BIM-Based seismic analysis of existing reinforced concrete buildings

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Abstract

The work reported paper aimed to develop a BIM-based framework to facilitate the process of seismic analysis of existing reinforced concrete buildings, through a streamlined set of modelling rules and interoperability between Autodesk Revit (BIM platform) and SeismoStruct (seismic analysis software). This is achieved through a visual programming script developed in Dynamo. The developed script can export geometry, sections, material properties, supports as well as reinforcement data for structural columns and beams. Furthermore, an important contribution of the framework was the consideration of infill walls which are normally ignored in the usual practices of design offices during the seismic assessment of existing buildings. The interoperability script can query the necessary information from the BIM model and export it to an XML (Extensible Mark-up Language) that can be directly recognized by the seismic analysis software. The operational capacity of the framework was assessed on an example of a regular building. The seismic capacity of the building was then evaluated using pushover analysis in SeismoStruct, with an evaluation of the beneficial effects of consideration of infill walls, thus allowing more realistic assessments. Moreover, a method to input reinforcement data based on non-graphical data was proposed, facilitating the quickness of the input of information to the BIM model and hence to the seismic analysis software.

1. Introduction

Even though BIM processes and implementation are still mainly focused on new constructions [1, 2], there is a strong trend for application in the context of existing buildings, which cannot yet be claimed to be generalized at all. One of such relatively unexplored fields is the seismic assessment, inherent to renovation (and eventually retrofitting) projects [3, 4]. In order to be effective in this particular context, BIM processes need to overcome several challenges including compilation and correct interpretation of existing documentation, inspection monitoring data, identification of critical data required for retrofitting, uncertainty handling and efforts required to develop the BIM model of the existing structure [5]. Despite its acknowledged importance, there is very limited literature on BIM-based seismic risk assessment of existing buildings. Works found in the literature regarding this subject are mostly focused on matters related to 'Level of detail' [6] BIM implementation in existing buildings [7], cost optimization of seismic retrofit strategies [8], collaboration in BIM networks [9] and application of a federated model for seismic analysis [10]. No work was found to focus on the establishment of specific workflows including adequate data management and interoperability among BIM tools and seismic analysis software, towards a streamlined seismic assessment as a 'BIM use'. The seismic assessment of existing buildings is often needed because of change in use, rehabilitation, constructions works or due to continuity of occupancy after a moderate to severe earthquake. There are many software being used for structural and seismic analysis of structures, but most of these software were developed prior to the advent of widespread application of BIM methodology and the majority still have a limited capacity of BIM-oriented interoperability at several levels [11]. The case of seismic vulnerability assessment of existing buildings is one of the fields in structural engineering for which an integrated framework has not yet been set involving, modelling rules and interoperability with seismic analysis software, in a way considered readily available for the context of a structural design office. Opportunities such as explicit consideration of infill walls in seismic assessment rise, potentially allowing more realistic seismic assessments to be made and eventually avoid unnecessary retrofitting.

The main objective of this research is to fill the gap identified above, within the context of RC buildings, through the development of a BIM-based framework to directly export relevant BIM model data from the model authoring platform to seismic analysis software allowing a quick and effective seismic analysis. To achieve the goal, this research study has established modelling rules for geometrical and non-geometrical data, so the relevant information for seismic assessment can be input into the BIM model with minimal effort. Furthermore, it also explicitly includes infill walls in both the modelling strategy and interoperability with seismic analysis software, offering an opportunity of consideration of these non-structural elements, which are often ignored in seismic assessment.

2. Proposal of a framework for BIM-based seismic analysis

The proposed framework was defined based on a set of performance requirements:

- To fully export necessary data from the BIM platform to seismic analysis software including geometry of columns, beams, infill walls, material properties and supports.
- To limit the operation of the structural engineer on the seismic analysis software to the verification of input data, to provide basic details and perform critical analysis.
- The modelling rules/definitions for the framework/script to operate should not have any kind of conflict with the other BIM uses intended from the structural BIM model.
- A set of assumptions was defined, which can assist in understanding the reasoning behind several of the choices and simplifications are taken throughout the development of the framework:
- The framework is devised to be applicable in existing buildings, but there are no actual limitations on applying it to new construction.
- Slabs are considered as rigid diaphragms and there is no need to model slab in Revit if the purpose of the modelling is just to perform the seismic assessment.
- Reinforcement is not explicitly modelled in the structural elements but rather placed as non-graphic information in each relevant element on the BIM modelling platform.

2.1. Proposed workflow

In this research, it is attempted to assess the seismic performance of an existing building by using a BIM-based framework. Autodesk Revit 2020 and SeismoStruct [12] were used for the development of the BIM model and seismic assessment of the existing structure respectively. The explanation of the workflow of the framework is based on the diagram of Figure 1, which contain labels for each activity/part, from 1A to 7A. First, based on the availability of all the necessary data for the job (Figure 1-1A), the building is modelled in the selected BIM authoring platform (Revit – Figure 1-2A), following the modelling guidelines stated in section 2.2. Because SismoStruct is not able to import IFC data, specific developments were needed for the interoperability of data. This was achieved through the implementation of a Dynamo script, which can be run by the user in the GUI of Revit, according to step 3A of Figure 1 (using Dynamo player). After the script is successfully executed, a text XML file will have been generated, in an apt state to be directly inputted into SeismoStruct, and then to perform a non-linear static analysis to evaluate structural response for earthquake loading conditions (stage 6A of Figure 1). By analysing the post-processing results including the base shear-displacement relationship, drift ratios, and development of plastic hinges etc. for different loading conditions, the results will be interpreted.

2.2. Modelling requirements

The script was developed for direct use of the geometry/elements of the BIM model, while not operating at the level of the 'analytical model'. For the modelling of structure in Revit, the following guidelines need to be followed to successfully use the framework for exporting the structural model to SeismoStruct using the Dynamo Script.

- The model needs to have two structural categories i.e., columns and beams. To study the effect of infill walls on seismic capacity, the 'wall' category can also be included.
- For the modelling of columns and beams, first, the columns are modelled to the required level and then beams are modelled up to the columns.
- The material properties and dimensions which include concrete cover, depth and width of both beams and columns, as well as strength and cover, need to be provided as type-parameter for the relevant objects (shown in Figure 4, for example).
- The reinforcement information needs to be attached to structural elements as a type-parameter in the format shown in Figure 2. For shear reinforcement, the number of shear legs are considered in each direction and is marked as stirrup-width and stirrup-height. For column reinforcement where lower and upper bars do not exist, the concept can be understood in reference to the global X and Y axis which can be drawn at the centre of the column. If the reinforcement is above the Global X-axis, it will be considered as an upper bar and vice versa. The type-parameters which need to be provided in the case of defining the infill walls are shown in Figure 2 as well.

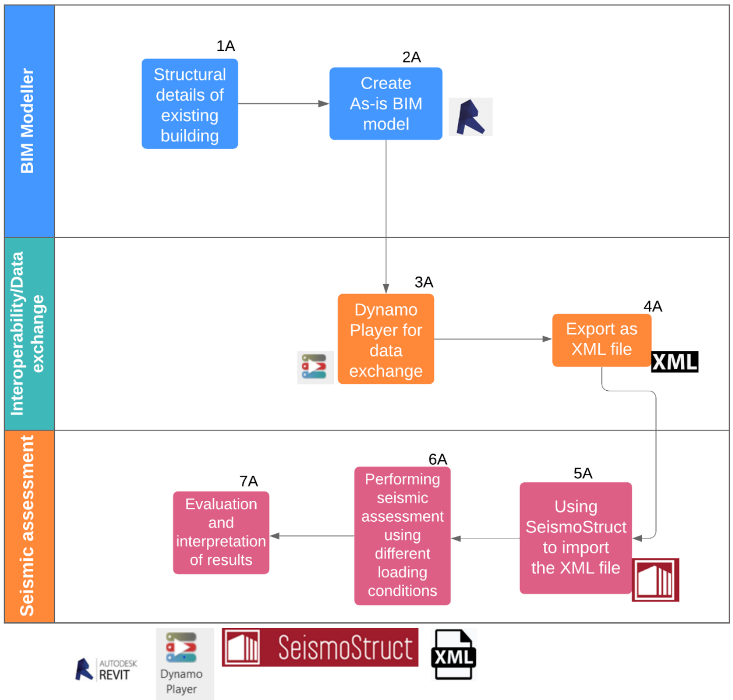
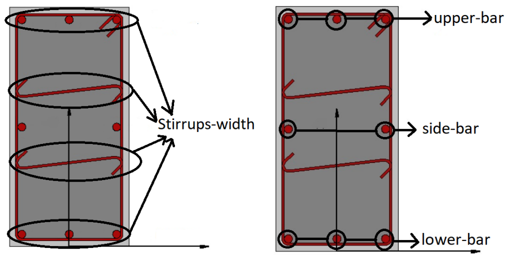


Figure 1
Workflow for the proposed methodology.

Structural
lower-bar
lower-bar-dia
upper-bar
upper-bar-dia
side-bar
side-bar-dia
stirrup-width
stirrup-height
stirrup-dia
stirrup-spacing



Structural
wall-thickness
compressive-strength
specific-weight
tensile-strength
young-modulus
shear-bond-strength
max-shear-resistance

Figure 2
Reinforcement information for columns and beams (left) Explanation of nomenclature used for the reinforcement data (middle) Infill wall parameters (right).

Additionally, it is noted that the units used for cover, depth and width of beams/ columns are taken in meters, while strength should be provided in kPa. Both longitudinal and transverse reinforcement should be provided in millimetres (mm), while its spacing is provided in meters.

Furthermore, for the script to detect and export the foundation of the columns as fixed support in SeismoStruct, an isolated footing needs to be provided to all columns in Revit.

2.3. Interoperability format for data – XML

The structure of XML format as well as the number of sections that are contained in the XML file which is exported by using the developed script is shown in Figure 3. The XML format starts with the program which is common data for any type of seismic analysis using SeismoStruct. The next is the Project Data which contains information regarding the type of seismic analysis, the number of nodes and number of elements etc. The project data is followed by the units used in the project and then all the materials are defined. The developed script assumes to take the SI units for the measurements of the above quantities. After that, sections are defined for all structural elements which include the materials assigned to these members, section dimensions, as well as the reinforcement information and its pattern, is presented. The sections are followed by element classes which explained the type of plastic hinges applied to the structural elements is defined. Nodes are defined following sections and elements classes, which provide the coordinates of all column ends and are connected further in the project elements where element classes are assigned to them.

```
<?xml version="1.0" encoding="utf-8"?>
<file>
  <Program>
    <Program_ID>/&amp;SeismoStruct file&amp;/</Program_ID>
    <Version>2020</Version>
    <Release>2</Release>
    <Build>50</Build>
    <VerifyProgramID>/&amp;SeismoStruct file&amp;/</VerifyProgramID>
    <Version_No>91</Version_No>
  </Program>
```

```
<file>
  <Program>
  <Project Data>
<Units>
<Materials>
  <Sections>
  <Element Classes>
<Nodes>
  <Project Elements>
</file>
```

Figure 3
XML program data (left), overview of the exported XML (right).

2.4. Dynamo script

To export the BIM model to the SeismoStruct, a framework was built-up in Dynamo to develop interoperability between Revit and SeismoStruct. This framework will export the geometry, material properties, reinforcement data and foundation details for all the elements defined in Autodesk Revit. Due to the complexity and large size, it is not possible to show the whole script and therefore the detailed script can be seen in the dissertation from which this article was originated [13]. The structure of the Dynamo script is broken down into the following parts:

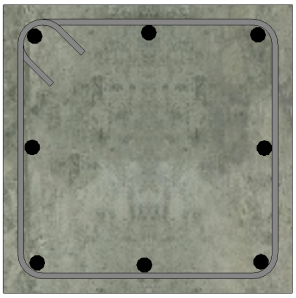
1. Defining input category for structural members and non-structural infill walls
2. Retrieval of input category and type name
3. Extraction of metadata of structural members
4. Extraction of node coordinates from the Revit Model
5. Defining sections and element classes
6. Defining project elements
7. Integration of the whole framework.
8. Defining a file path for exporting to XML file.

3. Pilot application and demonstration of feasibility

The developed script has been tested on an example building to check and understand its feasibility and to further perform the seismic assessment in SeismoStruct. The building considered is located in Lisbon. The building is made up of a reinforced concrete frame having a rectangular shape in-plane configuration. The structure consists of 4 storeys having each storey height is 2.8 m except the first floor, which is 3.3 m (see Figure 5). The geometrical and mechanical properties which include thickness, Compressive, and tensile strength, Young's modulus, shear bond strength, specific weight and maximum shear resistance were attached as Type parameters to the infill walls.

3.1. Modelling and execution of script/calculations

Autodesk Revit 2020 has been used to model the case study building according to the modelling requirements mentioned in section 2.2. The structure is a four-storey office building having 5 bays in one direction and 3 bays in another direction. The material properties, sizes of members, concrete cover as well as reinforcement information are attached to the respective structural member as non-graphical information. For information purposes, a section of the column, as well as the information attached to this column are shown in Figure 4.



Dimensions	
Cover	0.0150 m
Depth	0.3000 m
Offset Base	0.0000 m
Offset Top	0.0000 m
Width	0.3000 m
Identity Data	
Concrete-strength	22000
yield-strength	440000

Structural	
lower-bar	3
lower-bar-dia	16
upper-bar	3
upper-bar-dia	16
side-bar	2
side-bar-dia	16
stirrup-width	2
stirrup-height	2
stirrup-dia	6
stirrup-spacing	0.200000

Figure 4
Column section (left), size and material properties (middle), reinforcement (Right).

The model is exported as an XML file using the developed script which is then imported to SeismoStruct. The time required to execute the export depends on the performance of the operating system as well as the size of the model. For the given case study building, it takes almost 20-30 seconds to export the BIM model to XML file format. The modelled building in Revit and after importing to SeismoStruct is shown in Figure 5. After importing to SeismoStruct, it was found that all the geometrical properties, reinforcement information and footing are exported successfully from Revit to SeismoStruct, as shown in Figure 6.

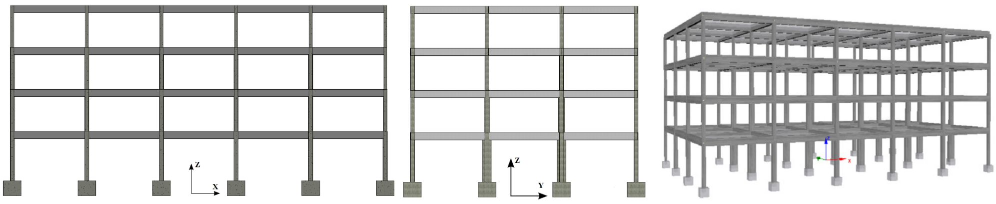


Figure 5
Structural model in Revit (Left) Structural model imported to SeismoStruct (Right).

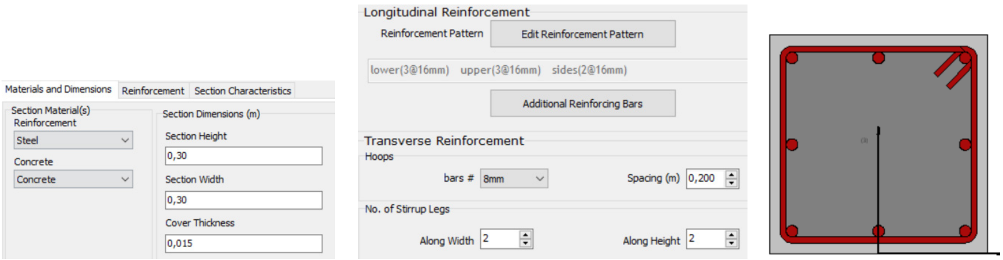


Figure 6
Section and materials (left), reinforcement data (middle), column section (right).

3.2. Pushover Analysis

After importing the BIM model to SeismoStruct, a few additional activities need to be defined in the pre-processing before performing the pushover analysis. This includes load distribution, loading phases, defining the target displacement and code response spectrum among others. The target displacement was assumed to be 2% of the total height of the building and the capacity curve was plotted up to that displacement. The structure is assessed at a target limit state of significant damage with a 10% probability of exceedance in 50 years showing significant damage with some residual stiffness and strength. Both triangular and rectangular lateral load distribution were assumed to perform analysis for seismic loads. The combination of permanent load and lateral loads were used to obtain the capacity curve for the building. The resulting capacity curves are shown in Figure 7 for uniform and triangular load distribution in both x and y directions.

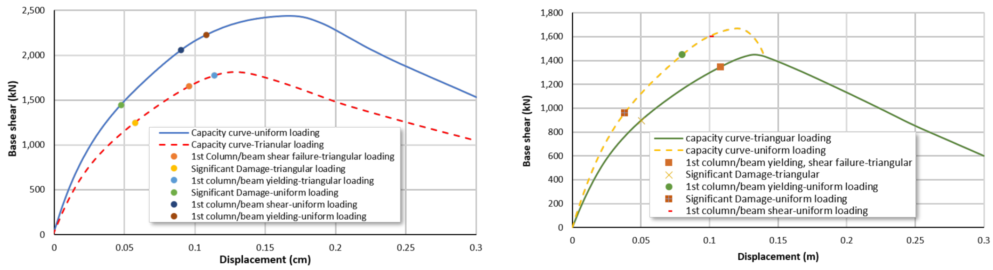


Figure 7
Capacity curves for lateral load patterns in x-dir (left) and y-dir (right).

The capacity curves depict that the building exhibits a higher capacity for a uniform lateral load configuration as compared to triangular lateral load when it is hit by an earthquake either in x or y-direction. The percentage difference between the maximum base shear of the case-study building for uniform lateral load pattern is 29% and 14% higher than the triangular lateral load pattern in x and y-direction respectively. Similarly, the case-study building shows more capacity when reaches to significant damage performance level for uniform lateral load than triangular lateral load pattern by 14% and 7% in x and y-direction respectively. However, the structure has a lower target displacement for the significant damage performance level for the uniform lateral load as compared to a triangular load pattern. For uniform lateral load in the y-direction, the structure shows significantly less ductility as compared to the other load pattern. Furthermore, the capacity of the structure increases roughly linearly in the beginning when the building is the elastic limit. However, the slope of pushover curves started decreasing gradually with an increase in lateral load due to the yielding of structural elements.

3.3. Effect of Infill walls

To understand the effect of the infill wall on the structural capacity and to fully explore the developed framework, various configurations of infill walls were applied to the structure as shown in Figure 8. In model 1, bare frame structure with no infill walls. In model 2, infill walls are provided throughout the plan and elevation while in model 3, infill walls are provided throughout except in the ground storey. In model 4, infill walls are provided in an irregular pattern both in plan and elevations to understand the effect of irregularity on the seismic capacity of the structure.

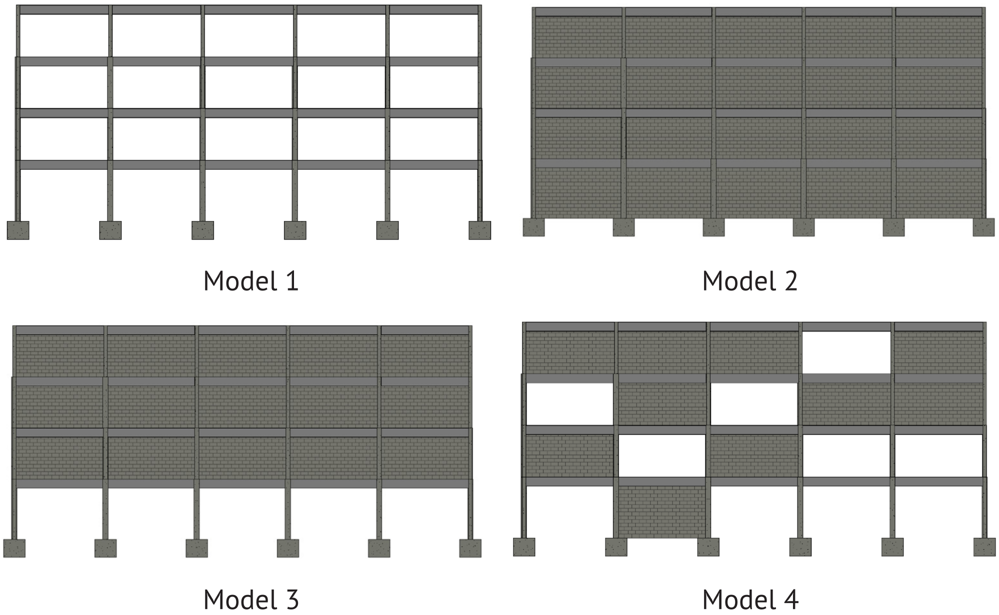


Figure 8
Building models to be analyzed.

After modelling in Revit, these structural models are exported using the framework into XML format and then imported into SeismoStruct. Pushover analysis of all the models is performed for different lateral load patterns and their corresponding capacity curves are obtained and shown in Figures 9-10.

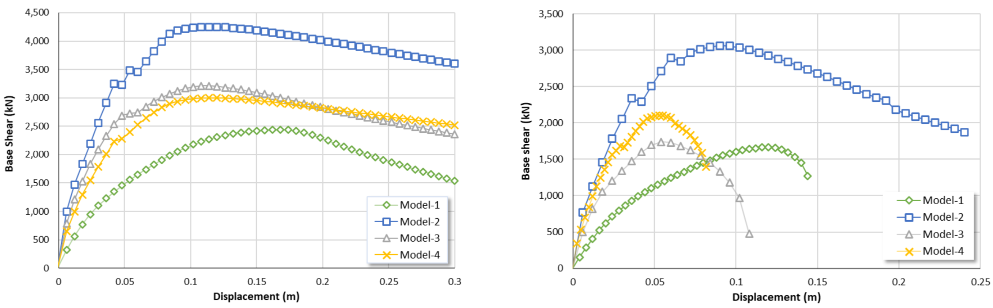


Figure 9
Uniform lateral load in the x-direction (left) and y-direction (right).

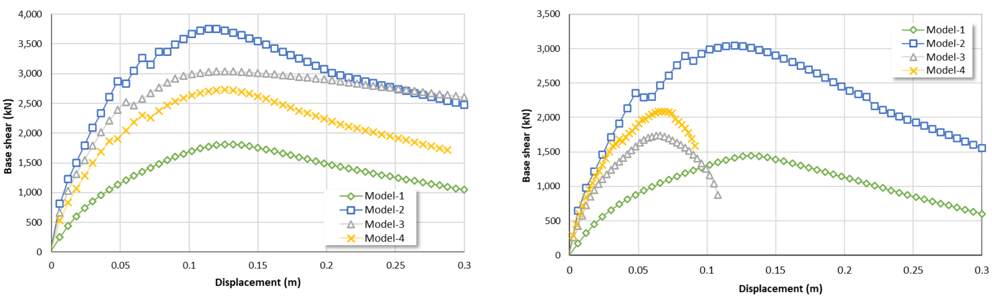


Figure 10
Triangular lateral load in the x-direction (left) and y-direction (right).

It can be observed that structural infill walls have significant effects on the behaviour of the structure under seismic forces. The presence of infill walls modifies both base shear and displacement and enhances the integrity and stability of RC frames.

However, the ductility of the structure decreases significantly in y-direction due to the addition of infill wall and the structure fail after reaching its ultimate base shear capacity. It can be seen that the structure has a higher load capacity in x-direction as compared to y-direction for both lateral load patterns.

4. Conclusions

The main objective of this work was to propose a BIM-based framework to facilitate the seismic assessment of existing RC buildings using non-linear pushover analysis. In this research, a framework based on a visual programming script was developed in Dynamo which is used to export data in XML format from the BIM model (in REVIT) to seismic analysis software (SeismoStruct) for its seismic assessment. A set of modelling rules were established for adequate export and discussed within the research, with a particularly time-effective process to model the reinforcement without the explicit need to model the actual reinforcement bars. The BIM model contained all the relevant data for export including geometry, material properties and reinforcement data. Furthermore, to study the effect of infill walls on the seismic capacity of the buildings, the interoperability framework allowed the direct import of the corresponding relevant data from the BIM authoring tool to the seismic analysis software. The framework is also capable of exporting the footings for the columns.

The following points can be concluded from the studies performed in this research.

- The geometry of all the structural elements including columns and beams is successfully exported from Revit to SeismoStruct, as well as non-graphical information such as material properties. Thus, the added value of having information available on a BIM model, allows the structural engineer to ease the tasks of modelling/input for the seismic analysis software, thus reducing errors and allowing to concentrate on the highly complex tasks of analysing results and taking decisions on the potential need for strengthening.
- Modelling of reinforcement is one of the complex tasks in the BIM modelling process. The alternative model developed herein, based on a set of non-graphic parameters has revealed itself effective. Time of modelling and chances of error in modelling is strongly reduced as compared to the full modelling of rebars in the BIM authoring tool.
- The results of the pushover analysis performed in this article show that the studied structure is sufficient to resist seismic loading. Although flexural and shear hinges are developed both in columns and beams at different storeys for different lateral load patterns, these were developed after target displacement had been achieved.
- The studies and research performed in this research show that infill walls have a significant contribution to the seismic capacity of the structure. The seismic capacity of the structure enhances up to 40% when infill walls are provided continuously both in plan and elevation.

- Overall, the proposed framework has satisfied the initially set requirements of interoperability and demonstrated the feasibility of operation with case study building.

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References

[1] ISO Standard. (2010) "Building Information Modelling – Information Delivery Manual – Part 1: Methodology and Format". ISO 29481-1:2010(E)

[2] Volk, R.; Stengel, J.; Schultmann, F. (2014): Building Information Models (BIM) for existing buildings – literature review and future needs – Automation in Construction 38, pp.109-127, DOI: 10.1016/j.autcon.2013.10.023.

[3] M. Khaddaj, I. Srour, (2016), "Using BIM to Retrofit Existing Buildings", in: Proc. International Conference on Sustainable Design, Engineering and Construction,Procedia Engineering 145 pp. 1526-1533, Elsevier.

[4] Raimar J. Scherer, Peter Katranuschkov, (2018), "BIMification: How to create and use BIM for retrofitting", Advanced Engineering Informatics 38, pp. 54-66

[5] J.J. McArthur, (2015), "A building information management (BIM) framework and supporting case study for existing building operations, maintenance and sustainability", Proc. Eng. 118 pp. 1104-1111.

[6] Zhen Xu, Xin zheng Lu, Xiang Zeng, Yongjia Xu, Yi Li, (2019), "Seismic loss assessment for buildings with various-LOD BIM data", Advanced Engineering Informatics, Volume 39, pp. 112-126.

[7] R. Volk, J. Stengel, and F. Schultmann, (2014), "Building Information Modelling (BIM) for existing buildings—literature review and future needs", Automation in Construction, vol. 38, pp. 109-127.

[8] U.Vitiello, V.Ciotta A.Salzano, D.Asprone, G.Manfredi, E.Cosenza, (2019), "BIM--based approach for the cost-optimization of seismic retrofit strategies on existing buildings", Automation in Construction Volume 98, pp. 90-101.

[9] M. Oraee, M. R. Hosseini, E. Papadonikolaki, R. Palliyaguru, and M. Arashpour, (2017), "Collaboration in BIM-based construction networks: a bibliometric-

-qualitative literature review", International Journal of Project Management, vol. 35, no. 7, pp. 1288-1301.

[10] Biagini C., Ottobri P. (2019) Federated Parametric Models for Seismic Risk Analysis in Existing Buildings. In: Cocchiarella L. (eds) ICGG 2018 – Proceedings of the 18th International Conference on Geometry and Graphics. ICGG 2018. Advances in Intelligent Systems and Computing, vol 809. Springer, Cham.

[11] Maggie Khaddaja, Issam Srour, (2016), "Using BIM to Retrofit Existing Buildings", International Conference on Sustainable Design, Engineering and Construction, Procedia Engineering 145, 1526-1533

[12] Seismosoft (2020), "SeismoStruct – A computer program for static and dynamic nonlinear analysis of framed structures". Available from URL: www.seismosoft.com

[13] Muhammad Yasir, (2020), "A framework for BIM-based assessment of seismic performance of existing RC buildings", Master Dissertation, European Master in Building Information Modelling, Universidade do Minho Escola de Engenharia.