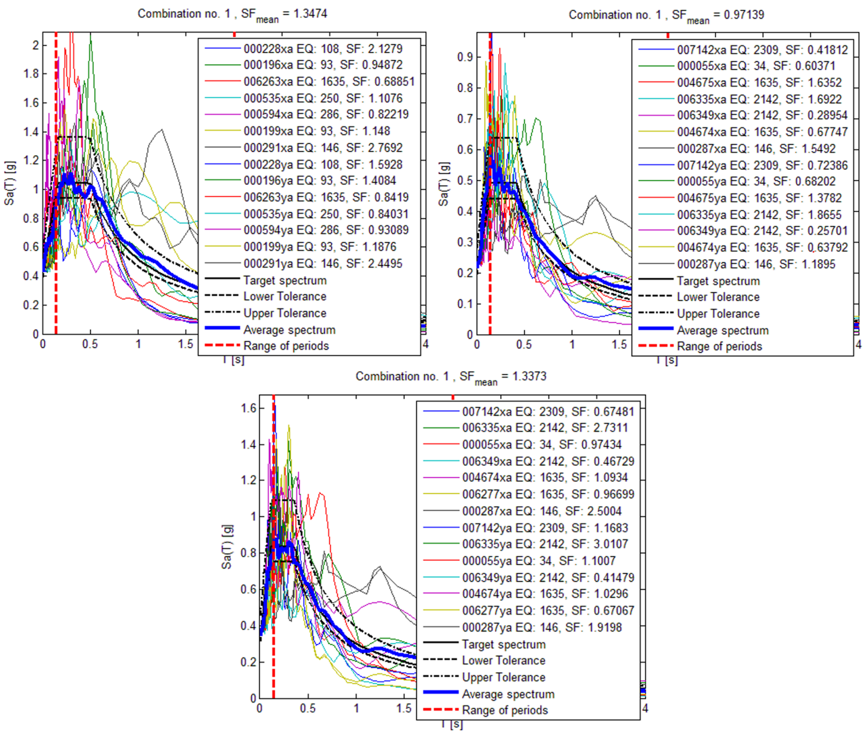


Fig. 12. Spectrum compatible accelerograms (CO, ME, SR)

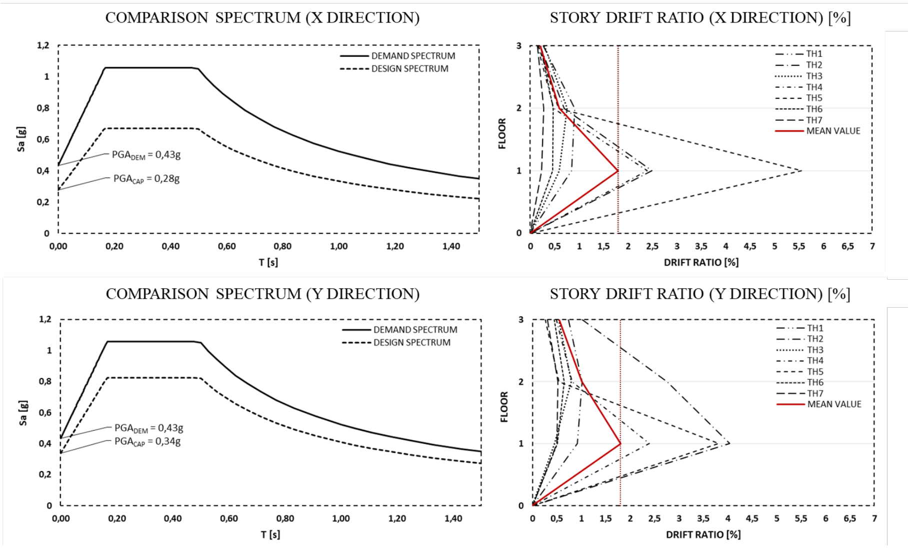


Fig. 13. Demand spectrum scaling until the target inter-floor shift is reached

Table 5. Comparison of results: Pushover indices in terms of forces

Collapse Analysis		Case ζ_E<1 (CO)	Case $\zeta_E \simeq 1$ (ME)	Case ζ_E >1 (SR)
		ζ_E	ζ_E	ζ_E
Incremental Dynamic Analysis		0.60	0.99	1.98
Pushover	N2 (force)	(*)	1.02	1.02
	CSM (force)	(*)	1.00	1.00
	PGA	0.96	1.09	1.69

Table 6. Comparison of results: Pushover indices in terms of displacements

Collapse Analysis		Case ζ_E<1 (CO)	Case $\zeta_E \simeq 1$ (ME)	Case ζ_E >1 (SR)
		ζ_E	ζ_E	ζ_E
Incremental Dynamic Analysis		0.60	0.99	1.98
Pushover	N2 (spost.)	(*)	1.08	1.69
	CSM (spost.)	(*)	1.13	2.30
	PGA	0.96	1.09	1.69

Tables 5 and 6 show the comparison of vulnerability indices between the incremental dynamic analysis (IDA, nonlinear analysis, the most accurate) and those computed through the Pushover analysis in terms of forces and displacements, respectively. It is worth noticing that when the vulnerability index computed through IDA is less than the unity, the performance point in the Pushover analysis can not be identified (*) with both N2 and CSM. This is because the performance point would be beyond the collapse where there is no longer a capacity curve. It highlights how the simplified and straightforward approaches based on the Pushover analysis are not able to provide sub-unit values (contemplated by NTC-2018). Therefore, the nonlinear dynamic analysis would have to be used to accurately assess ζ_E.

3 Conclusion

For existing and historical heritage, retrieving critical information to carry out seismic safety assessments is usually very time-consuming. The study proposes the setting up of a BIM digitalization process to organize a dynamic archive of information that can be updated over time. Therefore, the digital model's realization must be optimized given not only a specific intervention but also considering the possible survey, simulation, management and maintenance activities that may occur during the building's life cycle. In order to ensure an optimal workflow, much attention must be paid to interoperable processes between professionals, disciplines and software. In this study, interoperability tests were carried out to create a structural database and perform structural analyses. It is essential to set up a working environment, realized in this framework through a federated model, in which individual professionals can access the knowledge in the most appropriate format for specific purposes.

A case study has been analyzed to test the proposed approach in terms of horizontal modeling (using different software but consistent in the type of application) and vertical modeling (using different software by switching from BIM modeling to structural FEM modeling).

The process of analyzing complex structures also requires a high computational burden. In this regard, simplifications to be introduced into the analytical model were evaluated by verifying congruence with a reference model through an accurate sensitivity analysis, comparing the modal forms obtained from a linear dynamic analysis for the reference model with those obtained for the simplified model through the Modal Assurance Criterion. The linear dynamic analysis made it possible to understand whether modeling errors were present, compare the capacity and demand for each structural element of the building following current regulations, and identify the force distribution required for the subsequent non-linear static analysis. Based on the work rates obtained, it was possible to design local interventions to solve the seismic problem. The seismic vulnerability coefficient of the case study was calculated using a simplified method (non-linear static analysis, Pushover). This computational methodology has finally been evaluated against a more accurate methodology type, "incremental dynamic analysis", on a simple model adopted as an example and placed in different sites on the Italian territory, characterized by different seismic hazard levels. It can be observed that the adopted methods based on Pushover analysis can only give a preliminary assessment of the seismic vulnerability index. It is left to the non-linear dynamic analysis to more accurately assess the seismic vulnerability index through the relationship between the demand and capacity PGAs. It should be pointed out that this is a preliminary study to be repeated on structures characterized by different structural schemes.

The study, therefore, aims to evaluate a complete process from the data collection phase on a structure to seismic vulnerability assessment. In this framework, the horizontal and vertical interoperability analysis is intended as an iterative process where modeling must be optimized to maximize the information transfer. Furthermore, any inadequacies observed in seismic vulnerability would be resolved by repeating the process and introducing the necessary interventions and modifications to the existing structure by taking advantage of the support of this procedure.

Authors contribution

Abstract: all authors; Introduction: A.O; Methodology: F.M.U, M.D.; Data Collection: F.M.U, S.T; Data Modeling: F.M.U, S.M; Interoperability Tests: F.M.U, S.T, S.M., Structural Analysis: M.D, S.T, S.M., Conclusion: F.M.U, M.D.

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